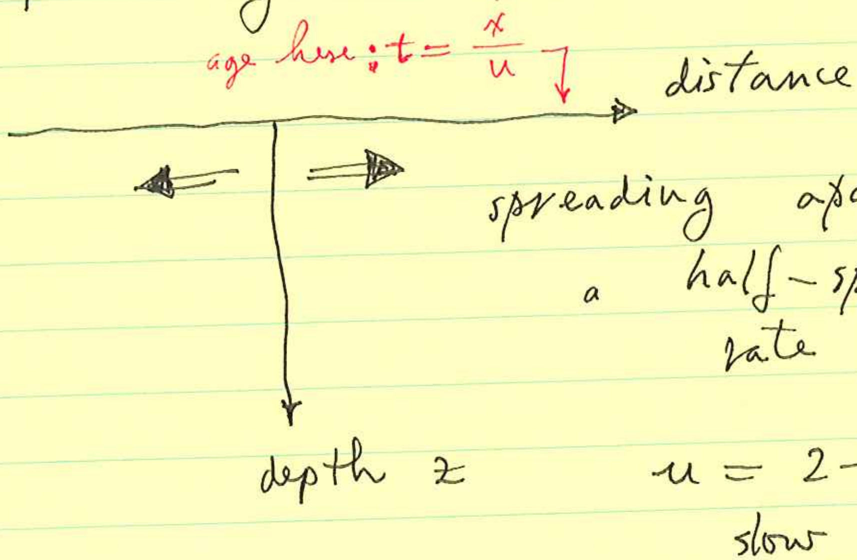
GEO 225 Week 4 Lecture #2

The oceanic <u>lithosphere</u>.

Today we will re-visit in more detail one aspect of the ⊕'s heat flow and temperature — the thermal structure of the spreading oceanic lithosphere — leads to one of most successful simple models of an important geologic process.

Model (highly idealized) of a spreading ridge

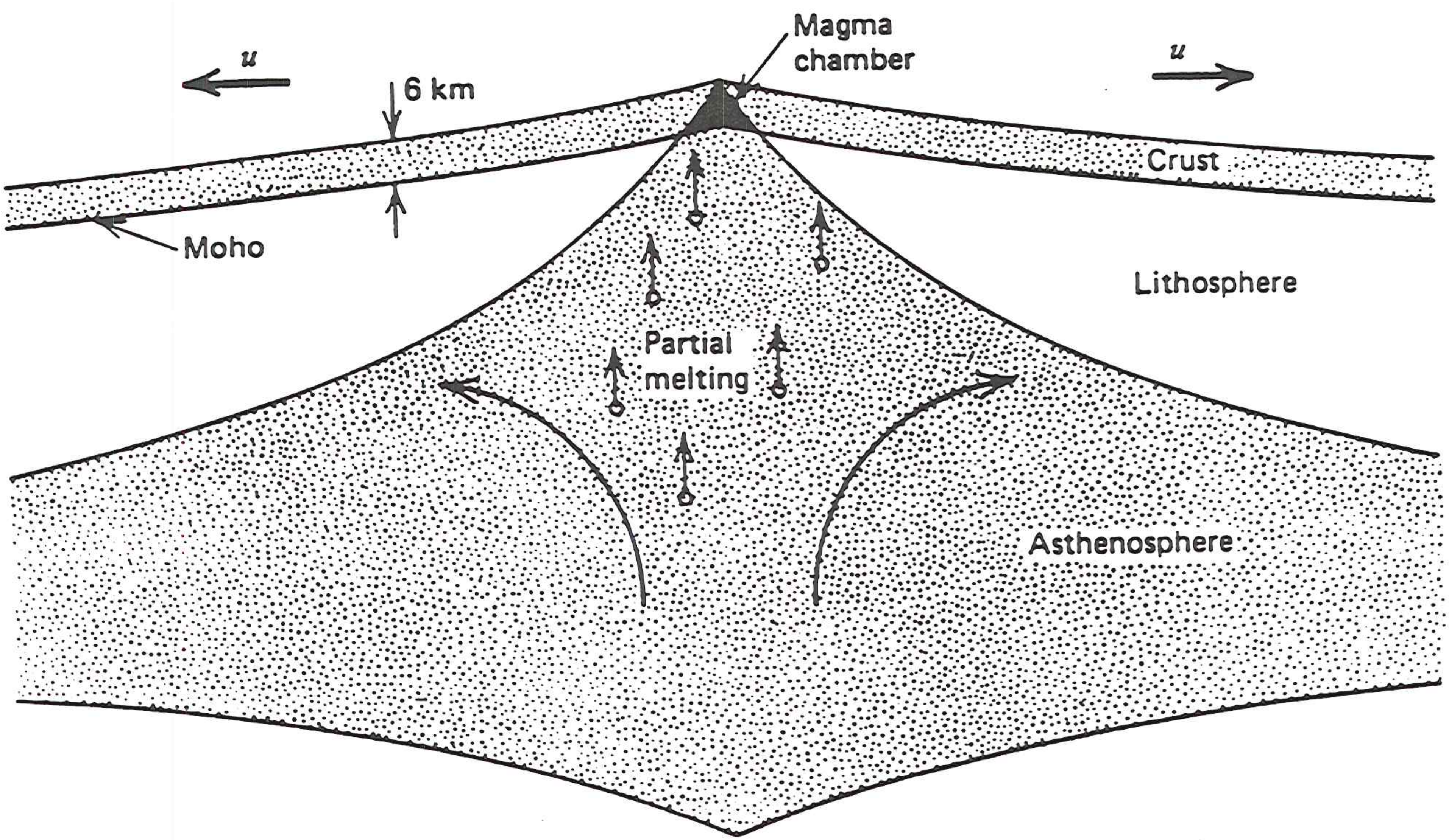


spreading apart at a half-spreading rate u

$u = 2-10$ cm/yr
slow fast
MAR EPR

Age of oceanic crust at a distance x from ridge axis

$$t \text{ (age)} = \frac{x}{u} \qquad \frac{\text{km}}{\text{km/sec}}$$



Magma chamber
u
u
6 km
Crust
Moho
Lithosphere
Partial melting
Asthenosphere

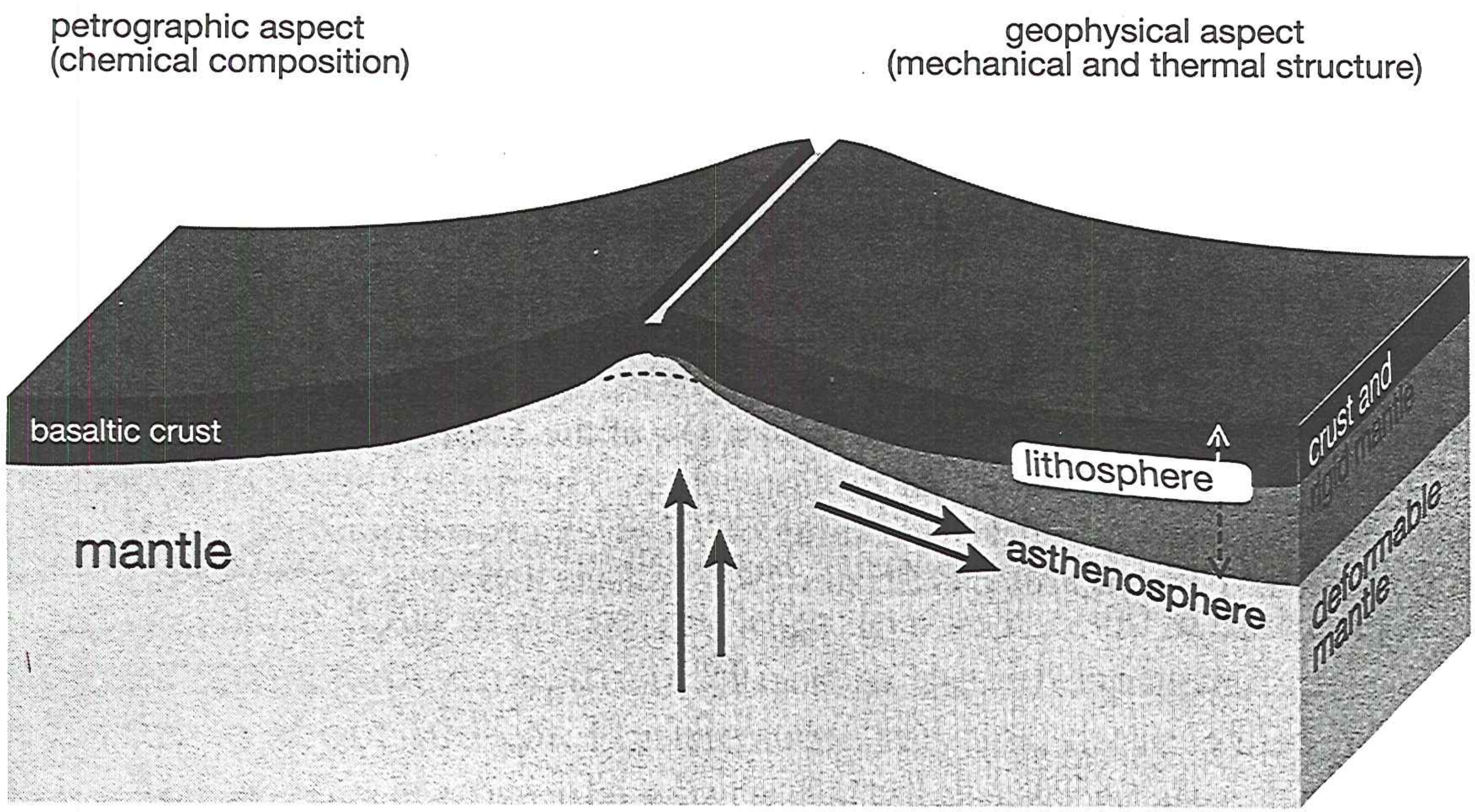


Figure 1.9
Petrographic aspect (chemical and mineralogical composition) and geophysical aspect (physical structure) of the ocean floors. Crust and mantle are chemically and mineralogically different entities. The concept of lithosphere vs. asthenosphere is based on differences in temperature and mechanical behaviour

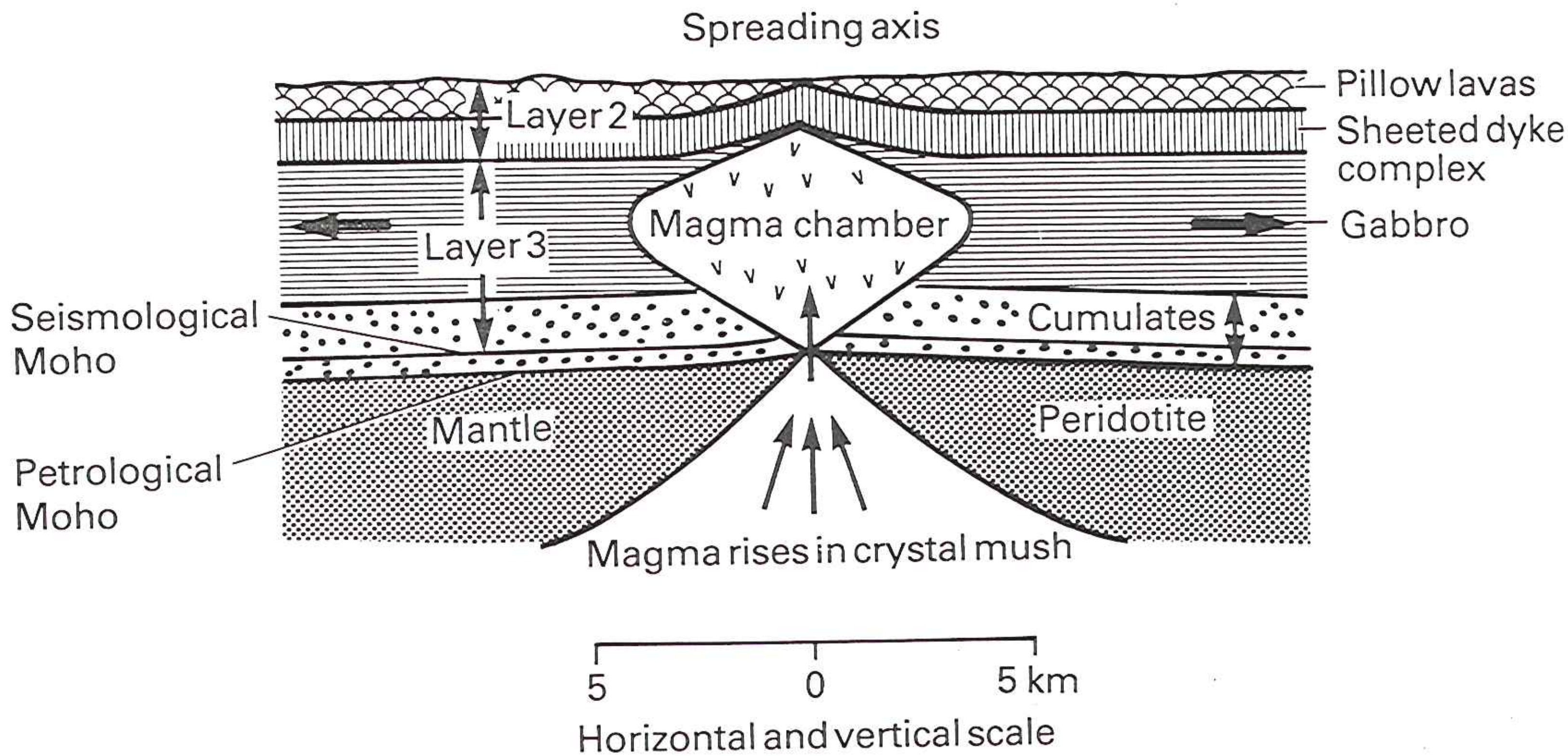


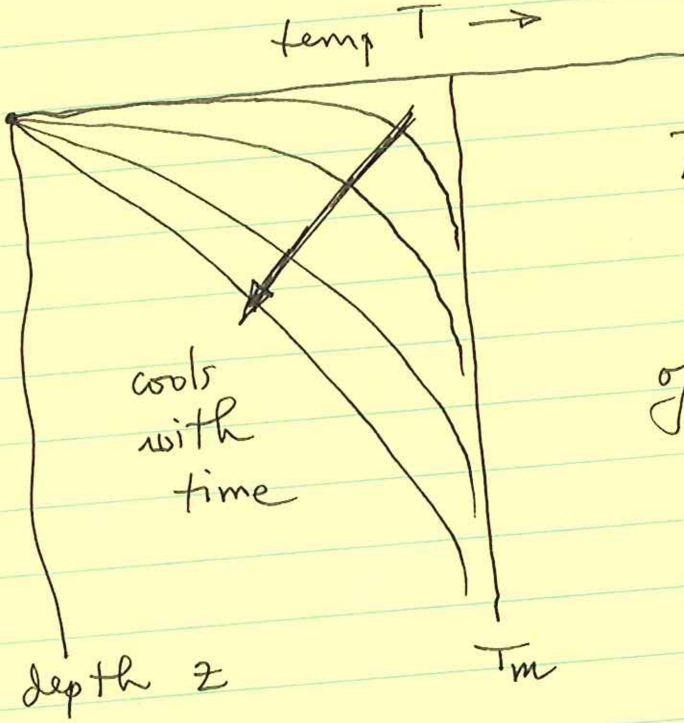
Fig. 6.15 Diagrammatic cross-section of the structure of the crust and upper mantle beneath the crestal region of a mid-ocean ridge. The shape of the magma chamber is based on the seismic reflection model of Detrick *et al.* (1987) (after Bott, 1982a).

The upwelling material just beneath the ridge is very hot — for simplicity say it is a constant temperature — T_m all the way down.

$\uparrow$ for mantle

$$\boxed{T_m \sim 1350°C}$$

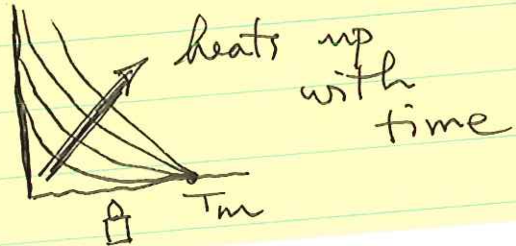
As the lithosphere spreads it cools off because it is cooled by the overlying seawater which is at $T \approx 0°C$.



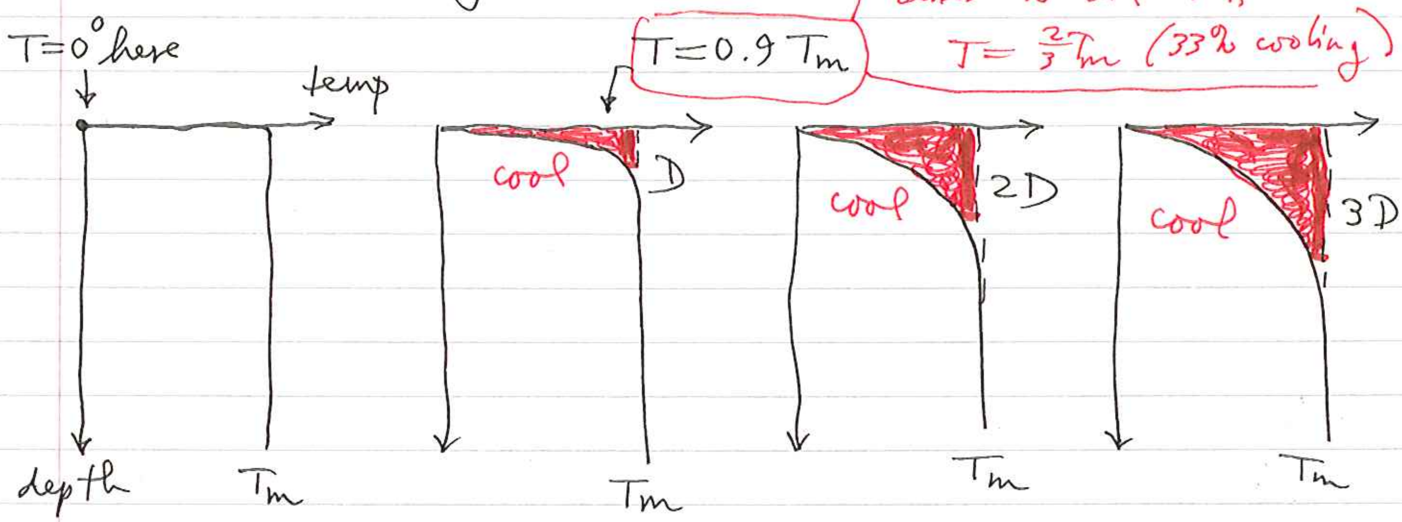
This is a simple problem — the conductive coolin
of a half-space

many other physical applications o
solution

e.g. if we turn problem around: heating of a very thick skillet



Better to draw picture as a series of snapshots



Cooling diffuses downward with time

Draw 4 snaphots with depths D, 2D and 3D.

Come back later and say they're pictures at 10 m.y., 40 m.y. and 90 m.y

In the deep mantle we approximate the ~0.6°C/km adiabatic gradient by

Can write down an analytic formula for the temperature as a function of depth z and time or age t

$$T(z,t) = \frac{2}{\sqrt{\pi}} T_m \int_0^{z/\sqrt{4kt}} e^{-u^2}\, du$$

$k = \kappa/\rho c$ thermal diffusivity

ρ = density gm/cm^3 or kg/m^3

c (specific heat) = heat required to raise temp. T by a fixed amount

By definition, a calorie is the amount of heat needed to raise T of one gram H_2O by 1°C.

$c(H_2O) =$ 1 cal/gm °C = 4180 $\frac{J}{kg\,°C}$

$c(\text{peridotite}) = 1170 \frac{J}{kg\,°C}$

$\rho(\text{peridotite}) = 3300$ kg/m^3

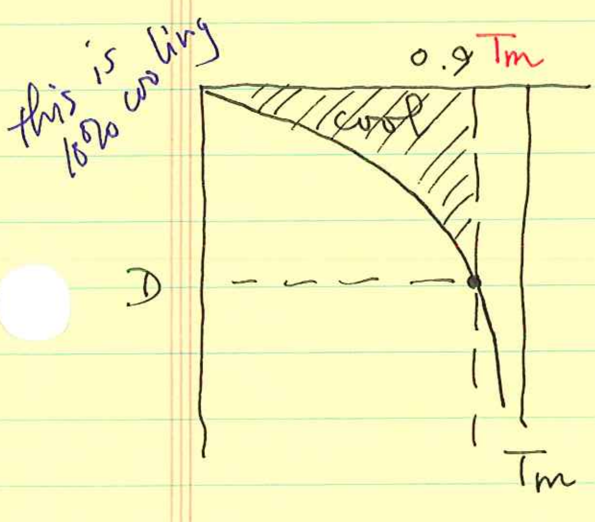
$$k = \frac{K}{\rho c} = \frac{\cancel{J}/s}{m\,^{\circ}\cancel{C}}\;\frac{m^3}{\cancel{kg}}\;\frac{\cancel{kg}\,^{\circ}\cancel{C}}{\cancel{J}} = \frac{m^2}{s}$$

material	k (cm^2/sec)
Cu	1.2
Al	1.0 ← forget this
Fe	0.2
H_2O	0.001
mantle rock	0.008 $\approx 1 \frac{mm^2}{sec}$
styrofoam	0.004

Suppose we ask — at a given time what is the depth D to which significant cooling has taken place

$\boxed{D = 1.4\sqrt{kt}}$ 33% cooling

"Significant" ≡ 90% of T_m



Then find that

$$\boxed{D = 2.32\sqrt{kt}}$$

← can be used to solve homework #1 & #2

other percentages give other numbers e.g.

95% → 2.76

Note that units check :

$$\sqrt{kt} = \sqrt{\frac{m^2}{s} \cdot s} = m$$

For $k = 0.008 \ cm^2/sec$, using

$1 \ year = 3.15 \cdot 10^7 \ s$

$1 \ m.y. = 3.15 \cdot 10^{13} \ s$

$$\boxed{D = 11.7 \sqrt{t}}$$

D in km, t in millions of years

$D = 7\sqrt{t}$ 33% cooling

thickness of lithosphere goes like square root of age!

Conductive cooling of the lithosphere is a slow process.

t (age in m.y.)	D (thickness of lithosphere in km)	33% cooling
0	0	0
1	11.7	7
10	37	22
50	83	49
100	117	70
200	165	100 km

oldest ocean crust in here →

A better way to present — realized after 10/10/96 lecture

Choose appreciably cooled to mean

$$\boxed{T = \frac{2}{3} T_m = 900°C}$$

i.e. cooling by $T_m - T = \frac{1}{3} T_m$ 33% cooling

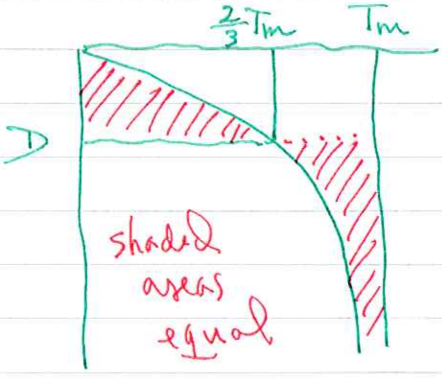
Then the law of ~~heat~~ cooling (or heating) is

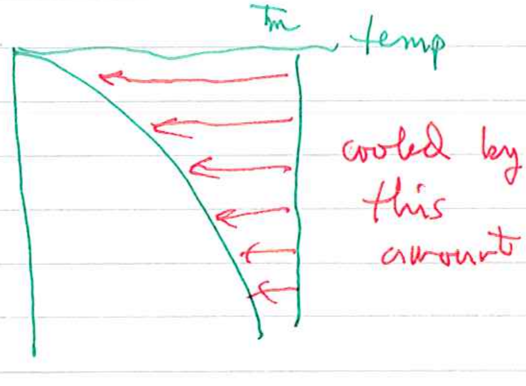
$$\boxed{\begin{aligned} D &= 1.4 \sqrt{kt} \\ D\,(km) &= 7 \sqrt{t\,(Myr)} \end{aligned}}$$

Then D_{max} ($t \simeq 200$ Myr) = 100 km

Now agrees well with Knopoff et al curve

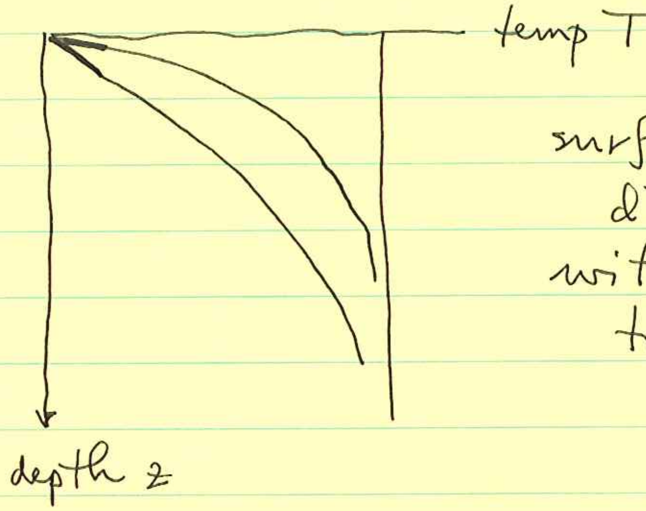
Need to replace lithospheric thickness determination on handout.





Two other parameters follow from this model:

The heat flow out the surface



surface gradient dT/dz decreases with time due to the cooling

$$q = \kappa \left(\frac{dT}{dz} \right)_{\text{surface}}$$

$$\boxed{q = \rho c T_m \sqrt{\frac{k}{\pi t}} = T_m \sqrt{\frac{\rho c \kappa}{\pi t}}}$$

$k = \kappa / \rho c$, diffusivity

units : $\frac{\cancel{kg}}{m^3} \; \frac{W \cdot s}{\cancel{kg}\, \cancel{{}^\circ C}} \; \cancel{{}^\circ C} \sqrt{\frac{m^2/s}{s}}$ ← i.e. J

$= \frac{W}{m^2}$ check

$$\underline{q} = \rho c T_m \sqrt{\frac{k}{\pi t}}$$

$$= (3300)(1170)(1350)\sqrt{\frac{8\cdot 10^{-7}}{\pi\,(3.15\cdot 10^{7})\,t}}$$

sec/yr

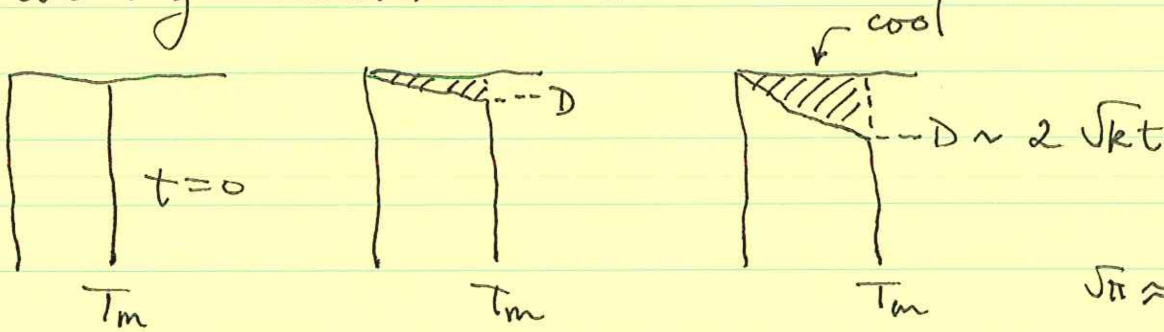
$$= \frac{0.47}{\sqrt{t\,(\text{m.y.})}}\ \frac{W}{m^2}$$

$$\boxed{\underset{\frac{mW}{m^2}}{\underline{q}} = \frac{470}{\sqrt{t}} \quad \text{millions of years}}$$

Goes like $\frac{1}{\sqrt{age}}$

Cooling depth goes like $\sqrt{age}$

This makes sense — in fact, to a very rough approximation, the cooling looks like



$\sqrt{\pi} \approx 2$

$$\frac{dT}{dz} \simeq \frac{T_m}{D} \qquad q \simeq k\frac{T_m}{D} \simeq \frac{\rho c k T_m}{2\sqrt{kt}} \sim \frac{1}{2}\rho c T_m\sqrt{\frac{k}{t}}$$

Finally, the sea-floor bathymetry.

As the lithosphere cools it thermally contracts.

This is determined by the thermal expansion coefficient α:

defn: α = fractional increase in volume $\delta V / V$ of a material due to 1°C rise in temp T

An increase in volume corresponds to a decrease in density — the constituent atoms are packed closer together at lower temp T

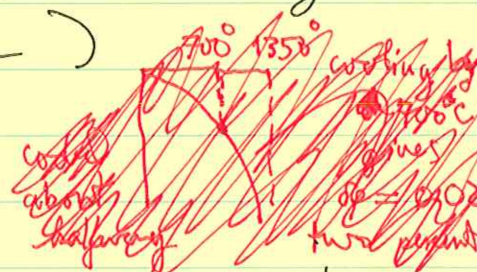
~~$\delta\rho = 86 \frac{kg}{m^3}$~~

~~cooling by 700°C~~

~~$\rho + \delta\rho = 3386 \frac{kg}{m^3}$~~

Typical value for rocks (high T peridotite in particular)

$$\boxed{\alpha = 3 \cdot 10^{-5} \, / \, ^\circ C}$$



Cooling by 1200 °C increases density by

$\approx$ 90% $T_m \approx 1200°$

use analysis on white page instead

$$\frac{\delta\rho}{\rho} = (3 \cdot 10^{-5})(1200) = 0.036 \quad \underline{\underline{3.6\%}}$$

$$\rho = 3300 \frac{kg}{m^3} \qquad \rho + \delta\rho = 3400 \frac{kg}{m^3}$$

Simplest approach — realized after 10/10/96 lecture:

Give $\frac{\delta\rho}{\rho} = \alpha\,\delta T$

For cooling by full 1350°C

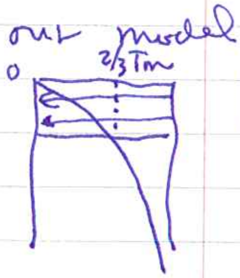
$$\frac{\delta\rho}{\rho} = (3\cdot 10^{-5})(1350) = 0.04$$

four percent

$$\boxed{3300 \rightarrow \cancel{3400}\ 3430}$$

$\delta\rho = \cancel{100}\ 130\ \mathrm{kg/m^3}$

Now derive

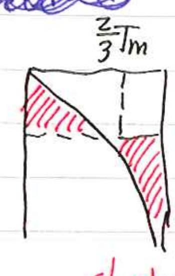


$$d = d_0 + \left(\frac{\delta\rho}{\rho-\rho_w}\right)D$$

$7\sqrt{t}$

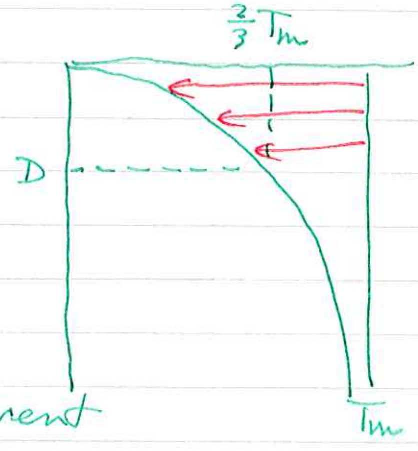
real picture — must integrate

$$\frac{\cancel{100}\ 130}{3300-1000} \approx 0.05$$



$$\boxed{d = d_0 + 350\sqrt{t}}$$

Actually



shaded areas equal

We said thickness D cooled by full 1350° — actually each layer cools (and increases in density) a different amount — must integrate — but a more careful analysis gives same result.

This is how much denser the lithosphere is than the asthenosphere

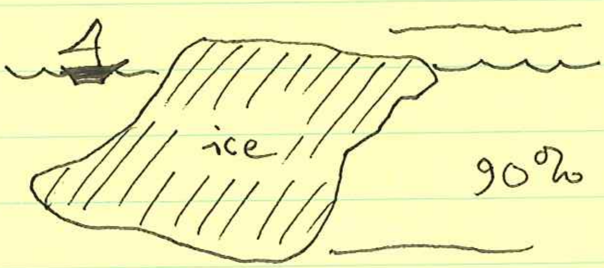
As a result of the increased density, the lithosphere sinks into the asthenosphere.

To find out how much it sinks we apply Archimedes principle, known in geology as the principle of isostasy.

Simple application: an iceberg in the ocean (or an icecube in a glass)

$$\rho_{ice} = 0.9\,\rho_{water} = 900\ kg/m^3$$

Ice expands upon freezing — a very unusual property



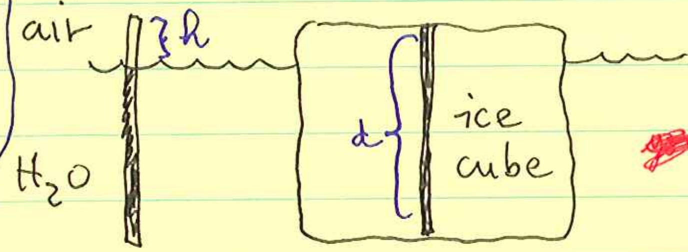
10% above – visible

90% below – this is why ship captains avoid icebergs

The principle of isostasy: equal mass in two columns

column balancing

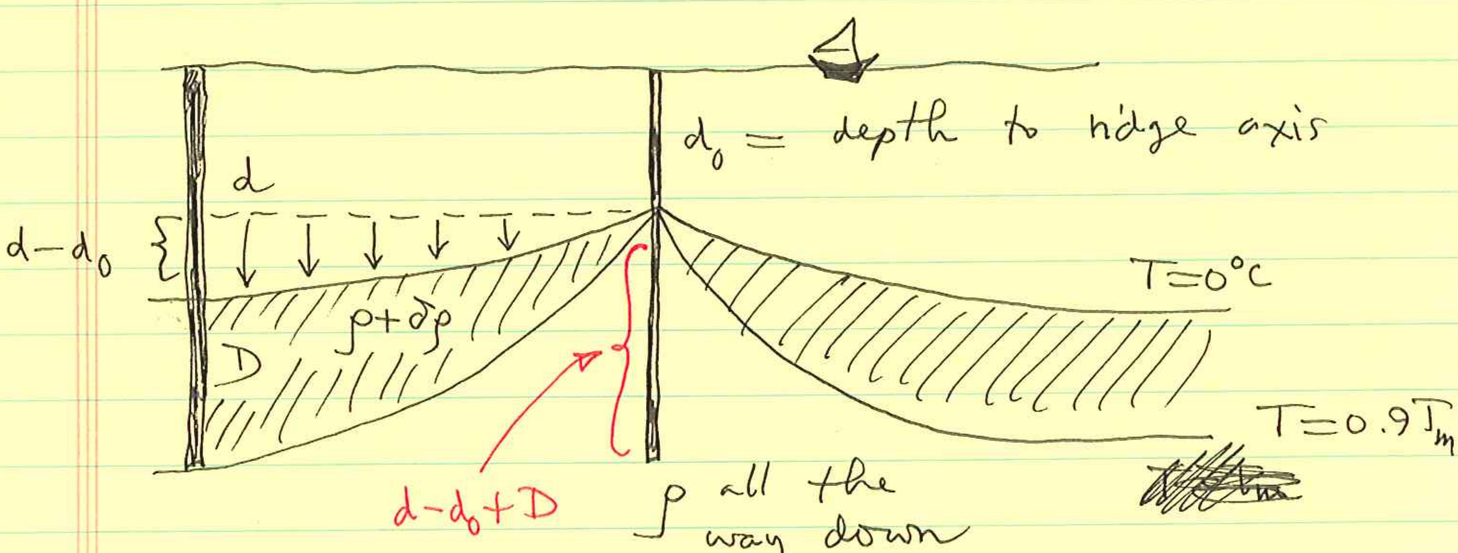
$$\boxed{\begin{aligned} \rho_i d &= \rho_w (d-h) \\ h &= \left(1-\frac{\rho_i}{\rho_w}\right) d \\ h &= \frac{1}{10} d \end{aligned}}$$



$\rho_{air} \approx 0$

~~go~~ need to draw similar sketch for homework #3

Applied to the oceanic lithosphere (note — heavy over light — inherently unstable — when lithosphere gets too old & heavy it subducts)



$$\underbrace{\rho_w d_0 + \rho\,(d-d_0+\cancel{D})}_{\text{ridge column}}$$

$$= \underbrace{\rho_w d + (\cancel{\rho}+\delta\rho)\,D}_{\text{off ridge}}$$

$$\rho_w d_0 + \rho_m (d-d_0+D)$$

$$= \rho_w d + \rho_m D + \int_0^D \delta\rho\, dz$$

$$\Rightarrow (\rho_m-\rho_w)(d-d_0) = \int_0^D \delta\rho\, dz = \int_0^\infty \delta\rho\, dz$$

see next page for simpler analysis

$$(\rho - \rho_w)\underbrace{(d - d_0)}_{\text{subsidence}} = \delta\rho\, D$$

recall $\sim \sqrt{age}$

Note: by $\delta\rho$ we really mean the lithosphere average:

$$\overline{\delta\rho}\, D = \int_0^D \delta\rho \, dz$$

In fact, a more careful analysis shows that

$$\overline{\delta\rho} = \frac{2}{2.32\sqrt{\pi}}\, \rho \alpha T_m \approx 0.49\, \rho\alpha T_m$$

$$\frac{(.02)(3300)}{3300 - 1000} = \frac{70}{2300}$$

$\overline{\delta\rho}/\rho \approx 2\%$ corresponds to cooling by $\sim 50\%$ $1350°C \rightarrow 700°C$

$$d = d_0 + \left(\frac{\overline{\delta\rho}}{\rho - \rho_w}\right) D$$

$$\boxed{d = d_0 + 2\left(\frac{\rho}{\rho - \rho_w}\right)\alpha T_m \sqrt{\frac{kt}{\pi}}}$$

$$\boxed{d = d_0 + \frac{350\ \text{m}}{\sqrt{\text{age in m.y.}}}}$$

An amazingly simple formula predicting ocean depths!

1 m.y. old lithosphere — very near the ridge has subsided by 350 m due to thermal contraction.

100 m.y. old lithosphere has subsided by 3.5 km.

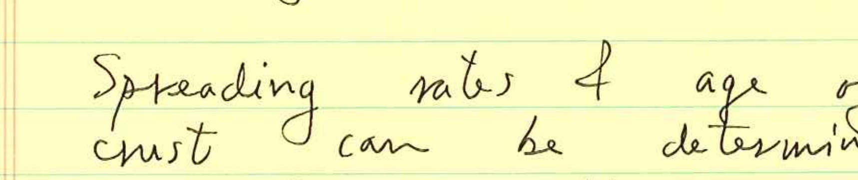
How is ocean depth measured — with acoustic pingers aboard surface ships. Speed of sound in seawater 1500 m/sec.

Spreading rates & age of ocean crust can be determined using magnetic anomalies, as we shall see later.

discuss this after showing Reykjanes and other profiles

For a careful comparison it is necessary to correct for <u>sediment thickness</u> (since $\rho_{seds} \neq \rho_{basalt}$ or peridotite)

$\rho_{seds} \neq \rho_{basalt}$



sed thickness — due to dead organisms increases with age — also affected by river influx — where correction most important

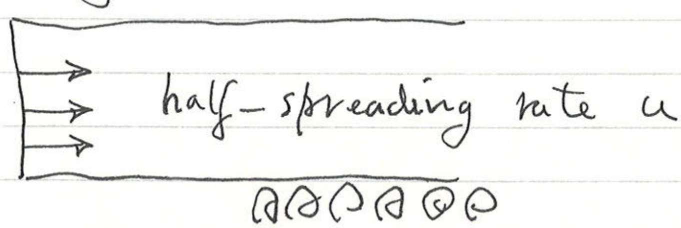
The sediment-corrected depths for ages < 80 m.y. agree very well with the model.

Beyond 80 m.y. the measured depths are slightly shallower.

Debate about the reason for this:

(1) thermal rejuvenation by passage over ascending mantle plumes or "hot spots"

(2) cooling plate (rather than cooling halfspace) model



temp. at base maintained at T_m by small-scale convection

The lithospheric thickness prediction $D = 7\sqrt{t}$ can be compared with seismic measurements.

Find that $D \sim \sqrt{\text{age}}$ as predicted.

Finally, can compare the <u>heat flow</u>

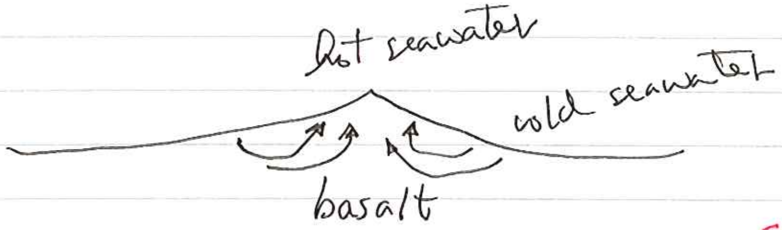
$$q = \frac{470}{\sqrt{t}}$$

Find a good agreement except for young ages near the ridges where the heat flow is

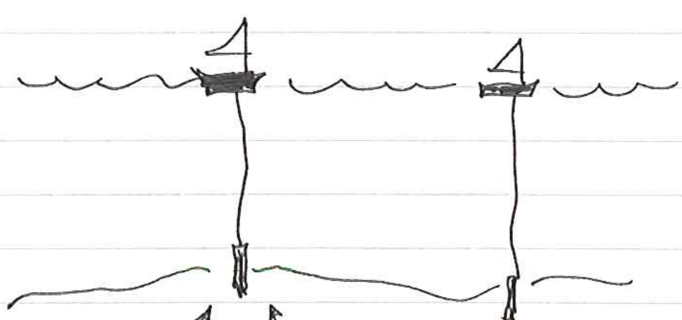
(1) highly variable on a small scale

(2) on average, lower than $\frac{470}{\sqrt{t}}$

Reason for both — hydrothermal circulation of seawater through the crust



see Figs 6.26 & 6.27 in Judson & Richardson



near a hot spring, heat transported by H_2O convection

not near a hot spring — normal

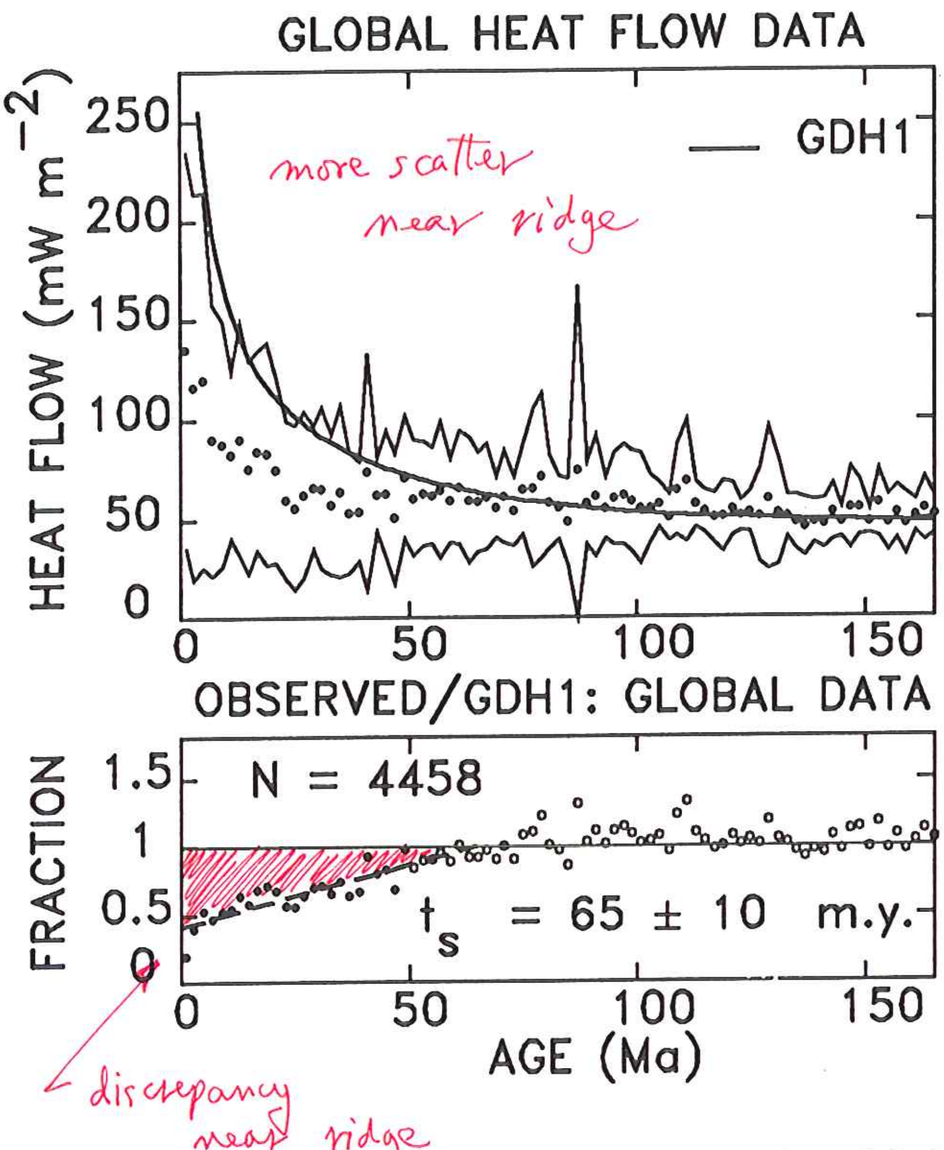
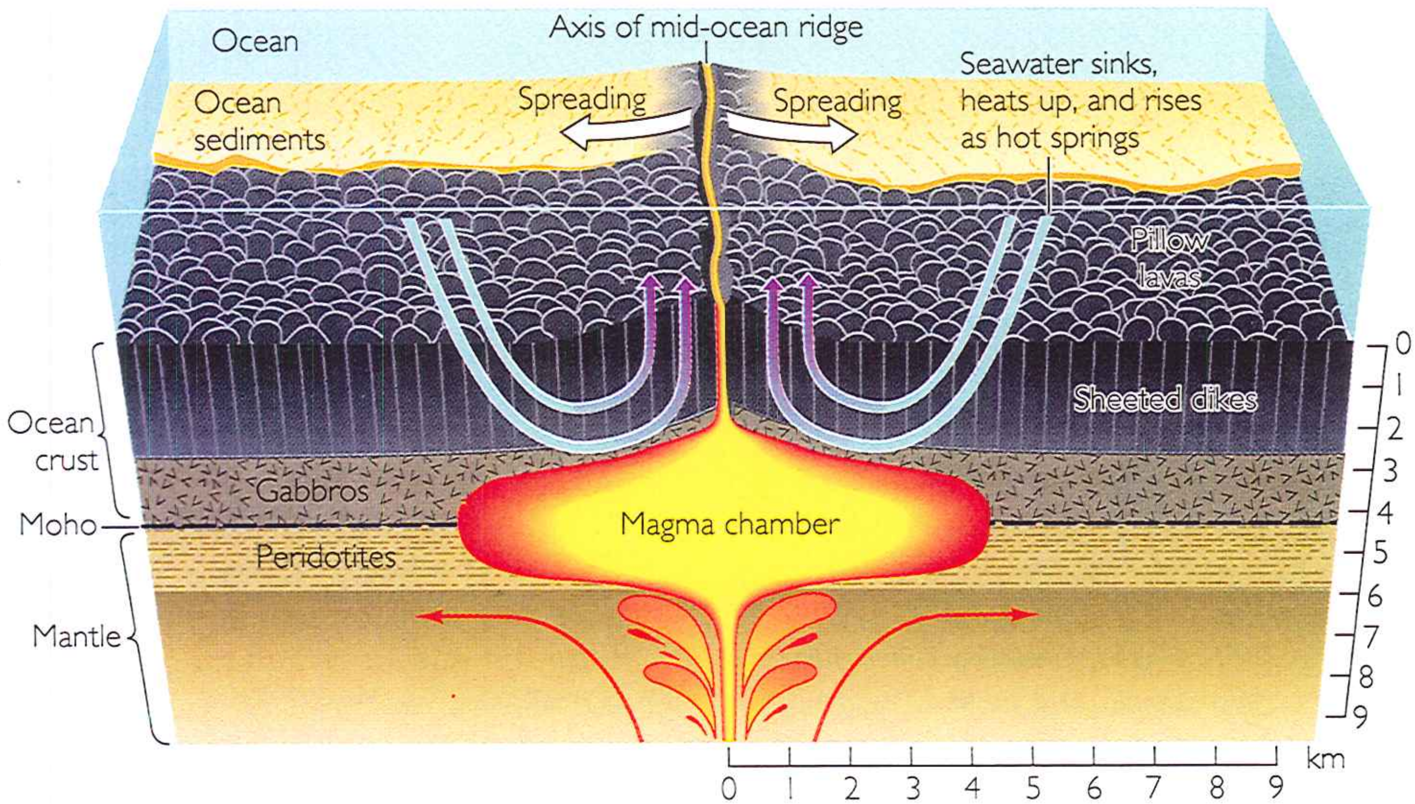


Fig. 2. Observed heat flow versus age for the global data set from the major ocean basins and predictions of the GDH1 model, shown in raw form (*top*) and fraction (*bottom*). Data are averaged in 2-m.y. bins. The discrepancy for ages < 50-70 Ma presumably indicates the fraction of the heat transported by hydrothermal flow. The fractions for ages < 50 Ma (closed circles), which were not used in deriving GDH1, are fit by a least squares line. The sealing age, where the line reaches one, is 65 ± 10 Ma [107].


Ocean
Axis of mid-ocean ridge
Seawater sinks, heats up, and rises as hot springs
Ocean sediments
Spreading
Spreading
Pillow lavas
Sheeted dikes
Ocean crust
Gabbros
Moho
Magma chamber
Peridotites
Mantle
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9 km

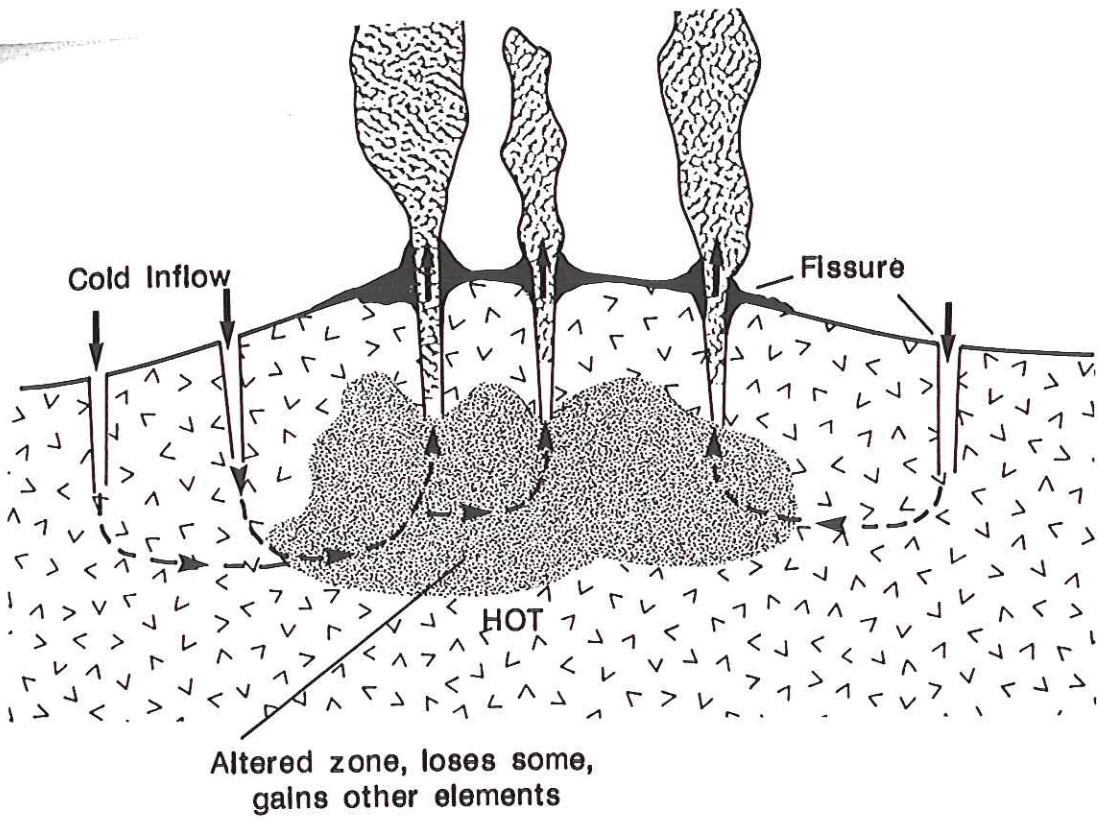
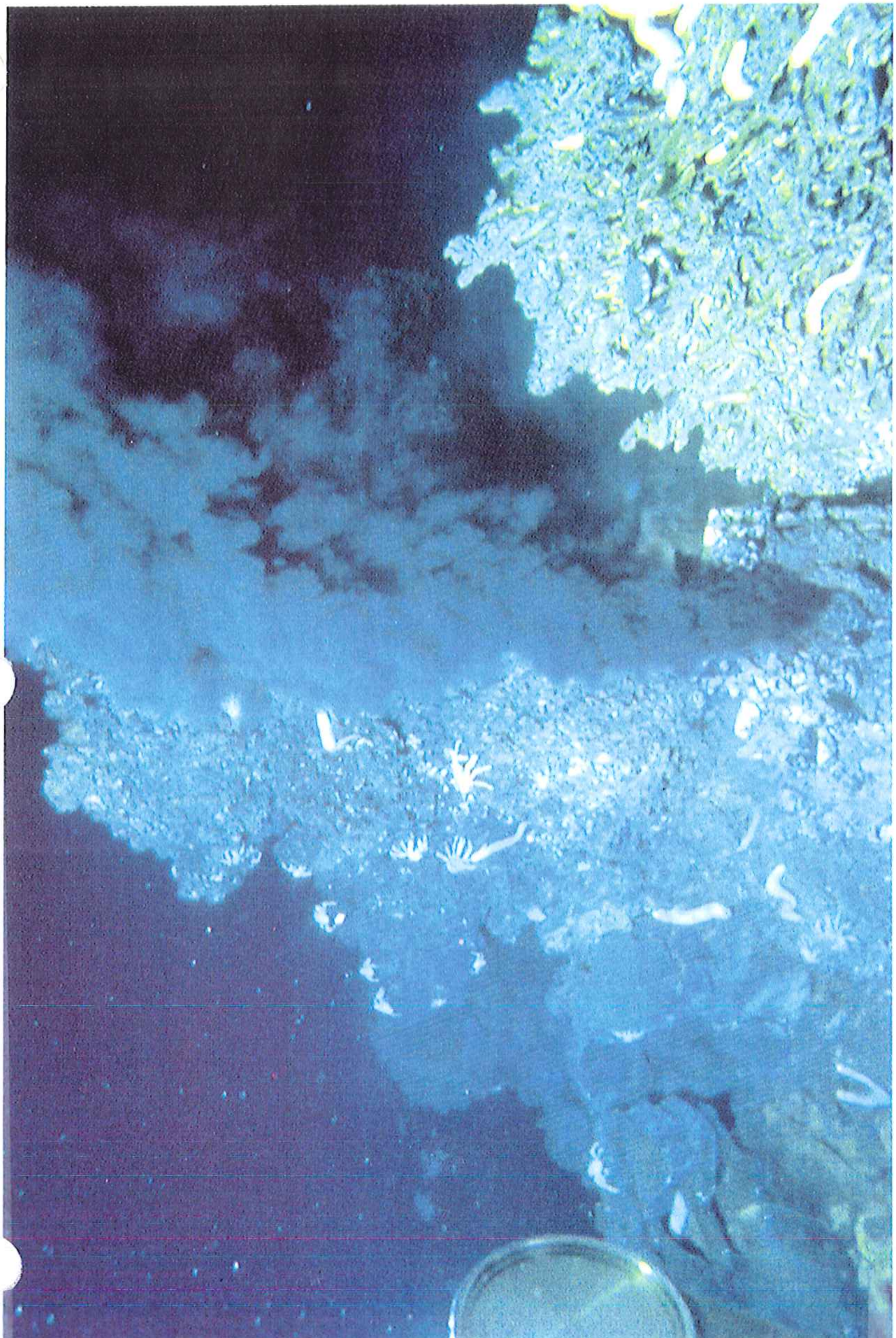
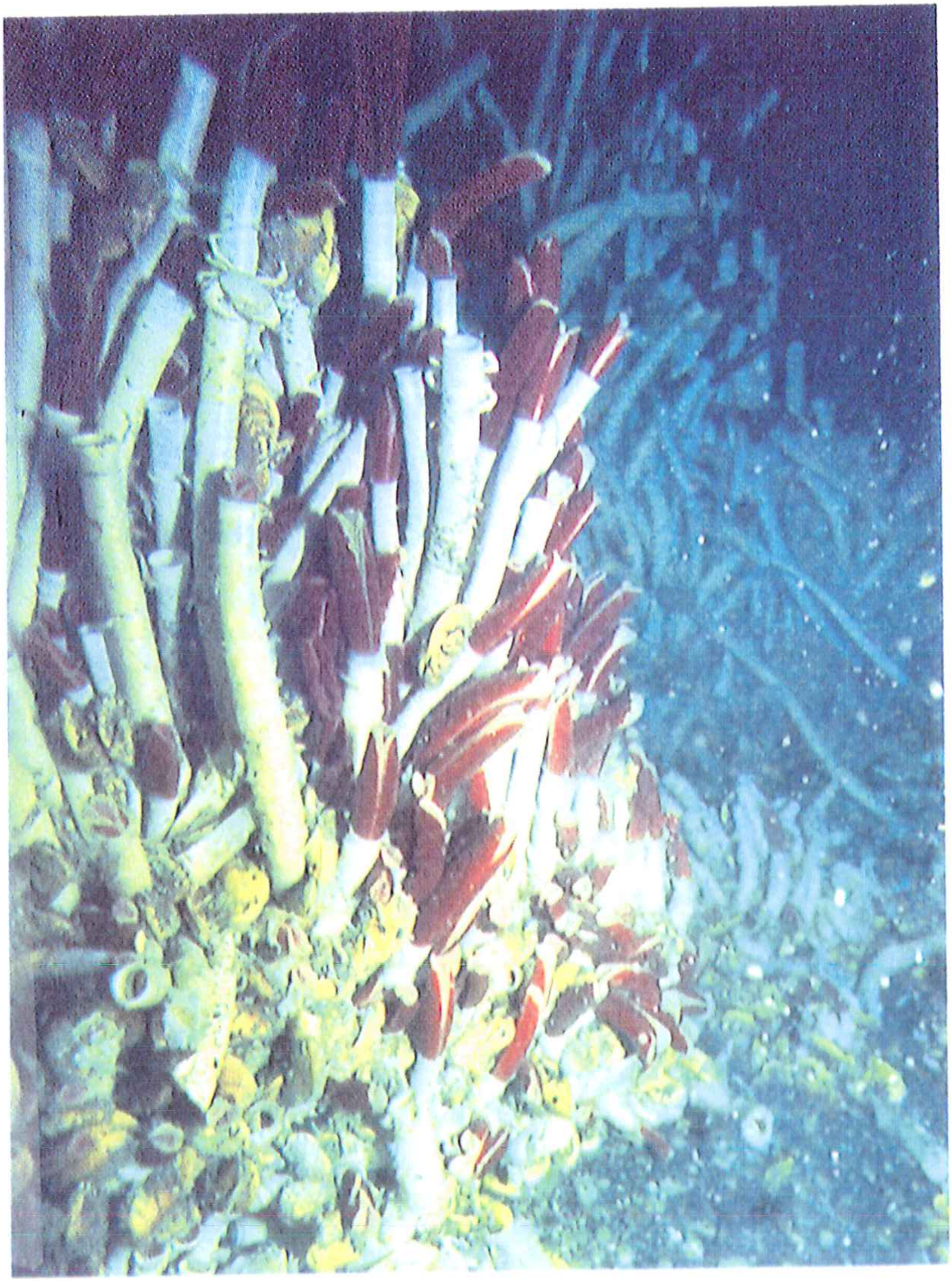


Figure 14.3. The hot crust of the mid-ocean ridges is cooled partly by conduction of heat to the seafloor. Almost as much heat is carried away by cold ocean water that enters fissures and circulates through the hot crust. Once heated, the water returns to the ocean as hotsprings, with exit temperatures that range from a few degrees to 350 °C. While passing through the hot crust the seawater leaves some constituents behind and extracts others, thereby altering the rocks substantially. At the vents, manganese and iron oxides and hydroxides (black) are deposited that may contain valuable amounts of such metals as silver and copper.

not boiling because
of high pressure





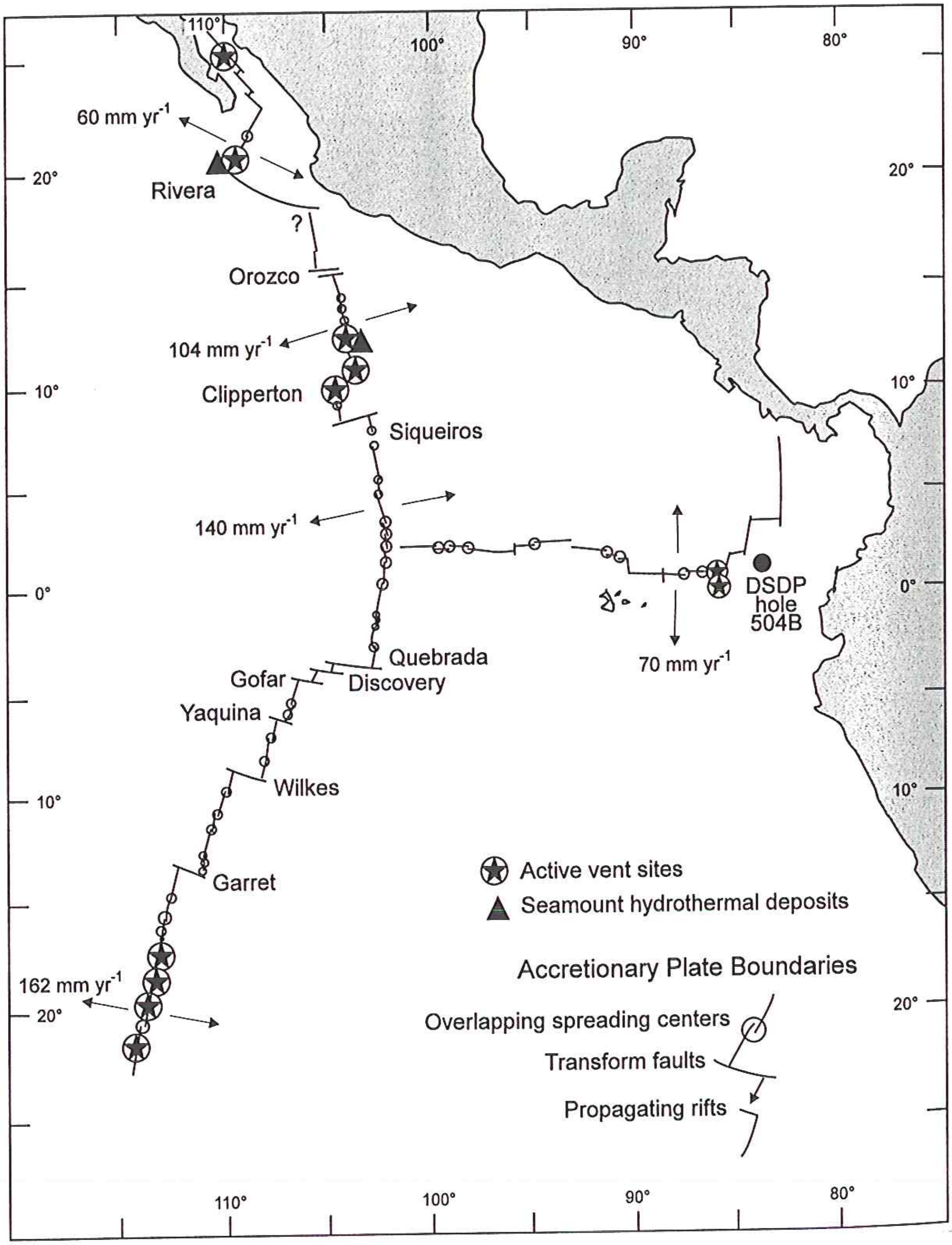


Figure 7.29. Distribution of known sites of active hydrothermal venting along the East Pacific Rise and Galapagos Rift. Solid stars mark sites of active venting; solid triangles mark locations of off-axis seamounts associated with hydrothermal mineral deposits. Solid circle shows location of DSDP Hole 504B. (Haymon 1989)

Only the conductive heat flow is measured.

In well-sedimented (high productivity) areas, the H_2O conduits get plugged up.

q from such areas matches $\frac{470}{\sqrt{t}}$ extremely well.

Existence of submarine hot springs first inferred on basis of heat flow measurements.

First direct evidence 1977 — now dozens of vents have been explored by submersible.

Black smokers — H_2O at 400°C — kept from boiling by high pressure — sulfide precipitation

Total rate of circulation of seawater through the crust

$$6000 \ \frac{m^3}{s} \approx \frac{1}{3} \times \text{flow of Mississippi at New Orleans}$$

Mississippi $= 18{,}000 \ \frac{m^3}{s}$

Entire ocean cycled through seafloor every 7 m.y. or 600 times since beginning of ⊕

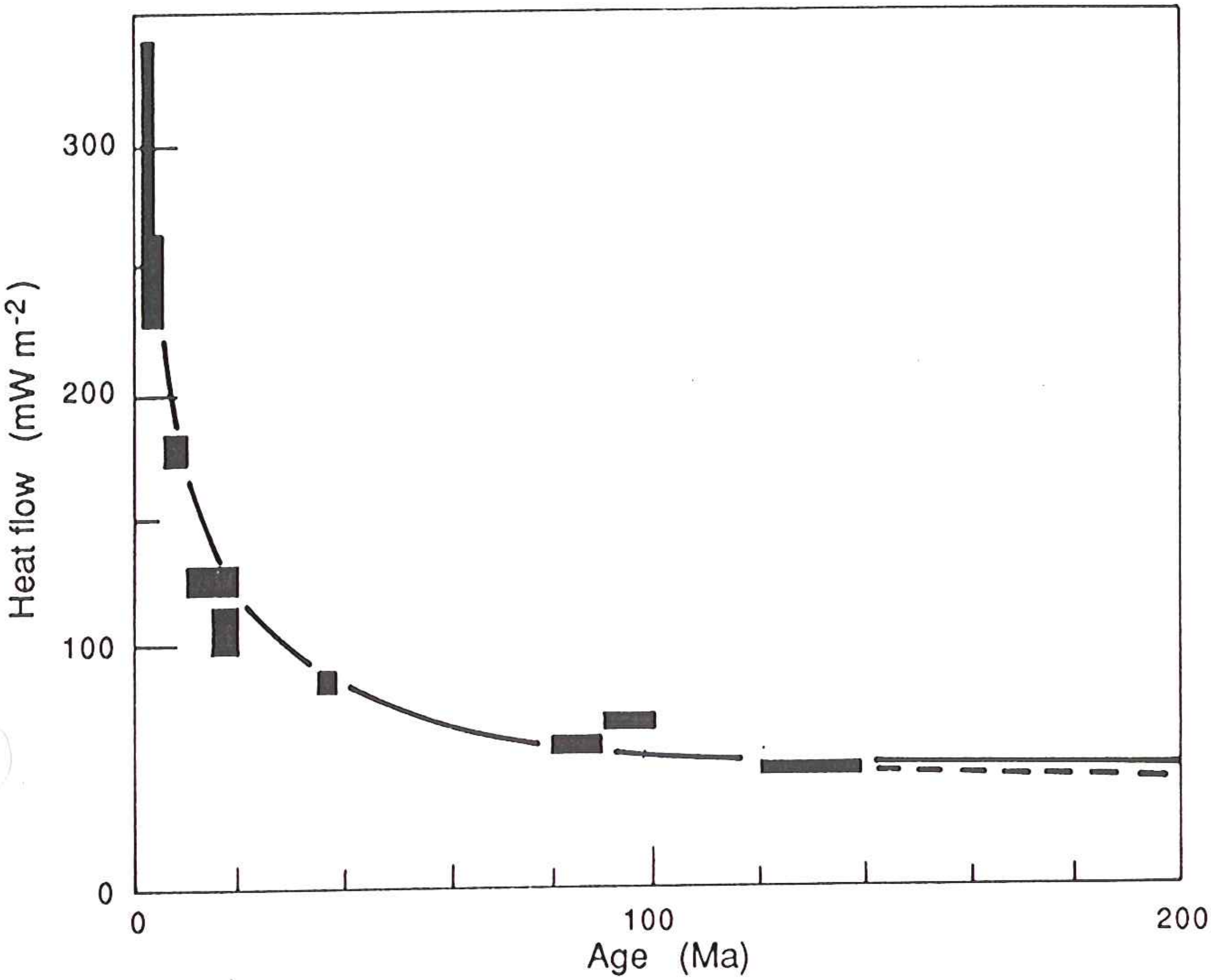


Figure 7.7. Mean heat flow for well-sedimented areas in the North Pacific and North Atlantic plotted against age. Solid curve is the heat flow predicted by the plate model; dashed curve, the heat flow predicted by the boundary layer model. (After Sclater et al. 1980.)

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 (including volcanoes)	149		8.8
Continental shelves	52		2.8
Total continents and continental shelves	201	57	11.6
Deep oceans	282		27.4
Marginal basins	27	25% of total	3.0
Conductive contribution	$\frac{1}{3}$ of oceanic	66	20.3
Hydrothermal contribution		33	10.1
Total oceans and basins	309	99	30.4
Worldwide total	510	82	42.0

Note: Estimate of convective heat transport by plates is ~65% of total heat loss; this includes lithospheric creation on oceans and magmatic activity on continents. Estimate of heat loss as a result of radioactive decay in the crust is ~17% of total heat loss. Estimate of the heat loss of the core 10^{12}–10^{13} W; this is a major heat source for the mantle.

Source: Sclater et al. (1980, 1981).

$Q_{hydrothermal} \approx 6 \cdot 10^{12}\ W \approx$ ~~20%~~ 25% Q_{total}

← due to near-ridge deficit

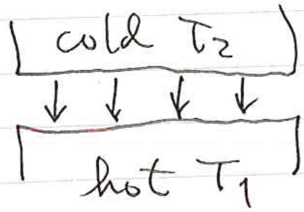
For example, had been known for a long time that there was much less Mg in the oceans than should have been given measured amount coming in in rivers.

H_2O in vents has no Mg — it is all stripped out through the crust during passage through the crust

Ancient vents now obducted onto cont. margins are also a source of heavy metal sulfide ores.

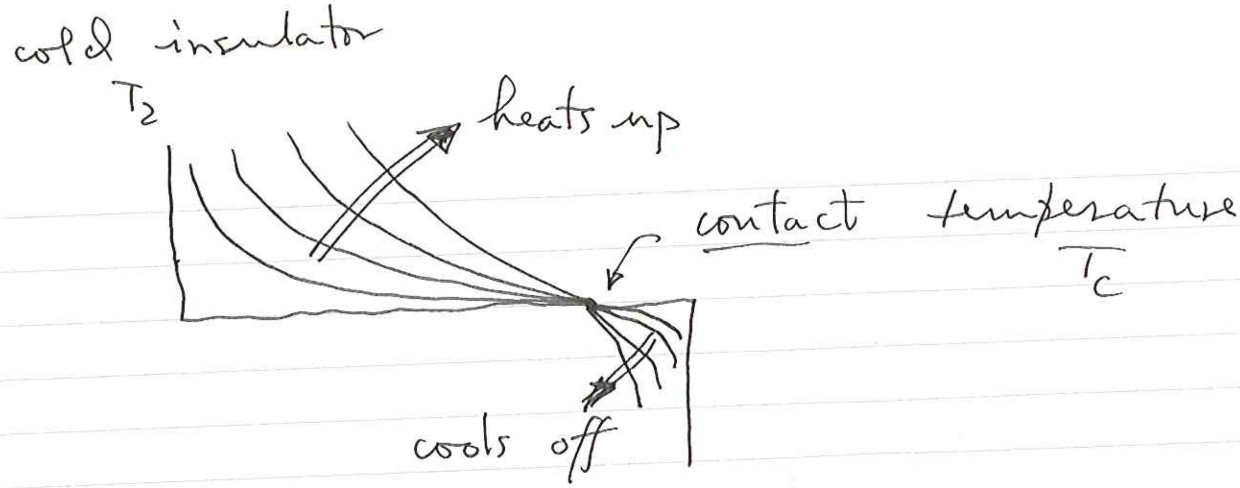
Aside: with a slight extension the above problem can be extended to deal with another application.

Two materials : ρ_1, c_1, k_1
ρ_2, c_2, k_2



$T_1 > T_2$

The heat flow from the hot (q_1) must equal that into the cold (q_2)



$T_1 > T_2$
hot conductor

$$b = \sqrt{\rho c \kappa} = \rho c \sqrt{k}$$

$$q_1 = \frac{b_1 (T_1 - T_c)}{\cancel{\sqrt{\pi t}}} \qquad q_2 = \frac{b_2 (T_c - T_2)}{\cancel{\sqrt{\pi t}}}$$

$$b_1 (T_1 - T_c) = b_2 (T_c - T_2)$$

$$\boxed{T_{contact} = \frac{b_1 T_1 + b_2 T_2}{b_1 + b_2}}$$

note that $T_c \approx T_1$ if $b_1 \gg b_2$ i.e. if material 1 is a much better conductor than material

material	b ($J/m^2\,^\circ C\,\sqrt{s}$)
Fe	17,000
concrete	1700
oak	500
cork	90
human skin	1100

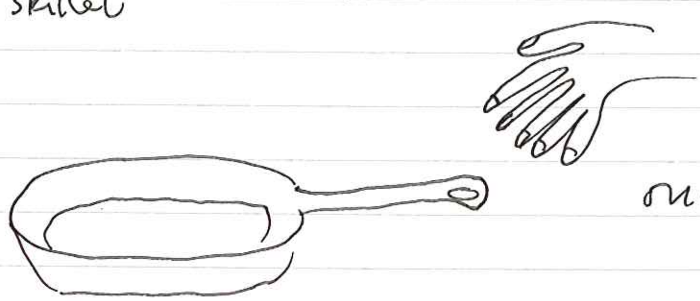
$T_{skin} = 30°C$

$T_{max} = 45°C$ without blistering

$$T_{contact} = 45°C = \frac{b_{skin}\, 30° + b_{Fe}\, T_{skillet}}{b_{skin} + b_{Fe}}$$

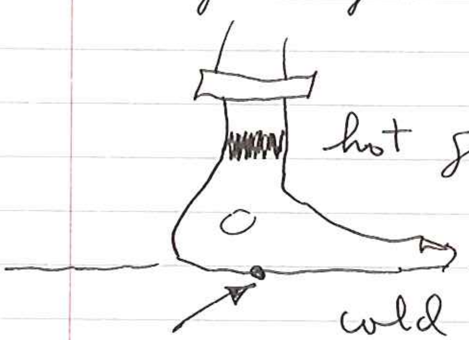
$T_{skillet} = 46°C$

six fingers!



ouch!

A foot feels noticeably cold if $T_c = 25°C$



hot foot $T_1 = 30°C$

cold floor $T_2 = T_{floor}$

$T_c = 25°C$

oak floor 15°C
cork floor −30°C — best insulator
concrete floor 22°C

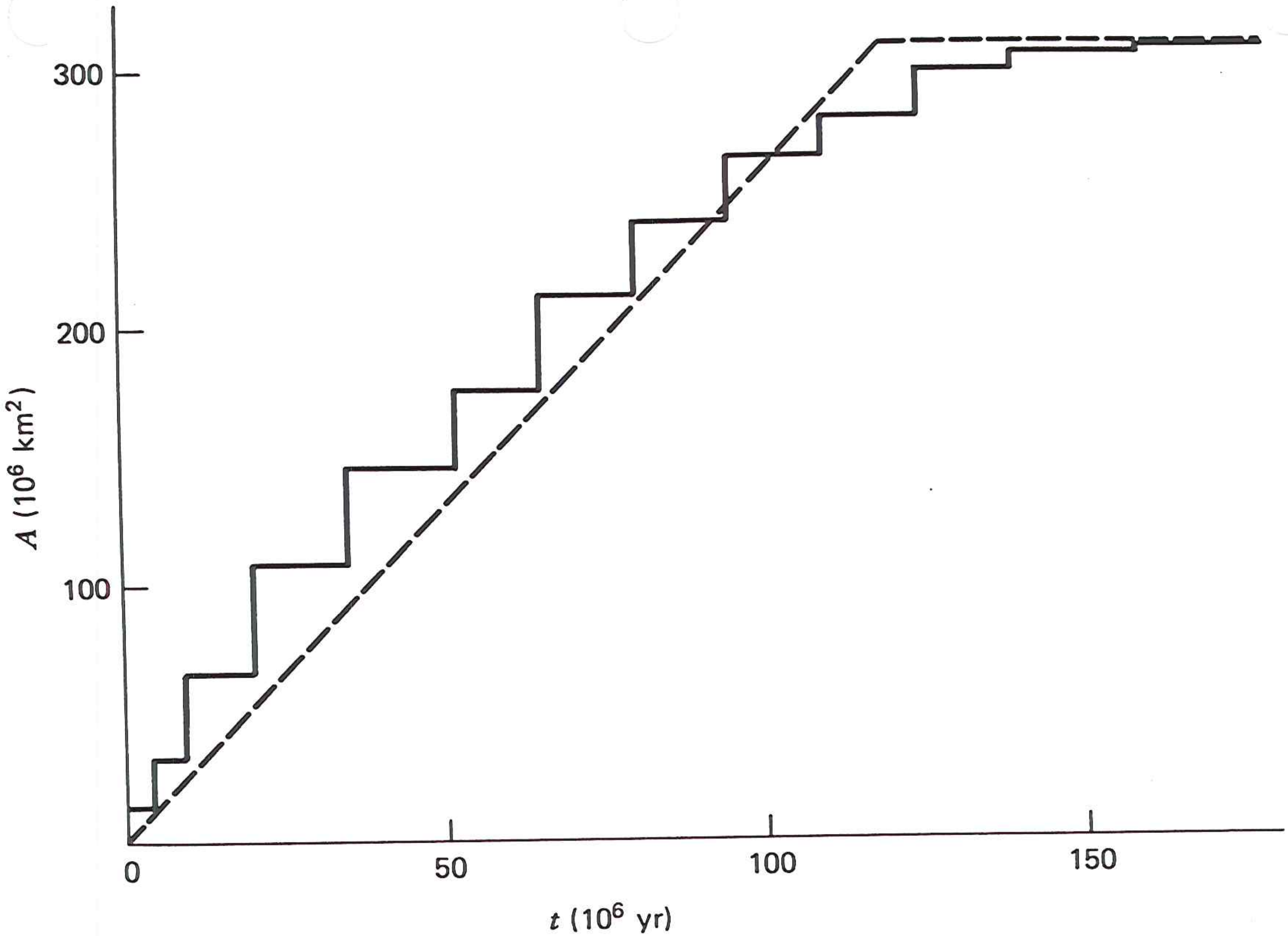


Figure 4-26 Cumulative area of seafloor A as a function of age t (the area of seafloor with ages younger than a given age) (solid lines). The dashed line is a cumulative area function for a model seafloor produced at a constant rate of $0.134\ m^2\ s^{-1}$ and subducted at an age of 120.8 Myr.

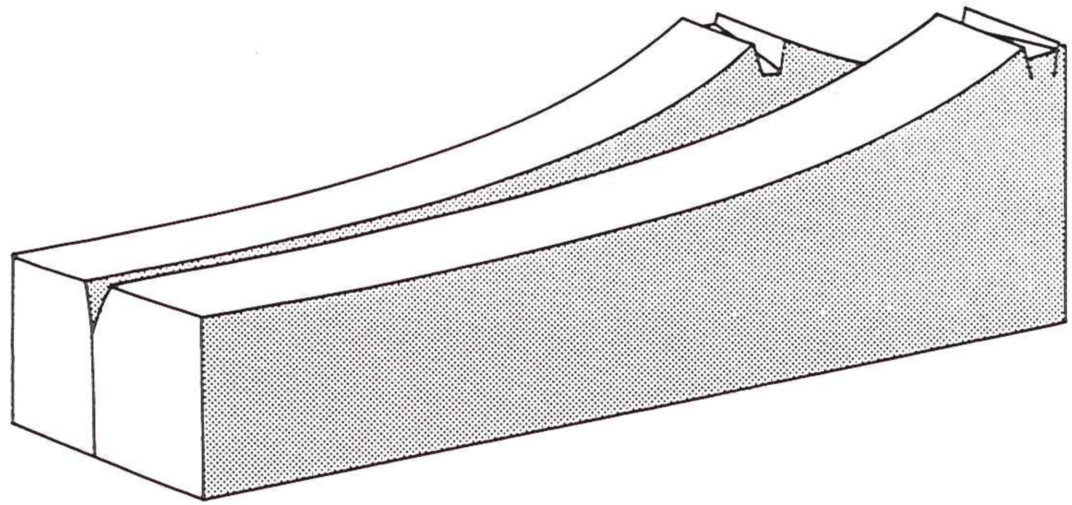


Fig. 7.5 Differential topography resulting from transform faulting of a ridge axis.

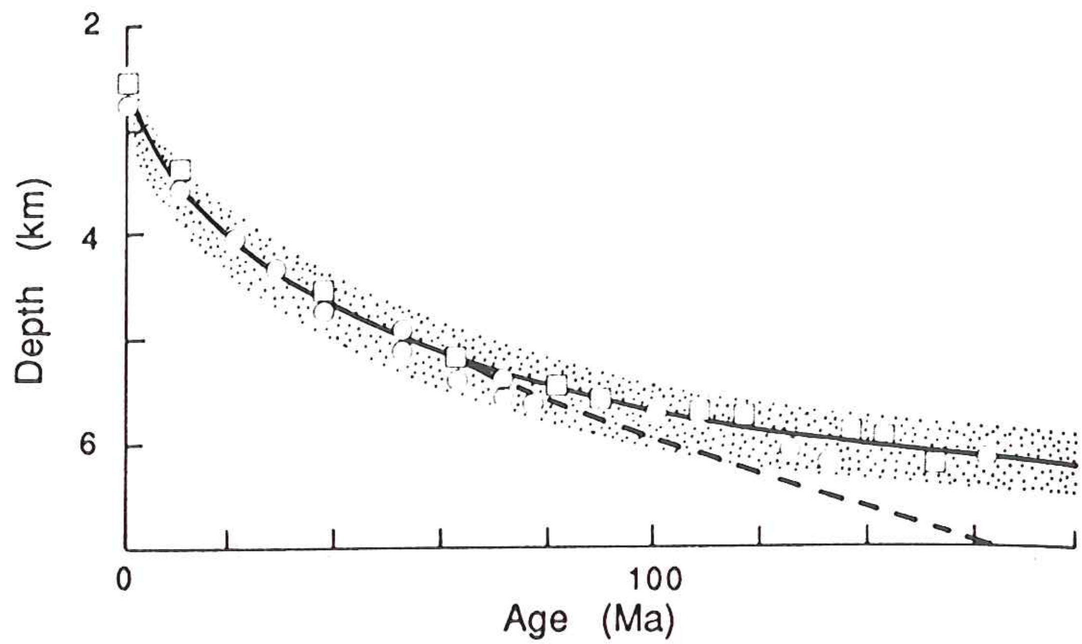


Figure 7.8. Mean depth for the North Atlantic (squares) and North Pacific (circles) plotted against age. Shaded region represents the scatter in the data. Solid curve is the depth predicted by the plate model; dashed line, the depth predicted by the boundary layer model. (After Sclater et al. 1980.)