NPTEL ONLINE CERTIFICATION COURSES

EARTHQUAKE SEISMOLOGY

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Module 12 : Seismology and Plate tectonics, Spreading centers, Subduction zones.
Lecture 02: Spreading centers and evolution of oceanic lithosphere

CONCEPTS COVERED

- Spreading Centers
- Evolution of the oceanic lithosphere
    - Half space model
    - Plate model
- Summary

Recap

- Plate tectonics treats the earth's outer shell as made up of about 15 rigid plates, about 100 km thick, which move relative to each other at speeds of a few cm per year.

- We observe spreading centres, subduction zones and transform fault as three types of plate boundaries.

- volcanism, hydrothermal circulation through cooling oceanic lithosphere, and the cycle of uplift and erosion) are the processes by which the solid earth interacts with the ocean and the atmosphere.

- The interplate earthquakes both delineate plate boundaries and show the motion occurring there.

Recap

- **Euler's theorem states that the displacement of any rigid body (in this case, a plate) with one point (in this case, the centre of the earth) fixed is a rotation about an axis.**

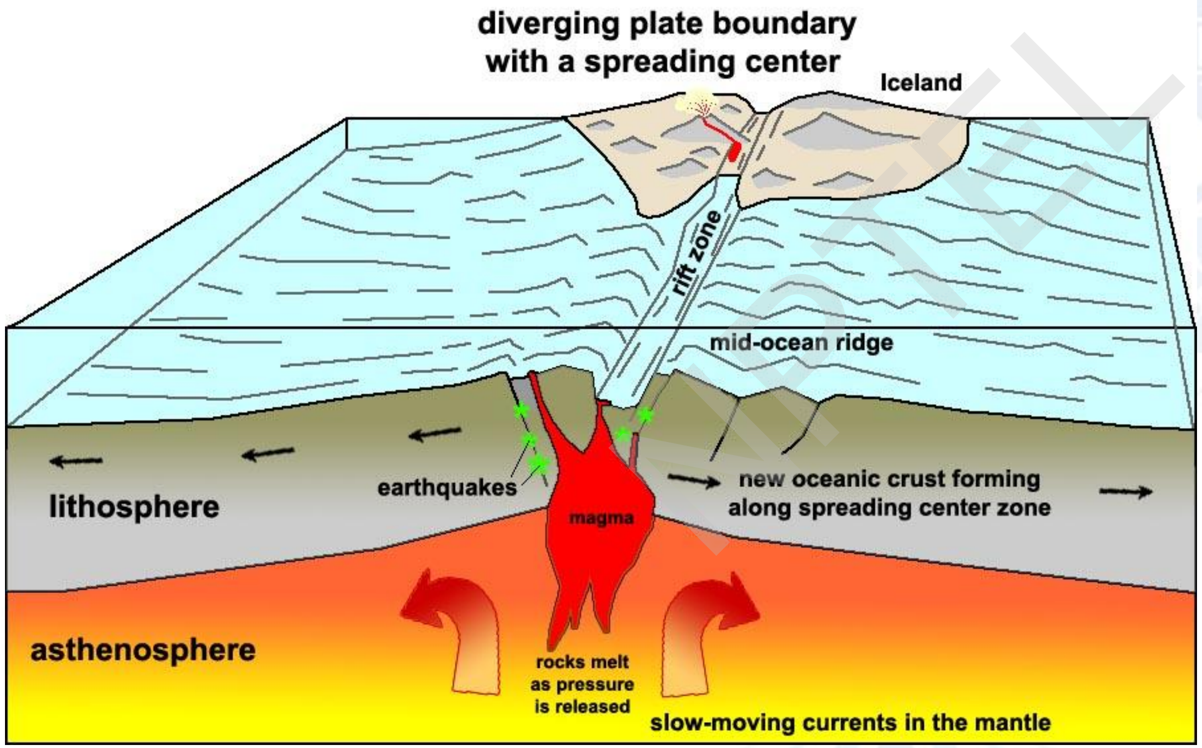
- **Hotspots and deep mantle plume are used to track the absolute plate motion.**

- **Relative and absolute Euler vectors are simply related as**
  $\omega_{ij} = \Omega_i - \Omega_j$

Spreading centers

Geometry of ridges and transforms

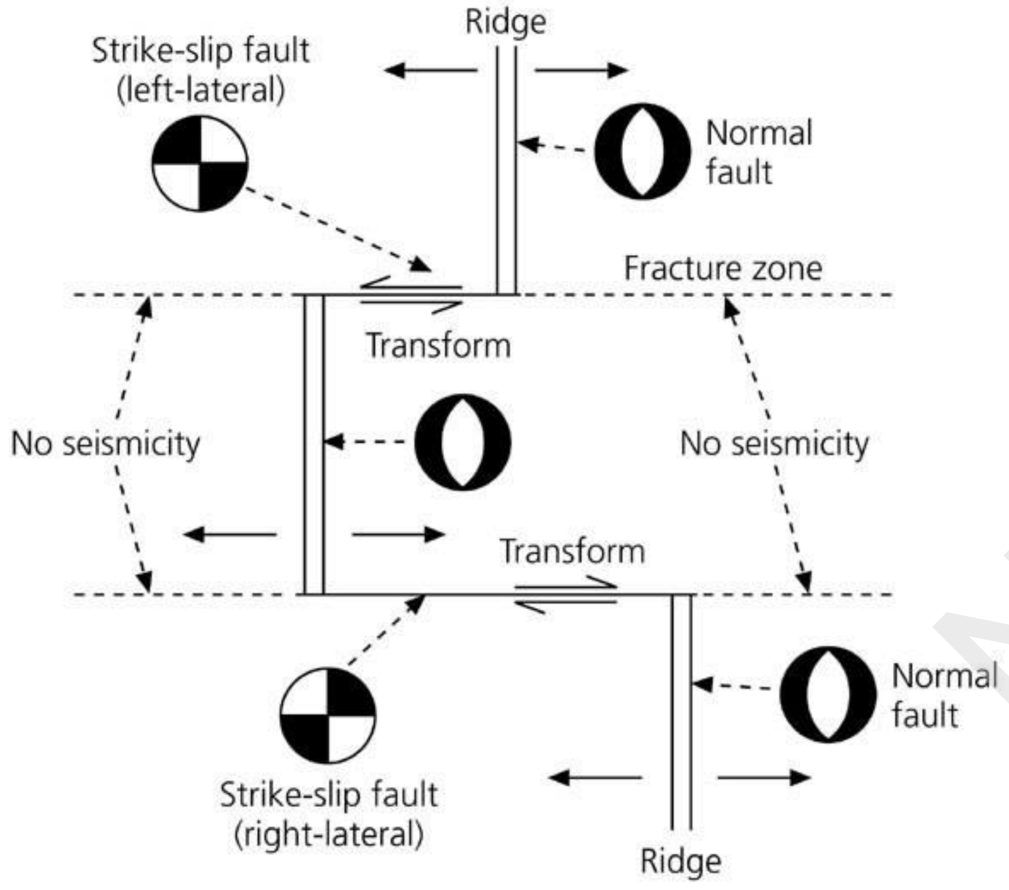
Lithosphere forms at spreading centers and they provide key evidence for the thermal-mechanical processes that control the formation and evolution of the oceanic lithosphere.



https://gotbooks.miracosta.edu/oceans/chapter4.html

Spreading centers

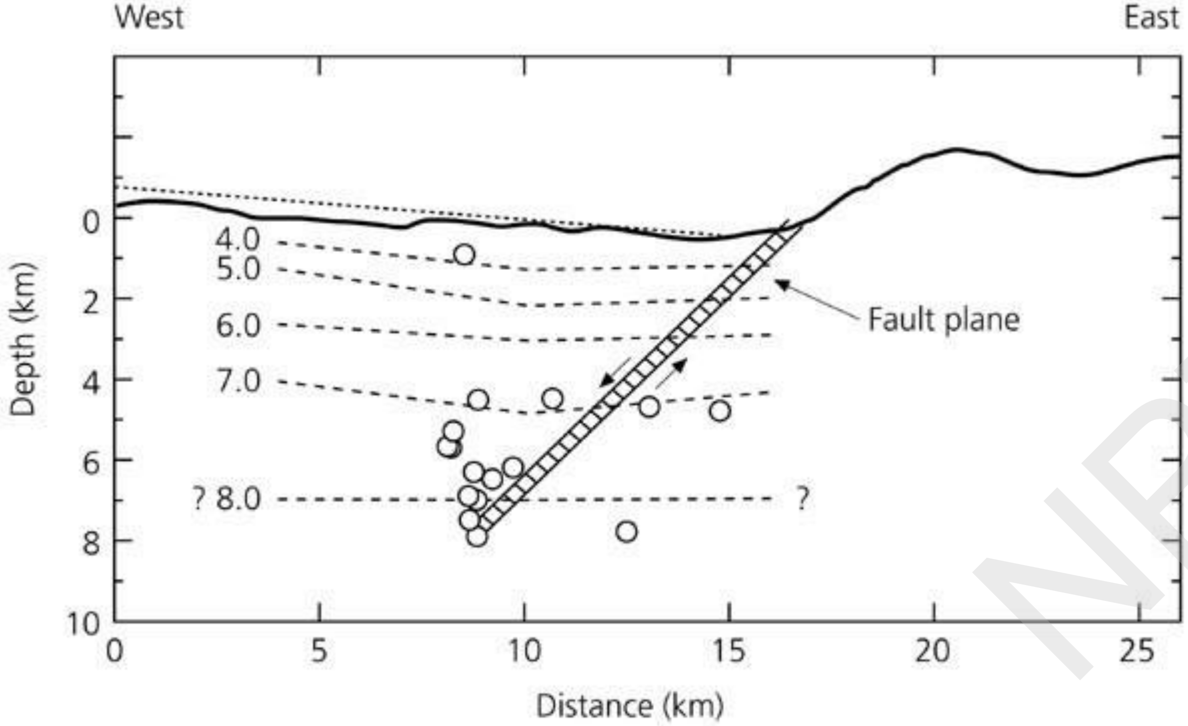
Figure 5.3-1: Tectonic settings of earthquakes along an oceanic spreading center.



- **The figure shows a portion of a spreading ridge offset by transform faults.**
- **Because new lithosphere forms at ridges and then moves away, transform faults are segments of the boundaries between plates, across which lithosphere moves in opposite directions.**
- **Transform faults can have either right- or left-lateral motion.**

Spreading centers

Figure 5.3-3: Cross-section of the Mid-Atlantic Ridge.



- **Fig shows a cross section through the Mid-Atlantic ridge.**

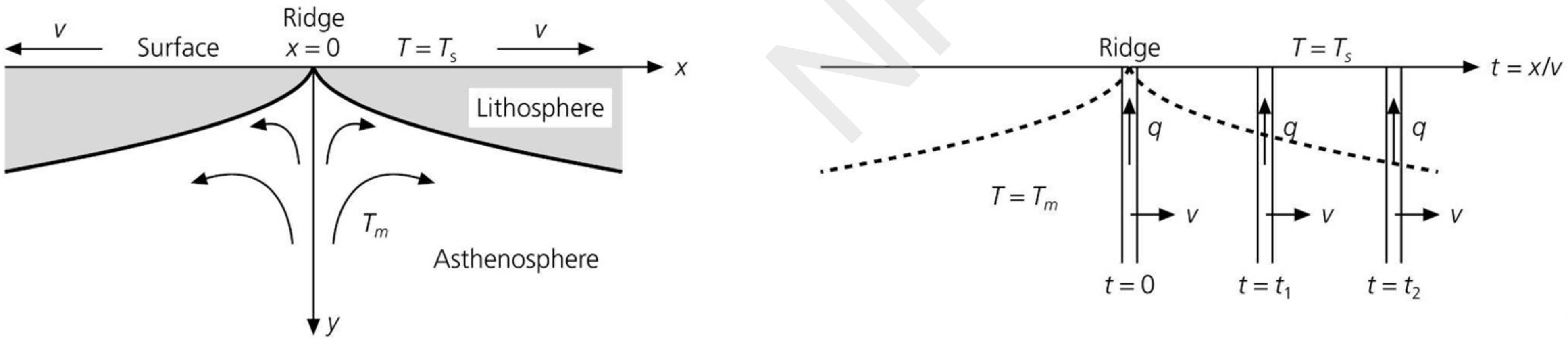
- **The locations of microearthquakes are consistent with normal faulting along the east side of the valley.**

Evolution of the oceanic lithosphere

- A powerful model is presented for the formation of the lithosphere by hot material at the ridge, which cools as the plate moves away.

- In this model, material at the ridge at a mantle temperature T_m (1300–1400 °C) is brought to the ocean floor, which has a temperature T_s. The material then moves away at a velocity v, while its upper surface remains at T_s

Figure 5.3-4: Model for the cooling of the oceanic plate.



Evolution of the oceanic lithosphere

Assumption: The plate slides away from the ridge faster than heat is conducted horizontally, we can consider only vertical heat conduction.

It is similar to the cooling of a halfspace originally at temperature $T = T_m$, whose surface is suddenly cooled to T_s at time $t = 0$. So we may apply the one-dimensional heat flow equation

$$\frac{\partial T(z,t)}{\partial T} = \frac{k}{\rho C_p}\frac{\partial^2 T(z,t)}{\partial z^2} = \kappa \frac{\partial^2 T(z,t)}{\partial z^2} \qquad \text{……….equ 1}$$

κ, known as the thermal diffusivity, is a property of the material that measures the rate at which heat is conducted.

$\kappa = k/\rho C_p$, where k is the thermal conductivity, ρ is the density, and C_p is the specific heat at constant pressure.

Evolution of the oceanic lithosphere

The solution to Eqn 1 is

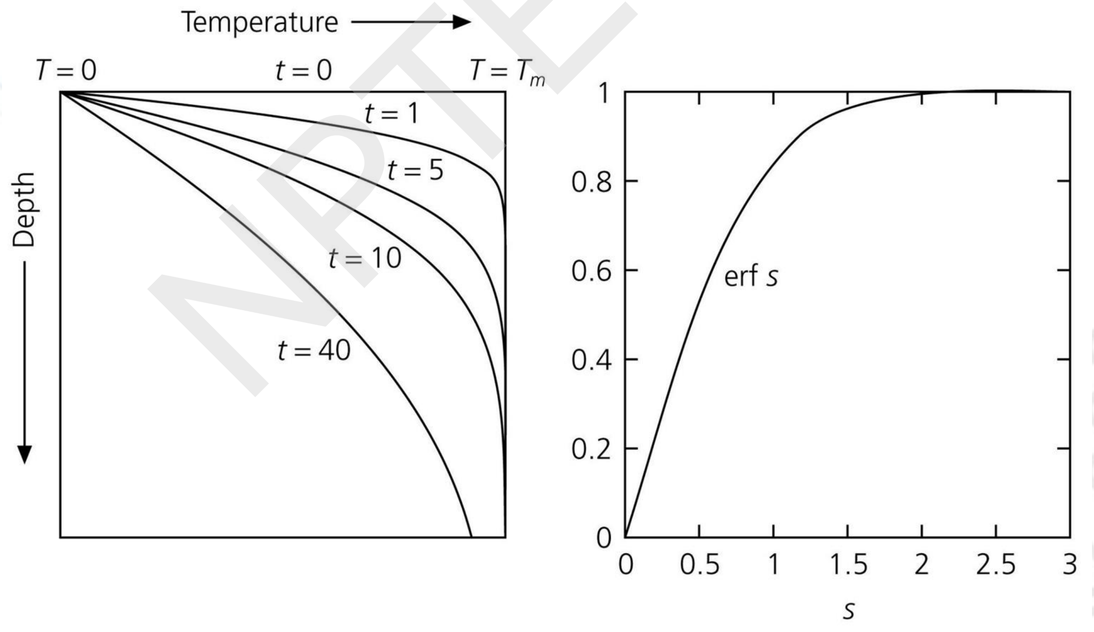
$$T(z,t) = T_s(T_m - T_s)erf\left(\frac{z}{2\sqrt{\kappa t}}\right),$$

where,

$$erf(s) = \frac{2}{\sqrt{\pi}}\int_0^s e^{-\sigma^2}d\sigma$$

Cooling begins at surface and deepens with time.

Figure 5.3-5: Cooling of a halfspace.



Evolution of the oceanic lithosphere

Let's suppose, the sea floor temperature is T_s = 0 °C, then

$$T(z,t) = T_m erf\left(\frac{z}{2\sqrt{\kappa t}}\right),$$

provides the temperature at a depth ‘z’ for material of age ‘t’.

The age of the lithosphere is t = x/v, where ‘x’ is the distance from the ridge and ‘v’ is the spreading rate. Thus

$$T(x,z) = T_m erf\left(\frac{z}{2\sqrt{\kappa x/v}}\right),$$

An isotherm, lines of constant temperature, is a curve on which the argument of the error function is constant,

$$\frac{z_c}{2\sqrt{\kappa t}} = c \ or \ z_c = 2c\sqrt{\kappa t}$$

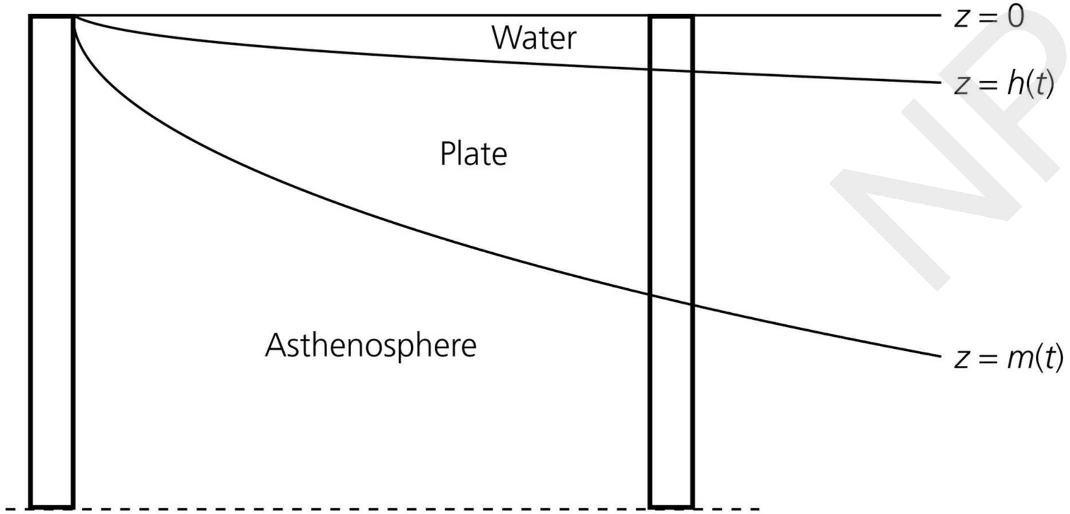
The depth to a given temperature increases as the square root of the lithospheric age.

Evolution of the oceanic lithosphere

- This means that the lithosphere cools with time and and isotherms deepen with the square root of age.

- It further indicate that the ocean depth should vary with age.

Figure 5.3-6: Parabolic increase in ocean depth and plate thickness in the halfspace cooling model.



The increase in ocean depth with lithospheric age due to the cooling of the lithosphere can be modeled using isostasy, the assumption that the mass in a vertical column is the same for all ages.

Evolution of the oceanic lithosphere

- Assume that the lithosphere, defined by the $T = T_m$ isotherm, has thickness zero at the ridge and $z = m(t)$ at age t, where the water depth is h(t).

- Let's assume that the asthenosphere is at temperature T_m and has density ρ_m.

- The temperature and thus density in the cooling lithosphere vary, such that at the point (z, t) the temperature is T(z, t) and the corresponding density is

$$\rho(z,t) = \rho_m + \frac{\partial \rho}{\partial T}[T(z,t) - T_m] = \rho_m + \rho'(z,t)$$

- The change in density due to temperature, at constant pressure, is given by the coefficient of thermal expansion,

$$\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P$$

Evolution of the oceanic lithosphere

➔ **hence, the density perturbation for the halfspace cooling model is**

$$\rho'(z,t) = \alpha\rho_m[T_m - T(z,t)] = \alpha\rho_m T_m\left[1 - erf\left(\frac{z}{2\sqrt{\kappa t}}\right)\right]$$

➔ **If the density of water is ρ_w, equal mass in the two columns requires that**

$$\rho_m m(t) = \rho_w h(t) + \int_{h(t)}^{m(t)} [\rho_m + \rho'(z,t)]\,dz$$

➔ **which gives the isostatic condition for ocean depth,**

$$h(t) = \frac{1}{(\rho_m - \rho_w)} \int_{h(t)}^{m(t)} \rho'(z,t)\,dz$$

Evolution of the oceanic lithosphere

- Because temperature and density in the plate are defined for all values of z (the thickness of the plate is defined as some chosen isotherm), let z′ = z – h(t) and m(t) → ∞. Then

$$h(t) = \frac{\alpha \rho_m T_m}{(\rho_m - \rho_w)} \int_0^{\infty} \left[1 - erf\left(\frac{z'}{2\sqrt{\kappa t}}\right)\right] dz'$$

- To evaluate the integral, substitute $s = z'/2(\kappa t)^{1/2}$ and integrate by parts (try it!) to show that

$$\int_0^{\infty} [1 - erf(s)] ds = 1/\sqrt{\pi}$$

- Thus ocean depth should increase as the square root of plate age,

$$h(t) = 2\sqrt{\frac{\kappa t}{\pi}} \frac{\alpha \rho_m T_m}{(\rho_m - \rho_w)}$$

Evolution of the oceanic lithosphere

- The cooling of the lithosphere should also cause heat flow at the sea floor to vary with age.

- By Fourier's law of heat conduction, the heat flow (q) at the sea floor is the product of the temperature gradient at the seafloor and the thermal conductivity k

$$q = k\frac{dT}{dz} \quad \text{at} \quad z = 0$$

- Approximating the gradient at the surface by the average gradient through the lithosphere,

$$q(t) = k\frac{\Delta T}{\Delta z} \approx \frac{kT_m}{\sqrt{\kappa t}}$$

predicts that the heat flow decreases as the square root of age.

Evolution of the oceanic lithosphere: Half space model

The same result can be obtained by differentiation of the temperature structure using

$$\frac{d}{dz}erf(s) = \frac{d}{dz}\frac{2}{\sqrt{\pi}}\int_0^s e^{-\sigma^2}d\sigma = \frac{2}{\sqrt{\pi}}e^{-s^2}\frac{ds}{dz}$$

which gives

$$q(t) = k\frac{dT}{dz}\Big|_{z=0} = k\frac{2T_m}{\sqrt{\pi}}e^{\frac{-z^2}{4\kappa t}}\frac{1}{2\sqrt{\kappa t}}\Big|_{z=0} = \frac{kT_m}{\sqrt{\pi\kappa t}}$$

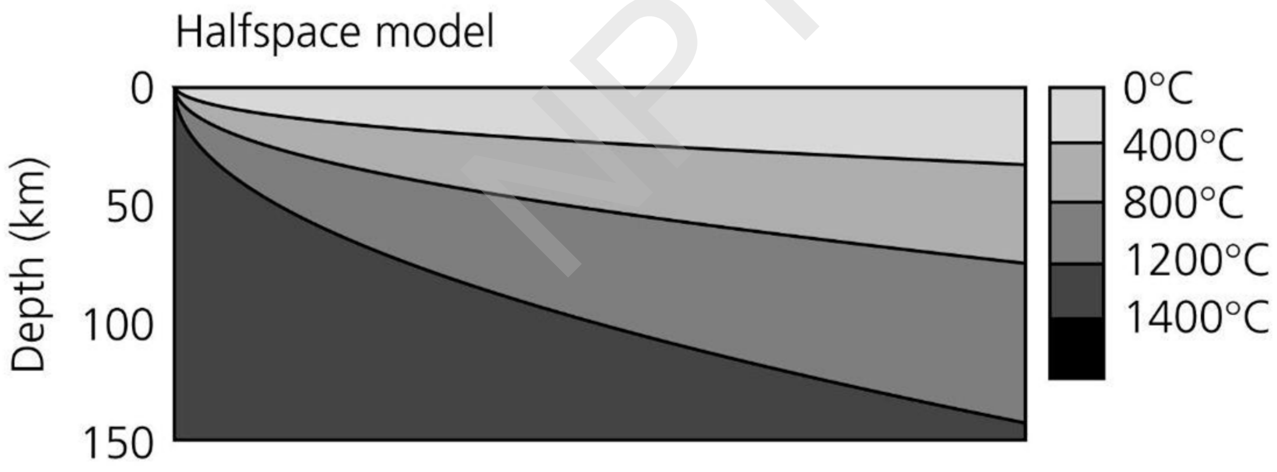
This model, which predicts that lithospheric thickness, heat flow, and ocean depth vary as the square root of age for all ages is called a half-space model.

Evolution of the oceanic lithosphere: Half space model

In it, the lithosphere is the upper layer of a half-space that continues cooling for all time.

In reality, oceanic lithosphere never gets older than 200 million years old because it gets subducted.

The model does a good job of describing the average variation in ocean depth and heat flow with lithospheric age.



Evolution of the oceanic lithosphere: **Plate Model**

However, because ocean depth seems to "flatten" at about 70 Myr, we often use a modification called a plate model

It assumes that the lithosphere evolves toward a finite plate thickness L with a fixed basal temperature T_m.

In this model, temperature vary as a position and depth is given as:

$$T(x,z) = T_m \left[\frac{z}{L} + \sum_{n=1}^{\infty} c_n \exp\left(\frac{-\beta_n x}{L} \right) \sin\left(\frac{n\pi z}{L} \right) \right]$$

where $c_n = 2/(n\pi)$, $\beta_n = (R^2 + n^2\pi^2)^{1/2} - R$, $R = vL/(2\kappa)$.

The constant R, known as the thermal Reynolds number, relates the rates at which heat is transported horizontally by plate motion and conducted vertically.

Evolution of the oceanic lithosphere: Drawback

- ➔ We can view ocean depth, heat flow, and several other properties of the oceanic lithosphere as observable measures of the temperature in the cooling lithosphere.
- ➔ Because the observables depend on different combinations of parameters, they can be used together to constrain individual parameters.

Observable	Proportional to	Reflects
Young ocean depth	$\int T(z,t)dz$	$k^{1/2}\alpha T_m$
Old ocean depth	$\int T(z,t)dz$	$\alpha T_m L$
Old ocean heat flow	$\left.\frac{\partial T(z,t)}{\partial z}\right\|_{z=0}$	kT_m/L
Geoid slope	$\frac{\partial}{\partial t}\int zT(z,t)dz$	$k\alpha T_m \exp(-kt/L^2)$

Source: Stein and Stein (1996).

- The depth depends on the integral of the temperature, whereas the heat flow depends on its derivative at the sea floor.

- Similarly, the slope of the geoid, a function of the gravity field depending on a weighted integral of the density, also varies with the age.

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Geoid slope	$\frac{\partial}{\partial t}\int zT(z,t)dz$	$k\alpha T_m \exp(-kt/L^2)$

Source: Stein and Stein (1996).

Summary

- The temperature as a function of depth and time is given by the one-dimensional heat flow equation

$$\frac{\partial T(z,t)}{\partial T} = \frac{k}{\rho C_p}\frac{\partial^2 T(z,t)}{\partial z^2} = \kappa\frac{\partial^2 T(z,t)}{\partial z^2}$$

The solution of the heat equation is:

$$T(z,t) = T_s(T_m - T_s)erf\left(\frac{z}{2\sqrt{\kappa t}}\right), \qquad erf(s) = \frac{2}{\sqrt{\pi}}\int_0^s e^{-\sigma^2}d\sigma$$

- Temperature at a depth z for material of age t:

$$T(z,t) = T_m erf\left(\frac{z}{2\sqrt{\kappa t}}\right),$$

- An isotherm is a curve on which the argument of the error function is constant,

$$\frac{z_c}{2\sqrt{\kappa t}} = c \ or \ z_c = 2c\sqrt{\kappa t}$$

Summary

- **The temperature and thus density in the cooling lithosphere vary, such that at the point (z,t) the temperature is T(z,t) and the corresponding density is**

$$\rho(z,t) = \rho_m + \frac{\partial \rho}{\partial T}[T(z,t) - T_m] = \rho_m + \rho'(z,t)$$

- **Density perturbation for the halfspace cooling model is**

$$\rho'(z,t) = \alpha\rho_m[T_m - T(z,t)] = \alpha\rho_m T_m\left[1 - erf\left(\frac{z}{2\sqrt{\kappa t}}\right)\right]$$

- **The isostatic condition for ocean depth,**

$$h(t) = \frac{1}{(\rho_m - \rho_w)}\int_{h(t)}^{m(t)} \rho'(z,t)dz$$

Summary

- **Ocean depth should increase as the square root of plate age,**

$$h(t) = 2\sqrt{\frac{\kappa t}{\pi}} \frac{\alpha \rho_m T_m}{(\rho_m - \rho_w)}$$

- **For plate model, temperature vary as a position and depth is given as:**

$$T(x, z) = T_m \left[\frac{z}{L} + \sum_{n=1}^{\infty} c_n \exp\left(\frac{-\beta_n x}{L}\right) \sin\left(\frac{n\pi z}{L}\right) \right]$$

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THANK YOU !