8: PLATE BOUNDARIES & PLATE DRIVING FORCES

What makes the plates move?

Thermal evolution of oceanic lithosphere provides major plate driving force and hence plays major role in both oceanic and continental deformation.

Major role in thermal, mechanical, chemical evolution of the earth.

Spreading centers

Subduction zones

Smith & Cann, 2004

Van der Hilst, 1995
Mid-Atlantic ridge

Click for video
https://www.youtube.com/watch?v=sgDM6m0lUGY
How do ridges work?

Click for video
Midocean ridge decompression melting

Ice does the opposite – pressure melting

https://opentextbc.ca/geology/chapter/3-2-magma-and-magma-formation/
Class Question 31

To see why the phase diagram result makes sense, explain intuitively why rocks at a lower pressure melt at lower temperature.
Plate tectonics is top of Earth’s heat engine

Spreading centers & subduction zones are opposite ends

Use thermal models to study both

Stein & Wysession
Heat and temperature (1)

Temperature is related to heat by a mathematical relation that says that for a given temperature change $\Delta T$, the heat energy $Q$ within an object of mass $m$ or volume $V$ changes by

$$
\Delta Q = mC_p\Delta T = \rho VC_p\Delta T.
$$

(11)

Here $\rho$ is the density (mass per unit volume) and $C_p$ is the specific heat per unit mass at constant pressure. $C_p$ has dimensions of energy/degree-mass, which in SI units is either J/°C-kg or J/K-kg.

This equation also tells us that if the heat energy in a body changes by $\Delta Q$, its temperature changes by an amount

$$
\Delta T = \Delta Q/\rho VC_p
$$

(12)

inversely proportional to the specific heat. For example, water has a specific heat of 4.186 kJ/kg-°C ($4.186 \times 10^3$ J/kg-°C), much higher than rock, which has a value about 1 kJ/kg-°C. As a result, energy from the sun raises the temperature of land much more than of an adjacent body of water. Thus both over day and night and over the seasons, coastal temperatures vary less than inland areas.
These definitions show how heat and temperature are related. Temperature is related to the transfer of heat: heat flows from a hotter (higher temperature) object to a colder (lower temperature) object. Thus a person, with a body temperature of 37°C can cool off (lose heat) by jumping into a lake whose temperature is 20°C. The person is "hotter" in that his temperature is higher, but the much larger lake contains more heat. In other words, the direction of heat transfer depends not on the total heat in two objects, but on their relative temperatures.⁵
Heat transfer by conduction

The flow of heat by conduction from a hot region (one at higher temperature) to a colder one (at lower temperature) is described in a one dimensional object by Fourier’s law of heat conduction

\[ q = -k \frac{dT}{dz} \]  

(1)

where \( q \) is the heat flux, the flow of heat per unit time and unit area.

Heat flux is proportional to the gradient - the spatial derivative - of the temperature. Thus if the temperature changes from \( T + \Delta T \) to \( T \) over a distance \( L \) (Fig. 5.2-1)

\[ \frac{dT}{dz} = \frac{T - (T + \Delta T)}{L} = -\frac{\Delta T}{L} . \]  

(2)

\[ q = -k \frac{dT}{dz} = k \frac{\Delta T}{L} . \]  

(3)

The heat flow is also proportional to a constant \( k \), the material’s thermal conductivity. Materials with \( k \) large conduct heat well, whereas those with low \( k \) insulate. Thus on a winter day there is a large temperature gradient between our warm skin and the cold air, but an insulating coat reduces the heat flow from our bodies.
Class question 32

The minus sign in Fourier’s law

\[ q = -k \frac{dT}{dz} \]

is very important.

What would happen without it?
To describe how the heat and hence temperature inside an object change with time, we use the *heat equation*. We assume that the heat content $Q$ of a one dimensional object of length $dz$ changes in only two ways: heat is conducted in or out of it, and heat is produced or absorbed within it (Fig. 5.2-2):

heat change inside = heat conducted in or out + heat produced or absorbed. (4)

Hence we describe the temperature $T$ as a function of position $x$ and time $t$ using

$$
\rho \ C_p \ \frac{\partial T}{\partial t} (z, t) \ dz = q(z) - q(z + dz) + \rho \ H \ dz. \ (5)
$$

The left side of the equation is the time derivative of Eqn 5.1.11, and describes how the temperature and hence the heat inside the object change. The terms on the right describe what causes these changes.

**HEAT CHANGE INSIDE** = **HEAT CONDUCTED IN OR OUT** + **HEAT PRODUCED**

$$
\rho \ C_p \ dz \ \frac{\partial T}{\partial t} (z, t) = q(z) - q(z + dz) + \rho \ H \ dz
$$

- difference in heat going in and out
- heat production (phase changes, radioactive)

$$
\frac{dz \quad \rho H \quad dz}{q(z) \quad q(z+dz)}$$
How heat and temperature change (2)

The conduction term, the first term on the right, is the difference between the heat conducted in at \( z \) and that flowing out at \( z + dz \). To simplify this, we expand \( q(z + dz) \) in a Taylor series

\[
q(z) - q(z + dz) = q(z) - \left( q(z) + \frac{dq}{dz} dz \right) = - \frac{dq}{dz} dz.
\]

(6)

We then substitute for \( q \) using Fourier’s law of heat conduction

\[
q = -k \frac{dT}{dz}
\]

\[
\frac{dq}{dz} dz = - k \frac{\partial^2 T}{\partial z^2} dz
\]

(7)

assuming the thermal conductivity \( k \) is constant.

The second term on the right describes the heat produced or absorbed per unit mass per unit time via the production term \( H \). \( H \) is positive if heat is produced by radioactivity, and can be either positive or negative if heat is produced or absorbed by chemical reactions. For example, melting ice absorbs heat, whereas freezing water releases heat.\(^2\)
The heat equation !!!!

$T(z,t)$ - temperature as a function of space and time

The heat equation (5) thus becomes

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

(8)

after dividing by $dz$. This is called the 1-dimensional (only $z$ coordinate) heat equation with conduction only, which does not include heat transfer by convection. It is a partial differential equation that relates the change in temperature with time to the change in temperature with position. Partial differential equations arise when we want to describe how some quantity varies in space and time, as we discussed for the wave equation (Chapter 3).
Class question 33

The graphs of $T(z)$ for different times, computed using the heat equation, show that if at time $t_0$ a hot region is surrounded by a cold ones, the hot region will cool and the cold regions will warm up.

Draw the temperature distribution at a time, $t_2$, that is later than $t_1$. 
SIMPLE AND VERY POWERFUL THERMAL MODEL

Vertical heat conduction as cooling plate moves horizontally

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

One-dimensional heat flow equation:
(how temperatures changes in a material as a function of the rate at which heat is conducted out of it)

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

\( \kappa \) = thermal diffusivity, \( k \) = thermal conductivity, \( \rho \) = density, \( C_p \) = specific heat at constant pressure

It’s solution has the form

\[
T(z, t) = T_s + (T_m - T_s) \text{erf}(\frac{z}{2\sqrt{\kappa t}})
\]

with \( T_s \) = surface temperature, \( T_m \) = mantle temperature, and \( \text{erf}(s) = \frac{2}{\sqrt{\pi}} \int_0^s e^{-\sigma^2} d\sigma \)
COOLING OF HALFSPACE DESCRIBED BY 1-D CONDUCTIVE HEAT FLOW EQUATION

Cooling starts at surface and deepens with time

\[
\text{erf}(s) = \frac{2}{\sqrt{\pi}} \int_0^s e^{-\sigma^2} d\sigma
\]
IN COOLING HALFSPACE MODEL, LITHOSPHERE COOLS WITH TIME SUCH THAT ISOTHERMS DEEPEN WITH THE SQUARE ROOT OF AGE

Consequences:

By isostasy, ocean depth increases as square root of age (ridge is shallow)

Seafloor heat flow decreases as square root of age (highest at ridge)
Seafloor depths are shallowest at the ridge and increase as the square root of crustal age

Seafloor topography reflects the cooling of the oceanic lithosphere described by the heat equation
COOLING HALFSPACE MODEL WORKS WELL, WITH INTERESTING MISFITS

Depth seems to "flatten" at ~70 Myr: use variant called cooling plate model in which lithosphere evolves toward finite thermal thickness.

For ages <~ 50 Ma, observed heat flow is lower than predictions, because water flow in the crust transports some of the heat.
However, because ocean depth seems to “flatten” at about 70 Myr, we often use a modification called a plate model (Fig. 5.3-7, lower left), which assumes that the lithosphere evolves toward a finite plate thickness $L$ with a fixed basal temperature $T_m$. In this model,

$$T(x, z) = T_m \left[ \frac{z}{L} + \sum_{n=1}^{\infty} c_n \exp \left( -\frac{\beta_n x}{L} \right) \sin \left( \frac{n\pi z}{L} \right) \right], \quad (19)$$

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. In this model isotherms initially deepen as the square root of age, but eventually level out.

Ocean depth & heat flow versus age jointly constrain plate model of temperature in the cooling lithosphere

Search model space for plate model parameters $T_m$ and $L$ that best fit data

Inversion yielded GDH-1 (Global Depth & Heat flow) model
“RIDGE PUSH” - PLATE DRIVING FORCE DUE TO COOLING LITHOSPHERE

Ridge Push: \[ F_R = F_1 - F_2 - F_3 \]

\[ F_R = \alpha \rho_m T_m g \kappa t \]

For a plate model, this approaches a constant value for old lithosphere.

“Ridge push” is zero at the ridge and increases linearly with plate age. It results not from force at the ridge but from the total force due to the density anomaly within the cooling plate out to any given age.

\[ \alpha \text{ Coefficient of thermal expansion} \]
\[ P_m T_m \text{ mantle density and temperature} \]
\[ \kappa \text{ thermal diffusivity} \]
\[ g \text{ acceleration of gravity} \]
\[ t \text{ plate age} \]
Slow Mid-Atlantic Ridge has earthquakes on both active transform and ridge segments. Strike-slip faulting occurs on a plane parallel to the transform. On ridge segments, normal faulting occurs with nodal planes parallel to ridge trend.
Fast East Pacific Rise has only strike-slip earthquakes on the transforms, since there is no axial valley.

Macdonald, 2004

Stein & Wysession, 2003
At a given distance from the ridge, faster spreading produces younger lithosphere and isotherms closer to the surface than slow spreading.

If region beneath the 1185°C isotherm and above Moho depth of 5 km is a magma chamber, a fast ridge has a larger magma chamber. Hence crust moving away from a fast-spreading ridge is more easily replaced than from a slow ridge.

Thus in contrast to the axial valley and normal faulting earthquakes on a slow ridge, a fast ridge has an axial high and an absence of earthquakes.

Sleep and Rosendahl, 1979
Class question 34

The observed depth of normal fault earthquakes at midocean ridges varies with spreading rate.

a) What’s the trend?

b) Explain what causes it.

c) What would you expect for a half spreading rate of 50 mm/yr? Does this make sense?

S&W 5.3-13
HYDROTHERMAL SYSTEMS AT RIDGES

Water flowing into hot fractured basaltic crust reacts to form minerals and changes chemistry of sea water.

Hot (350°C) mineral-rich water discharges at vents called black smokers and forms mineral deposits rich in zinc, copper, and iron.

Even more (10x?) heat transferred by cooler diffuse flow that’s harder to observe.

Away from ridge axes, flow occurs by less spectacular seepage of low temperature water, but probably carries more heat.

Humphris, 2004
SUBDUCTION ZONES

Cold, dense, slabs of oceanic lithosphere subduct into the mantle generating island arc volcanism, causing the largest earthquakes, and providing a major force driving plates

Clift, 2004
Van der Hilst, 1995
SUBDUCTION ZONES

Cold, dense, slabs of oceanic lithosphere subduct into the mantle generating island arc volcanism, causing the largest earthquakes, and providing a major force driving plates

Clift, 2004
Van der Hilst, 1995
Subduction system:
Details complicated and variable

Figure 5.4-1: Cartoon of a subduction zone.
Subduction zone volcanism

http://www.columbia.edu/~vjd1/subd_zone_basic.htm

https://opentextbc.ca/geology/chapter/3-2-magma-and-magma-formation/
EARTHQUAKE LOCATIONS & MECHANISMS ILLUSTRATE TECTONICS

Figure 5.4-2: Various earthquake types observed at subduction zones.

- Small earthquakes
- Bending earthquakes
  - few, small
- Great thrust earthquakes
  - often, but not always
  - e.g., 1960 Chile, 1964 Alaska
- Intermediate earthquakes
  - near slab top
  - primarily down-dip tension
- Normal fault earthquakes
  - few, large
  - e.g., 1933 Sanriku, 1965 Rat Island, 1977 Indonesia
  - not observed everywhere
- Deep seismic zone
  - either single or double
  - primarily down-dip compression
  - dip may vary considerably
  - depth may vary considerably

Plate boundary process

“Slab Pull” Plate driving force

Stein & Wysession, 2003

Wadati-Benioff zone
Largest earthquakes are thrust faulting at subduction interface

2011 Tohoku M 9.1
2004 Sumatra earthquake M 9.1-9.3

Tsunami generated along fault, where sea floor displaced, and spreads outward

Hyndeman and Wang, 1993

Red - up motion, blue down

http://staff.aist.go.jp/kenji.satake/animation.gif

Click for animation
BANDA ACEH: 8 minute tsunami travel time

First Line of Surviving Structures – Concrete and on Columns

Some shaking damage

Complete Destruction
1. Earthquakes cause the ocean floor to collapse in places and rise elsewhere, displacing water and generating waves.

2. Initial waves, largely underwater, travel very fast toward the shore.

3. In the shallow waters near the shore, the waves decrease in speed while rising in height above the surface.

4. The tsunami reaches the shore, causing severe flooding and extreme currents.

Illustration by The Associated Press; Graphic by The Washington Post

KHAO LAK, THAILAND  DECEMBER 26, 2004

8:26

8:28

8:30

Seattle Times 2/24/05
Class question 35

The biggest earthquakes are great thrust fault earthquakes on the plate interface at subduction zones. To see why, compare the magnitudes and fault areas of the 1906 San Francisco and 2004 Sumatra earthquakes. Here fault length is the distance along the fault parallel to the earth’s surface, and width is distance down the fault plane.

a) What are the differences in the geologic setting?

b) What are the differences in fault area?

c) What causes them?
PACIFIC NORTHWEST EARTHQUAKE HAZARD HAS THREE COMPONENTS:

Large interplate thrust (rare, but paleoseismology & tsunami history from Japan find big one in 1700): largest earthquakes but further away

Overriding (North American) plate: smaller but closer to population

Intraslab (Juan de Fuca) earthquakes: smaller but closer to population
JUAN DE FUCA PLATE
SUBDUCTING BENEATH NORTH AMERICA

2001 Nisqually earthquake  M 6.8 ($2B damage) within subducting plate

Mt Saint Helens
1980 (57 deaths; $2B damage)
Earthquakes in cold, strong, subducting plates go to depths of hundreds of km, unlike in other places where they go no deeper than ~50 km.

Why? Are deep earthquakes different?
Subducting slabs pass through transition zone between upper & lower mantles bounded by 410 and 660 km discontinuities

Mineral phase changes occur at depth due to higher pressure

Olivine (\(\text{Mg,Fe}_2\text{SiO}_4\))

\((\alpha\text{ phase}) \rightarrow \text{spinel (}\beta\text{ phase})\)
gives 410 km discontinuity outside slab

Ringwood, 1979
SIMPLE ANALYTIC THERMAL MODEL

Consider a semi-infinite slab of thickness $L$ subducting at rate $v$. The surrounding mantle is at temperature $T_m$, and the plate enters the trench with a linear temperature gradient from $T = 0$ at its surface to $T_m$ at its base. Define the $x$-axis down the dip of the slab, and the $y$-axis across the slab. The evolution of the region is given the heat equation (5.3.1) used

$$\rho C_p v \frac{\partial T}{\partial x} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right),$$

describes the evolution of the temperature field, $T(x, y, t)$, as a function of time and the two space coordinates. We further assume that physical properties of the material such as the density $\rho$, specific heat $C_p$, thermal conductivity $k$, diffusivity $\kappa = k/\rho C_p$ are independent of position. This has a series solution

$$T(x, y) = T_m [1 + 2 \sum_{n=1}^{\infty} c_n \exp(-\beta_n x/L) \sin(n \pi y/L)],$$

with

$$c_n = (-1)^n/(n \pi) \quad \beta_n = (R^2 + n^2 \pi^2)^{1/2} - R \quad R = vL/(2\kappa).$$
Model predicts maximum depth of isotherm in slab varies with thermal parameter

\[ \phi = t \nu \sin \delta \]

- \( \phi \): maximum depth of isotherm
- \( t \): age of subducting plate
- \( \nu \): subduction rate
- \( \delta \): dip of slab

The temperature \( T_0 \) reaches a maximum down-dip distance

\[ x_0 = -\frac{\nu L^2}{(\pi^2 \kappa)} \ln[\pi(T_m - T_0)/(2T_m)]. \]

To convert this distance to depth in the mantle, we multiply by \( \sin \delta \), where \( \delta \) is the slab dip. This correction converts the subduction rate \( \nu \) to the slab’s vertical descent rate \( \nu \sin \delta \). Thus an isotherm’s maximum depth is proportional to the subduction rate and the square of the plate thickness, so faster subduction or a thicker slab allows material to go deeper before heating up. If the square of the plate thickness is proportional to its age, the maximum depth to an isotherm in the slab is proportional to the vertical descent rate times the age \( t \) of the subducting lithosphere.

If the maximum depth of earthquakes is temperature controlled, earthquakes should cease once material reaches a temperature that is too high. To compare various subduction zones, we examine the maximum depth of earthquakes as a function of their thermal parameter

\[ \phi = t \nu \sin \delta. \]
Compare models for younger and slower-subducting slab ($\phi \sim 2500 \text{ km}$), approximating Aleutian arc, and older faster-subducting slab ($\phi \sim 17000 \text{ km}$), approximating Tonga arc.

Slab with higher thermal parameter warms up more slowly, and is thus colder.

Prediction consistent with observation that Tonga has deep earthquakes whereas Aleutians do not.

Test thermal models using earthquake locations (should be in cold interior) & seismic velocities from tomography.

Stein & Stein, 1996
Thermal model gives force driving subduction due to the integrated negative buoyancy (sinking) of cold dense slab from density contrast between it and the warmer and less dense material at same depth outside.

Negative buoyancy associated with cold downgoing limb of convection pattern.

Depends on thermal density contrast so increases for:

- Higher $v$, faster subducting & hence colder plate
- Higher $t$, older & colder plate

Expression similar to that for “ridge push” since both thermal buoyancy forces
"Slab pull" driving force due to subduction zones has a major effect on plate motion.

Average absolute velocity of plates increases with the fraction of their area attached to downgoing slabs, suggesting that slabs are a major determinant of plate velocities.

Figure 5.4-12: Plate velocity as a function of the amount of subducting lithosphere.

Forsyth and Uyeda, 1975
The analytic expressions for the "ridge push" force

\[ F = g \alpha \rho m T m \kappa t \]

and slab pull force

\[ F = \frac{g \alpha \rho m T m vt^{3/2}}{24 \kappa} \]

are similar, because both are thermal buoyancy forces.

What factors are the same between the two?

What factors differ?

Explain physically why these differ.
"RIDGE PUSH’ AND “SLAB PULL" FORCE BOTH ARE THERMAL BUOYANCY FORCES DUE TO THE DENSITY CONTRAST RESULTING FROM THE TEMPERATURE DIFFERENCE BETWEEN THE PLATE AND ITS SURROUNDINGS

Ridge push is due to oceanic lithosphere cooling after it forms; slab pull is due to the cooled lithosphere heating up again as it subducts.

Although it is useful to think of the forces separately, both are parts of the net buoyancy force due to mantle convection.

Analogy: rain occurs by negative buoyancy of the drops relative to surrounding air, as part of the process by which solar heat evaporates water which rises as vapor due to positive buoyancy and is transported by wind to the point where it cools, condenses into drops, and then falls.
50 years after discovery of plate tectonics, lots of interesting issues remain under study, including:

- How do continents rift?
- Are plumes & microplates involved?
- Why are there quakes in ENA? How dangerous are they?
- What's the seismic hazard in areas including California & Nepal?
- Are there physical differences between quakes on plate boundaries & in plate interiors?
- Why do earthquakes within continents move around between faults?
- Why does steady plate motion cause earthquakes clustered in time?
- How are tectonic & human-induced earthquakes related?
- Are there physical differences between quakes on plate boundaries & in plate interiors?
- How do continents rift? Are plumes & microplates involved?