Introduction and Tectonic Plates

- What is a plate?
- Why do plates move?
- What is the source of tectonic plate motion?
Introduction and Tectonic Plates
Outline Today

- Plate Tectonics Introduction
- Heat Energy in the Earth
- Heat Conduction
- Lithospheric plates
Theories on tectonic plate motion

• **Dynamic Theory**
  - forces which give rise to deformation or change
  - cause of magmatism, metamorphism which affect the Earth's crust

• **Kinematic Theory**
  - describes motions but does not consider forces that move them
We know it's true because it's “scientifically proven”

• What does “scientifically proven” mean?
• Geodynamicists develop models to study problems
  - build models using computers of labs
  - test models with observed data
  - improve and update models
  - results may show same observations but may be non-unique, others may give similar results
  - so models may indicate and explore possible phenomena but don't necessarily prove this result
• Newton's theory of gravity:
  - did well at explaining gravity in the vicinity of the Earth
• However, Einstein's theory on the subject did better on a larger spacial scale
Time Scales of Geology and Tectonic Motion

- The idea that continents move or shift on the Earth's surface is only believable when you can appreciate geologic time.

- What is geologic time? How long is this? How is it different from time that we think of ordinarily?

- Since the theory of plate tectonics was first introduced, how far has the tectonic plate we're standing on moved? Where did it go?

- (Frank Taylor first proposed this idea in 1910, Alexander du Toit later in 1937, Harry Hess explored the geomorphology of the seafloor by ship in 1960's)
Time Scales of Geology and Tectonic Motion

• Hutton and Hall studied geologic processes in Siccar Point, Britain where a subhorizontal Devonian sandstone rests on near-vertical Silurian slates.

“We felt ourselves necessarily carried back to the time when the shistus on which we stood was yet at the bottom of the sea, and when the sandstone before us was only beginning to be deposited....An epoch still more remote presented itself, when even the most ancient of these rocks, instead of standing upright in vertical beds, lay in horizontal planes at the bottom of the sea, and was not yet disturbed by that immeasurable force which has burst asunder the solid pavement of the globe...”

- John Playfair, 1788

• They had no quantitative estimate of the exact time intervals, but knew these periods were much greater than thousands of years.
Time Scales of Geology and Tectonic Motion

• Lyell in the 1850's provided a better estimate of geologic time with his theory of *uniformitarianism*.

• He stated that catastrophies played no part in the past and all observable processes occurred by slow action.

  “Stupendous as is the aggregate result, there is no escape from the necessity of assuming a lapse of time sufficiently enormous to allow of so tedious an operation.”
Time Scales of Geology and Tectonic Motion

- Charles Darwin in his "Origin of the Species" gave one of the most quantitative estimates of geologic time.
Time Scales of Geology and Tectonic Motion

• Charles Darwin in his “Origin of the Species” gave one of the most quantitative estimates of geologic time.

• As an illustration, he estimated the time to erode a formation in England was 300 million years.

• Upon his arrival in south America on the vessel, *Beagle*, he noticed the elevation of strata in the Andes mountains correlated with declining proportion of fossil species. He inferred progressive uplift of strata and the mountain itself.

• Darwin's experience of a powerful *earthquake* in the Andes influenced his observation that *catastrophes may play a role* in geologic processes. They observed uplift of 1-2 meters from the quake, suggesting that at 100 year intervals, this could produce the mountain range in roughly 100 million years!
Time Scales for the Age of the Earth

• Estimates for the age of the Earth produced long standing arguments, but these values were surprisingly similar....

• Lord Kelvin calculated the time for the Earth to cool after formation if most of the planet's surface was molten. Using known values for *thermal conductivity* of mantle rocks and their *melting temperature*, he came up with something < 100 My.

• Other geologists estimated the time to accumulate sedimentary strata (from the Phanerozoic) was a *few hundred million years*.

• Both of these estimates are within the same order of magnitude, and only off by a factor of 2 or 3.

• Even the time estimate from scripture is close if you consider the time since the written record and civilization.
We still can't directly measure the age of the Earth.

The oldest rocks are 4 Ga (crustal rocks) to 4.27 Ga (zircons).

Meteorites by comparison are 4.57 Ga.

The Earth's mean lead isotope composition with some assumptions for lead sources suggests that the Earth is about 50-120 million years younger than meteorites (~4.5 Ga).

But the lead isotope event assumed may actually be an “event” like the separation of metal from silicates.
Heat Energy in the Earth

- Heat energy drives the Earth's interior mantle system

- If the Earth was hotter in the past and is cooling with time, then we strive to understand what processes act to cool the Earth down?
  - Subducting cold plates
  - Volcanic eruptions at convergent boundaries
  - Volcanic eruptions at spreading centers
  - Others?
  - Heat conduction
  - Rising plumes
Heat Energy in the Earth

• Lord Kelvin claimed in his calculations that there were “no unknown physical processes at work”.

• Was this true?

• Radioactivity (discovered by Marie Curie in late 1800's)

• The Earth was not totally solid and rigid as assumed. Later understanding of crustal rebound showed that mantle rocks “creep” slowly over time and behave “plastically”.

• This style of slow deformation allows for formation and transport of convective structure like plumes and convection cells.
Heat Energy in the Earth's Crust

• They did know the *thermal conductivity* of crustal rocks.

• They could estimate the temperature gradient with depth to the base of the crust which suggested it should be 1200°C. Is this normal?

• No! Crustal Moho temperatures are actually 400 – 700°C! What is the problem?

• Maybe conductivity is not the only active heating process? What else?

• *Radiogenic material* was later found to be highly concentrated in the continental crust compared with other tectonic structures.
Heat Energy in the Earth's

- **Reviewing**: What are the 3 heat transport processes in the Earth that we have discussed so far?
  - Conductivity
  - Radioactivity
  - Convection

- Which are the most important in the Earth? Why?
Let's start with conductivity of heat.

Heat, as everyone knows, flows from a hot body to a cold body (not in the reverse).

The rate heat is transferred depends on..... what?

- the temperature gradient
- thermal conductivity of material
Heat Conduction

• The *rate* heat is transferred depends on..... what?
  - the temperature gradient \((T_2 - T_1)\)
  - thermal conductivity of material \((k)\)

The rate of heat flow across the plate is described by \(Q\).

\[
Q = -k \frac{T_2 - T_1}{L}
\]
The rate of heat flow across the plate is described by $Q$, 

$$Q = -k \frac{\Delta T}{L}$$

- Thermal conductivity, $-k$, is negative because heat flows from hot to cold regions.

Units of $k$ are watts per meter per degree C ($\text{Wm}^{-1}\text{C}^{-1}$)

- The thickness of the plate is $L$.
- $Q$ is measured in units of watts per square meter ($\text{Wm}^{-2}$)
Heat Conduction

To describe this in terms of a differential equation, let's replace \( \Delta T \) with \( (T_{\text{hot}} - T_{\text{cold}}) \).

Distance, \( L \), can be written as \( \delta x \).

\[
Q = -k \frac{\Delta T}{L} \quad \text{(for the whole distance)}
\]

\[
Q = -k \frac{(T + \delta T) - T}{\delta x} \quad \text{(for a small distance)}
\]
Heat Conduction

So if a block or plate is thicker, how will heat flow $Q$ vary?
What if the block is made of granite and has low conductivity?
What if it is made of basalt?
Let's Go Back to those Plates

• What is a plate? What does a tectonic plate consist of?

• We think of plates as the outer shell of the Earth divided up into a number of thin rigid plates.
Lithospheric Plates

- Plate velocities vary from 1-10 cm/yr
- A large fraction of all earthquakes, volcanoes, and mountains occur at plate boundaries
- How are plates created?
Lithospheric Plates

- Plates are made by cooling of magma into rock

- How thick of a rock section is created by cooling? (How thick are plates typically?)

- Lord Kelvin's estimate for the age of the earth assumed this process, but only achieved cooling of the top 100 km of the earth!
Lithospheric Plates

• What is the *lithosphere*?

• The interior of the Earth which is made up of plates is called the *lithosphere*.

• Lithospheric rocks are cool and behave rigidly.

• These rocks **do not deform significantly** in geologic time.

• Most geophysicists opposed the hypothesis of plate tectonics in the early 1900's, even as late as the 1960's. Why is this?
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Surface observations and seismic waves showed that the Earth's interior was solid. How would solid material accommodate movement in this solid body?

No clear driving mechanism for plate movement.
Lithospheric Plates

• Most geophysicists opposed the hypothesis of plate tectonics in the early 1900's, even as late as the 1960's. Why is this?

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Lithospheric Plates

- Later studies of gravity surrounding mountain ranges and rebound observed in Scandinavia (Haskell, 1935) showed that deep mantle rocks shift or move in some sort of semi-solid fashion.

- Much later the study of solid state creep suggested that mantle material deforms and has a “viscosity” which allows movement of rigid plates at its surface. (Viscosities $\sim 10^{21-23}$ Pas)
• The lithosphere can be defined thermally by an isotherm at the base of the lithosphere which should be around 1350°C.

• Mantle rocks below this isotherm are cool and behave rigidly.

• Rocks above this isotherm are hotter and may deform.
Lithospheric plates are rigid and behave elastically.

- Plate transmit stress over long distances providing important implications for **plate driving mechanisms**.

- Rigid plates can bend when subject to a load such as volcanism or seamounts (e.g. Hawaii).
• Does the entire lithospheric plate transmit stress in the same way?
• The lithosphere is found to have an elastic portion which is roughly the upper ½ of the plate.
• Stresses relax in the lower portion of the plate where creep processes dominate, but still behaves coherently with the plate.
Heat Conduction of Lithospheric Plates

• When you subject a plate to heat or cold, will it be in steady state immediately? Describe this process and what this is called?

• The one-dimensional, time-dependent heat conduction equation best describes this process.

• Read through pages 178-185 in your text for next time.
Early Case for Continental Drift

- Puzzle-piece fit of coastlines of Africa and South America has long been known
In early 1900s, Alfred Wegner noted South America, Africa, India, Antarctica, and Australia have almost identical rocks and fossils.

- *Glossopteris* (plant), *Lystrosaurus* and *Cynognathus* (animals) fossils found on all five continents.
- *Mesosaurus* (reptile) fossils found in Brazil and South Africa only.
Most of the Earth's ice is found in Antarctic continental glacier.

Where are some other continental glaciers?
• **Glacial striations** on a rock from stones grinding at the base of a heavy ice sheet leave these shiny linear marks on the bedrock below.
Glacial Characteristics

- Glaciers flow downhill as a solid mass that creates channels, and walls made of ground up rock debris known as a *merraine*. 
Erosional Landscapes

- Erosional landforms produced by valley glaciers include:
  - *U-shaped valleys*
  - *Hanging valleys*
  - Smaller tributary glacial valleys left stranded above more quickly eroded central valleys
Early Case for Continental Drift

- Wegner reassembled continents into the supercontinent *Pangaea*

- Late Paleozoic glaciation patterns on southern continents best explained by their reconstruction into (Pangaea) Gondwanaland
Early Case for Continental Drift

• *Coal beds* of North America and Europe indicate Laurasia super continent

• Continental Drift hypothesis initially rejected
  – Wegener could not come up with viable *driving force*
  – continents should not be able to “plow through” sea floor rocks
The Earth's Magnetic Field Can Give Us Clues
Paleomagnetism and Continental Drift Revived

- Studies of *rock magnetism* allowed determination of magnetic pole locations (close to geographic poles)

- *Paleomagnetism* uses mineral magnetic alignment and dip angle to determine the distance to the magnetic pole when rocks formed
  - Steeper dip angles indicate rocks formed closer to the magnetic poles

- Rocks with increasing age point to pole locations increasingly far from present magnetic pole positions
Paleomagnetism and Continental Drift Revived

• **Apparent polar wander** curves for different continents suggested plate movement!

• Wegner was right!
Earthquakes don't occur randomly – but in patterns.

Friction and motion at **plate boundaries** seem to produce **earthquakes**.