Plate Tectonics
T. Perron – 12.001

Overview:

- Today:
  - Lecture: History of ideas about plate tectonics
  - Lab: Scientific specialties
- Day 2
  - Lecture: Rates and patterns of plate motions
  - Lab: Plate groups
- Day 3
  - Lecture: Forces driving plate motions
  - Lab: Plate groups present, wrap-up discussion

Definitions

- Earth Science's Grand Unifying Theory (or at least, one that works very well for many things)
- From "tekton" (Greek, "builder")
- Tectonics does not necessarily equal plate tectonics. For 2 centuries, ideas had been formulated about how mountains, ocean basins, etc. are formed. Textbooks explained these just like your textbooks explain plate tectonics, but they were mostly wrong.
- What was the series of ideas & events that led to the discovery of plate tectonics?

Observations: what were geologists of the last 2 centuries trying to explain?

- [Your lab will focus one some of these observations]
- Topography [PPT: global shaded relief]
  - Mountains, ocean basins, continental basins
  - Some mountains are high and jagged, others low and subdued
- Global distributions of earthquakes, volcanoes [PPT: figures from Lab]
- Evidence that things were vastly different in the past
  - Some mountains made of marine sedimentary rocks. Fossils at the top of Mt. Everest (!)
  - Marine sediments covering the midwestern US (recall the Indiana Limestone of the main MIT buildings)

Alternate theories

- Noah's flood (The "Diluvian hypothesis"). Also works nicely for, e.g., Grand Canyon.
- Global contraction (motivated mainly by compressional mountain ranges)
- Global expansion (proposed later as an explanation for evidence of seafloor spreading)
- Sea level changes
- Geosynclines (Mom's college geology textbook)

Continental Drift
Wegener (German meteorologist), post-WWI, Origin of Oceans & Continents: Continents have moved!
Evidence:

- Geographic match (jigsaw) [PPT: relief map]
- Rock type match (flood basalts in S. Amer & Africa, old metamorphics in Canada, Greenland, Scandinavia)
- Fossil match (e.g., freshwater reptiles in S. Amer, Africa), followed by evolutionary divergence of later fossils
- Climate evidence (continental glacial deposits in S. Amer, Africa, India, Australia)

Wegener's mechanism: Continents are floating on oceanic crust, and move around like boats due to lunar and solar tides.

Counterarguments

- That's stupid.
- This guy is a meteorologist!
- Forces are insufficient to overcome huge frictional forces or deform entire continents. Geologists deferred to physicists.
- Even if forces were sufficient, continents would deform internally rather than drifting

But some stuck with the idea of continental drift, and proposed mechanisms other than Wegener's:

- Holmes (British), 1920s: Seafloor spreading driven by rising of melt from Earth's interior. Didn't advocate too strongly, for fear of ruining his career.

Evidence mounts

- Bathymetric mapping of sea floor [PPT: shaded relief]
    - Previously, very little known about what was there
    - Mountain ranges in ocean basins. Later found to be continuous along middle of ocean basins
    - Crack-like valley at middle of mountain range ("rift")
- Sampling of seafloor by dredging & drilling
    - Seafloor sediments not as thick as previously thought (if ocean basins 4+ Gyr old, should be thicker)
    - Oceanic crust made of basalt, not granite
    - Younger basalt and sediments near center of ocean basins
- Help from the Cold War:
    - Mapping magnetic lineations (differences in intensity of field) on seafloor as by-product of effort to detect submarines post-WWII.
    - Symmetric pattern about rifts @ middle of oceans: why? Enigma for 10+ yrs.

→ All these lines of evidence suggest that sea-floor spreading occurs, and that new crust is created by upwelling of magma at rifts.

→ But this created a new problem: where does this crust go?

- Expanding earth?
- Recycling of oceanic crust?
    - Lots of geologic action in certain narrow, linear zones on Earth's surface…maybe that's where it's happening (your lab!)
    - Most active deformation (high mountain ranges, young folds, fault offsets) appears to be occurring at these zones
    - [We can now image at least the first stage of oceanic crust being recycled, using seismic tomography: old → cold → dense → higher moduli → faster wave speed] [PPT: Zhao et al. 1997 Tonga trench]

During the mid-1960s, these observations led geologists to outline the main principles of plate tectonics:

1. Earth's outer, rigid layer ("lithosphere") is broken into discrete plates (≠continents), each of which moves more or less as a unit. [How many plates there are is a topic of debate]
2. This motion is accommodated by motion of Earth's mantle
3. Different types of relative motion and different types of lithosphere @ plate boundaries create distinctive sets of geologic features (the point of your lab – more details in our wrap-up discussion on Monday). Why does lithospheric type matter?
    a. Continental lithosphere is less dense → not as easily recycled
    b. Continental lithosphere is weaker → plate boundaries involving continents are more diffuse

II. Rates and patterns of plate motions

<u>Rates of plate motion: how fast, and how do we know?</u>

A. Geologic evidence
- Magnetic anomalies
    - Volcanic rock magnetized when cooling
    - We can date these rocks radiometrically
    - Earth's magnetic field reverses polarity
    - → construct global sequence of reversals and their timing (every ~500 kyr on average, but only quasi-periodic)
    - Seafloor spreading rate = anomaly width/duration or dist of reversal from ridge/age of reversal
        - mid-Atlantic = 18 mm/yr
        - East-Pacific Rise = 150 mm/yr
        - Global average = 50 mm/yr

  [PPT] Seafloor spreading & magnetic reversals
- Age of seafloor sediments from drilling

    - Foram species change through time, calibrated with dated ash beds [PPT: foram shells]
  - Age of offset features
    - Volcanic eruptions, e.g., Pinnacles volcanic field: half in central CA, half near LA
    - Radiocarbon dating of organic material in trenches through faults that have experienced recent EQs [PPT]

B. Direct measurement
  - Strain meters across faults [SKETCH]
  - Repeat surveys, e.g. triangulation on Berkeley stadium
  - Space geodesy
    - Satellite laser ranging [PPT] tracks changes in plate locations relative to precisely known orbits
    - VLBI [PPT] tracks phase (and therefore arrival time) difference of two sites on Earth relative to distant radio sources such as quasars
    - GPS (most common): direct measurement of plate motion vectors with long collection times and careful post-processing [PPT]

<u>Where were plates in the past?</u>

- Wegener's methods
  - Geometric matching of plate boundaries
  - Fossil matching
  - Rock type matching
  - Climate indicators in rocks (e.g. glacial deposits, coal beds from swamps, fossils) give paleo-latitude
- Back-tracing seafloor spreading (but oldest oceanic crust ~ 180Ma!)
- Back-tracing transform boundaries (but finite range → finite time)
- Volcanic features that suggest a fixed source in mantle: Hot spots (e.g., Hawaii-Emperor seamount chain)
- Mountain belts: age, orientation of collision
- Geologic indicators of closed plate boundaries
  - ophiolites: remnants of oceanic crust that indicate a closed ocean basin
  - Island arcs
  - General term for an accreted piece of crust: "terrane"
- Paleomagnetism (most powerful)
  - Angle of magnetic minerals relative to horizontal → latitude
  - Longitude is harder; usually no direct constraint
    - Absolute orientation relative to north, if not too much rotation has occurred (uncommon, hard to tell)
    - Multiple samples of same age with known latitude on a single plate → rotation of plate. Again, difficult to get.
- Plate motions described by rotation of rigid plate on a sphere about an Euler pole [PPT]

Case studies: [PPT] Movies of plate motions

- Breakup of Pangaea (existed ~250Ma): best constraints
- [short-lived Pannotia, ~600Ma]
- Breakup of Rodinia (existed 1100 - 750 Ma): less well constrained (no oceanic crust!)
- Assembly of Laurentia: Starting with Archean cratons 2Ga. Positions essentially unconstrained, just relative order and geometry of accretion

Are there any systematic patterns here? How many supercontinents have there been? J. Tuzo Wilson hypothesized in 1966 that plate tectonics is cyclic [PPT]:

1. Continental rifting (ex: E. Africa)

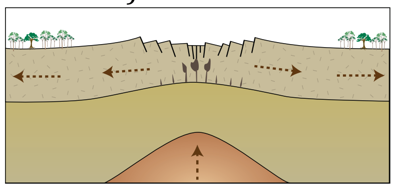
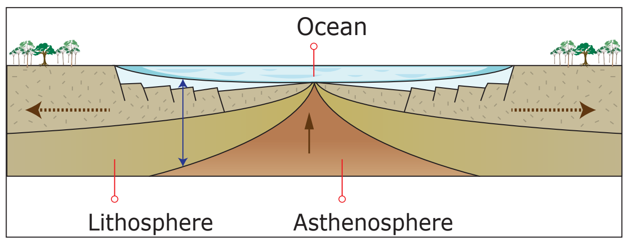


Image by MIT OpenCourseWare.

2. Formation of seafloor spreading center (ex: Red Sea)



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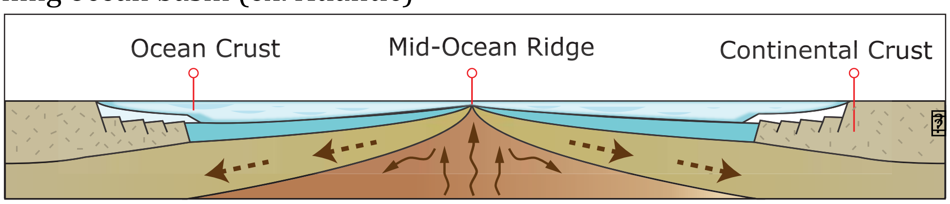
3. Widening ocean basin (ex: Atlantic)



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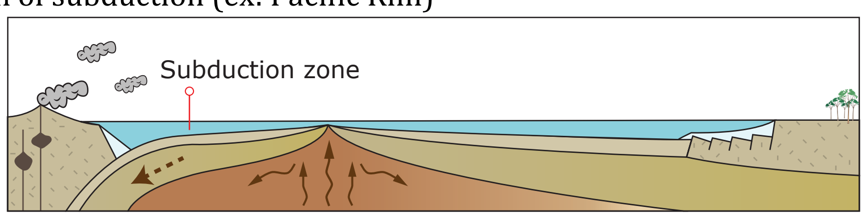
4. Initiation of subduction (ex: Pacific Rim)



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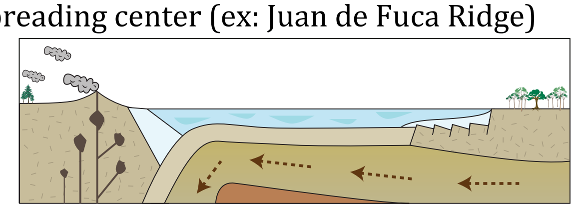
5. Subduction of spreading center (ex: Juan de Fuca Ridge)



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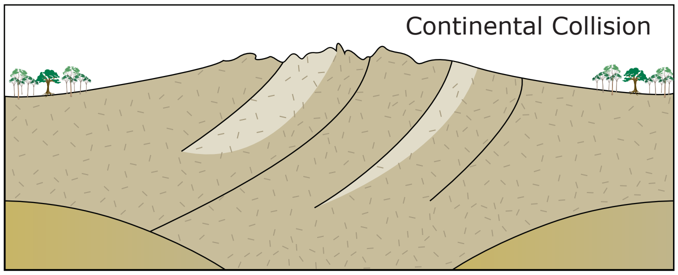
6. Closing of ocean, formation of collisional orogen (ex: closure of Iapetus Ocean to form the Appalachians, and rocks of the Boston Basin)



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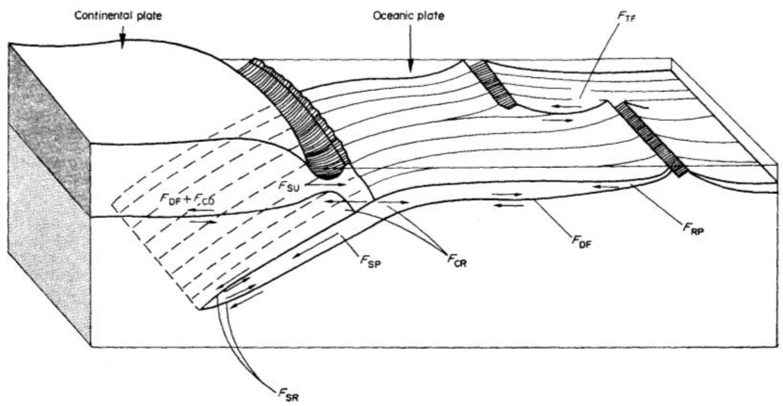
It has been suggested that this cycle takes 300-500 Myr, and controls the formation and breakup of supercontinents. What forces drive these motions?

III. Driving Forces: Why do plates move?

- A sketch of the potentially relevant forces (from Forsythe & Uyeda 1975):



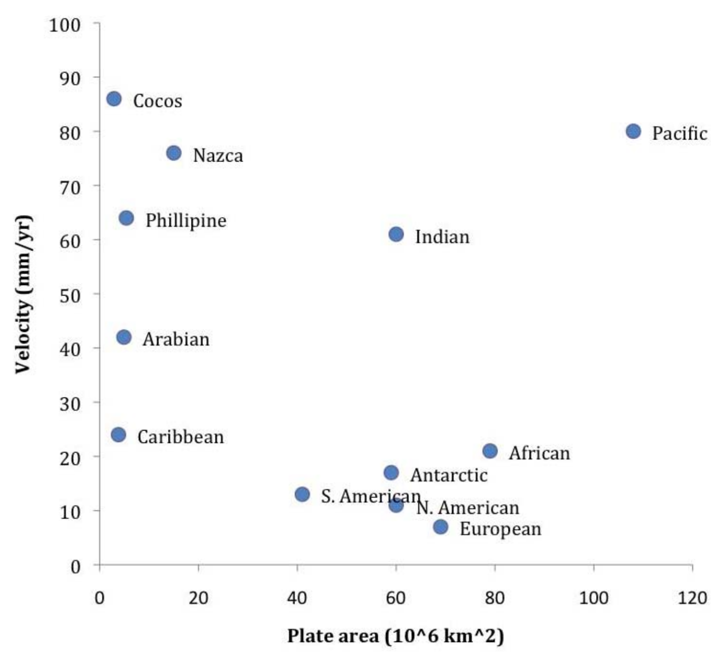
Source: Uyeda, S., and D. Forsythe. "On the Relative Importance of the Driving Forces of Plate Motion." *Royal Astronomical Society Geophysical Journal* 43 (1975): 163-200.

Force	Driving or Resisting?
F_{DF}=mantle drag: could be driving or resisting	D or R, depending on whether mantle flow assists or opposes plate motion
(F_{CD}=possible additional drag on continents due to different rheology of asthenosphere)	D or R, same reason as above
F_{RP}=ridge push due to gravity	D
F_{TF}=transform fault friction	R
F_{SP}=slab pull, gravitational body force	D
F_{SR}=slab resistance due to viscous drag	R
F_{CR}=friction between plates	R
F_{SU}=suction on overriding plate due to subduction	D

- A note about mechanical stratification
  - What I have drawn here is not crust and mantle – that is a compositional boundary.
  - This is lithosphere vs. asthenosphere – a rheological boundary
    - Lithosphere includes crust and uppermost mantle, down to about a few tens to 100 km. Behaves rigidly (brittle at surface)
    - Asthenes = weak (Greek). Down to 200 or perhaps as much as 400 km. Relatively low viscosity due to high T and perhaps

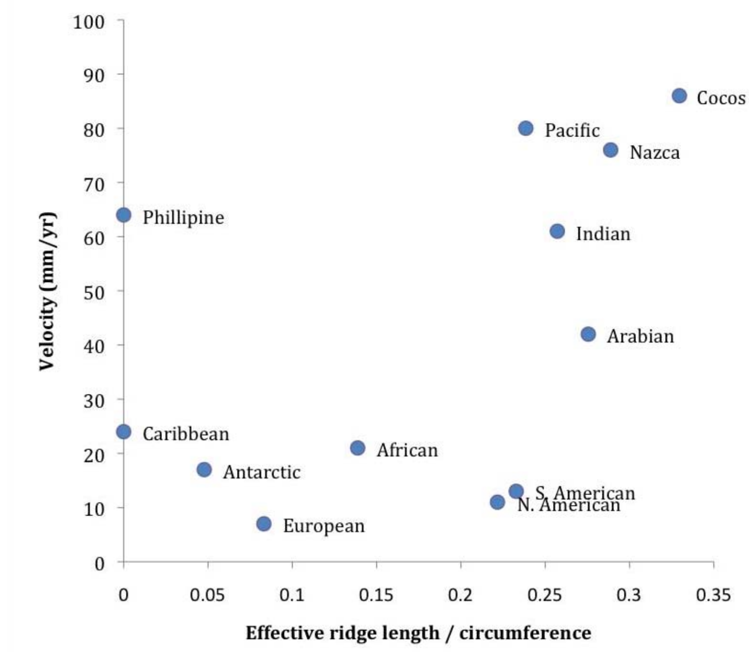
partial melting and the presence of water. Entirely within the mantle.
    - Asthenosphere first recognized from low velocity zone in seismic waves (= low moduli = less rigid), and low viscosities inferred for uppermost mantle in postglacial rebound studies

- What ultimately drives plate tectonics? Mantle convection.
  - How do we know this? Heat from Earth's interior is the only energy source sufficiently large to move plates. Solar, tides too small.
  - The way heat flow is converted into mechanical energy is by convection. [PPT: Rayleigh-Bénard convection]
    - Cold boundary layer develops at upper surface of internally heated fluid. This boundary layer transmits heat conductively
    - Cold boundary layer sinks due to negative buoyancy
    - By conservation of mass, this sinking must drive an upward return flow of hotter material
    - There will also be a thin thermal boundary layer at lower surface, which will also be unstable, and can give rise to positively buoyant plumes (→hot spots?)
  - But how does it drive plate motion? Which forces are the most important? For some forces (mainly viscous drag btw lithosphere and asthenosphere), we aren't sure of the sign!
- Mantle traction
  - Viscous drag btw lithosphere and asthenosphere
  - Initially assumed to be the main force driving plate motion
  - One way to test: plot velocity (in hot spot reference frame) vs. plate area, because F = stress*area:

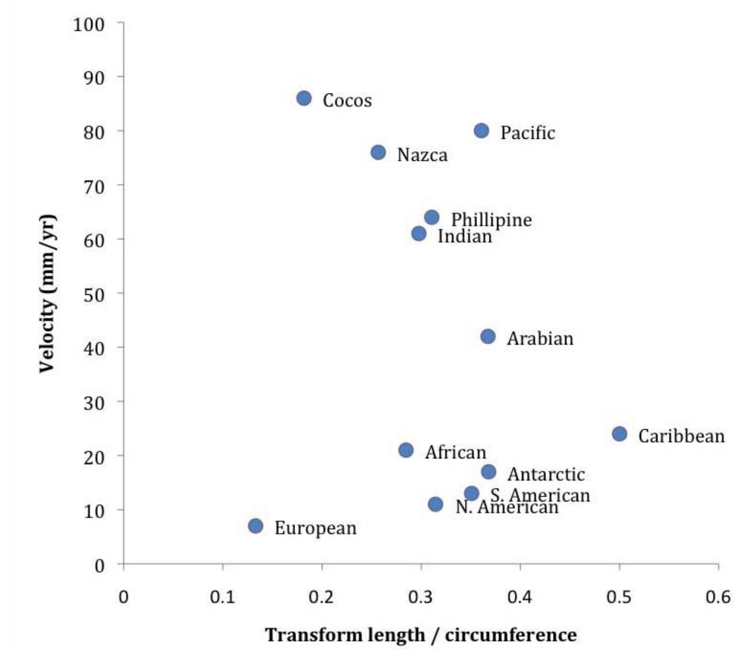


  - Not much of a relationship! The problem with this is that there are two interpretations, each consistent with a different argument

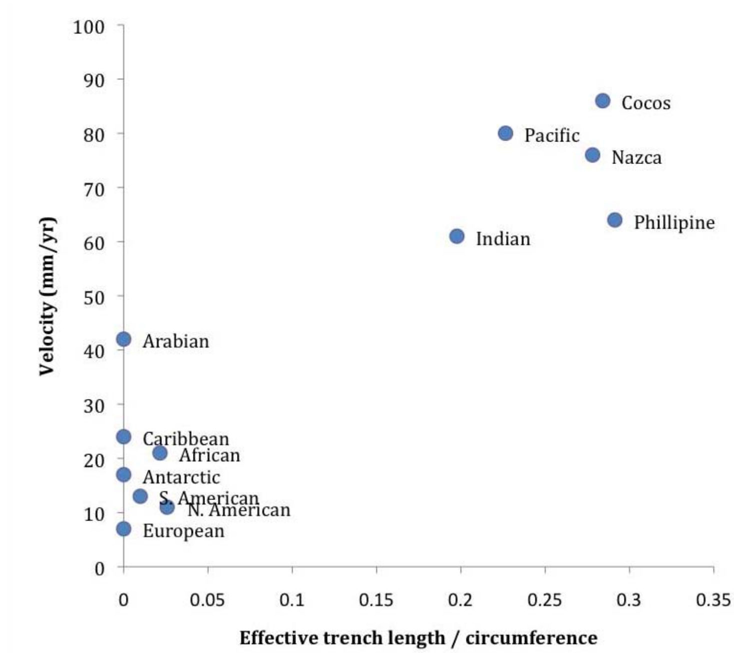
    - Plates are strongly coupled to convection cells, so the area doesn't matter – the plate velocity is set by convection velocity
    - The asthenosphere is so weak that plates are almost completely decoupled from asthenospheric flow, so area doesn't matter.
  - There are other problems with the idea that mantle traction is the main, active, driving force:
    - Why do ridges segment along transforms? Doesn't make sense that convection cells would segment that way. Works if the upwellings under ridges are localized and passive…
    - Why do ridges sometimes jump positions or start growing in a new orientation (e.g. East Pac Rise)? Convection cells shouldn't do this, but no problem if upwelling is localized and passive.
    - What happens when a ridge is subducted? Upwelling and downwelling currents would have to merge! Unless the upwelling is a localized, passive process…
  - These problems led geologists to investigate other potential driving & resisting forces. If it's not traction distributed across plate interiors, maybe it's forces acting on plate boundaries.
- Ridge/rift push
  - Gravitational stresses due to thermally elevated region
  - Not as strong, but appears to happen



  - Intraplate compressional EQs, maybe those in New England
- Transform friction
  - Resistance at offsets that develop where spreading direction is oblique to direction of plate motion
  - Data:

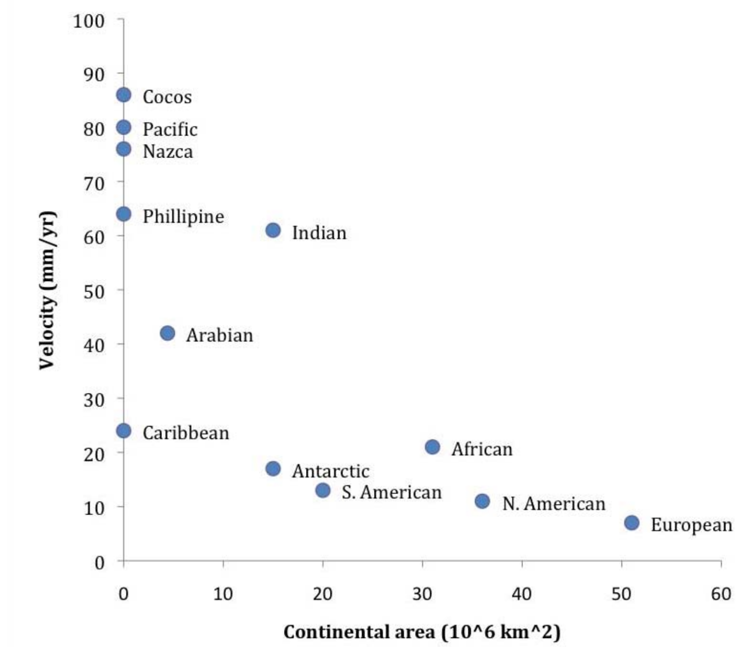


- Slab pull
  - Sinking of dense, cold oceanic crust pulls plate along
  - Data: main difference in velocities is between plates with and without subduction zones:



  - But can't be the only force, b/c Atlantic wouldn't have formed and supercontinents wouldn't have broken up! Part of the explanation could be "swell push" from insulated, elevated plate interior. Also →
- Trench suction?
  - Possible mechanisms
    - 1: slab rollback (The wet towel effect)

        - 2: secondary convection induced by slab
        - 3: water-induced flux melting thins overlying plate, new ridge starts to form
    - Not clear if it's important, but could help explain breakup of supercontinents
- So where does mantle traction fit in, if at all? A relevant plot:



    - A couple of potential interpretations:
        - Continents happen to be located on slow plates
        - Continents slow plates down (deeper roots, more drag?)
    - So mantle traction may not be the driver, but mantle drag may be a non-trivial resisting force, at least under continents
- The recognition of these empirical trends was followed up by more rigorous analyses of the entire system of plates
    - Basic assumption: no net torque on individual plates or entire lithosphere, because they are not accelerating
    - Least-squares analysis of relative magnitudes of the forces we've sketched out
        - Performed simultaneously for all plates
        - Using no net torque constraint
        - Using measured plate geometry and velocities as knowns, and force magnitudes as unknowns
        - Support idea that slab pull has the largest magnitude
- Details of how mechanics of these processes relate to mantle convection & how the whole system is sustained are still actively studied. E.g., what exactly is happening in the asthenosphere, and why has it persisted?
- Other datasets have been brought to bear in the last 30 years
    - Tomography: shows how far down slabs descend

    - Stress measurements within plates and at plate margins lend support to the slab pull and ridge push ideas
    - Numerical models of mantle convection, though they still have a hard time incorporating plates (usually just an area of high viscosity), so it's hard to just "solve the equations and get it over with"
- Note that I haven't said much about the different types of plate boundaries and the associated geological features. This is intentional, as it is the subject of your lab. We'll cover this in the wrap-up session in the final lab period.

Lab Wrap-Up Discussion

	Convergent	Divergent	Transform
Ocean-Ocean	**S:** N/A **V:** Narrow chain of volcanoes on overriding plate. **E:** Narrow band of EQs becoming deeper in direction of subduction [why?]. **T:** Trench on subducting plate side, may be island arc on overriding plate [why?]. Boundary often arcuate. **Ex)** Aleutian Arc, Fiji/Tonga, SE Asia	**S:** Symmetric, banded pattern of seafloor age. Active ridges will have ~zero-age rocks at center. **V:** Submarine volcanism focused in narrow band. **E:** Narrow (~10km wide) band of shallow EQs. **T:** Elevated ridge with rift valley at center. **Ex)** Mid-Atlantic, East Pacific, SW India	**S:** Asymmetric pattern. **V:** Sparse, unless there is a subduction component. **E:** Many shallow, centered on boundary. **T:** May be compressional mountains; otherwise no clear signature. **Ex)** New Zealand, Caribbean
Ocean-Continent	**S:** N/A **V:** Extensive volcanism on continent side, often set slightly inland from coast. **E:** Band of EQs becoming deeper in direction of subduction [what sets width of this band?]. **T:** Trench on subducting plate side, often compressional mountains in addition to volcanoes on overriding plate. **Ex)** Peru-Chile	N/A	**S:** N/A **V:** Sparse, unless there is a subduction component. **E:** Many shallow, centered on boundary. **T:** May be compressional mountains; otherwise no clear signature. **Ex)** N. America-Pacific
Continent-Continent	**S:** N/A **V:** Sparse. **E:** Diffuse EQs in continental interior. **T:** Major mountain ranges **Ex)** India-Asia	**S:** N/A **V:** Abundant volcanism, often associated **E:** Diffuse, shallow EQs. **T:** Broad, elevated region with major rift valley. **Ex)** E. Africa	**S:** N/A **V:** Sparse. **E:** Many shallow, centered on boundary. **T:** May be compressional mountains; otherwise no clear signature. **Ex)** Turkey; Eurasia-N. America?

S=seafloor age, V=volcanoes, E=earthquakes, T=topography