ESS 202 - Earthquakes

Attend your section

Check website for assigned reading

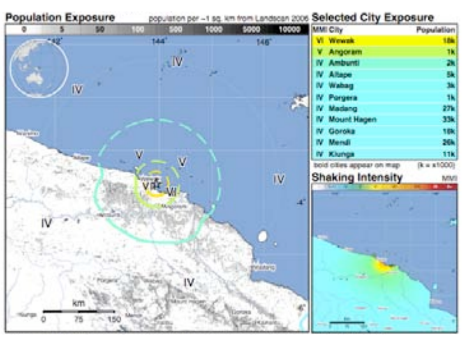
Press, 18-19

Class details

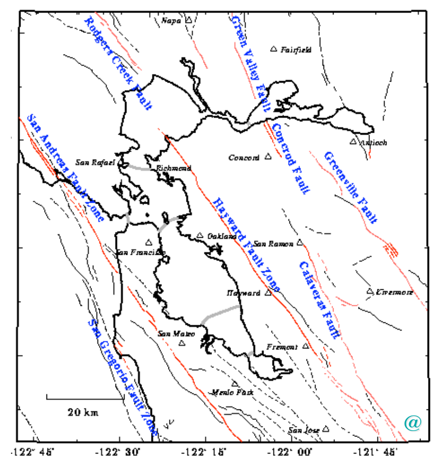
- Web page should be working.
  - http://courses.washington.edu/ess202/
  - Linked through myUW
- Now 64/70 enrolled, couple of slots in each lab open.
- Fill out intro questionnaire - it's the 1st quiz
- Remember, with notice, missed quizzes can be easily made up.
- We're tossing the lowest quiz score
  - So missing one quiz is not costly

Earthquakes yesterday

- M6.3 in New Guinea
- No damage or injuries reported
- No tsunami expected



- M4.3 in California
  - A modest earthquake from an anonymous fault struck in the middle of nowhere on Monday morning.
  - said Boatwright, "It's not worth a field trip. It will remain unknown. It was too small."
  - *Mercury News*



Major Bay Area Faults

Plate tectonics

- Provides driving force for earthquakes
  - and volcanoes
- Basics of plate tectonics
  - Essential Earth structure
  - How and why the Earth is convecting
  - Maps of the moving plates
  - Three types of plate boundaries
    - implications for faults, volcanoes

Get comfortable with Large Numbers

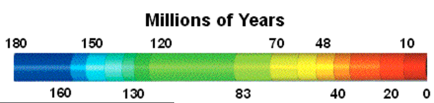
- Million = 1,000,000 = $10 \cdot 10 \cdot 10 \cdot 10 \cdot 10 \cdot 10 = 10^6$ =1000*1000
  - Example: number of people in medium-large city
- Billion = 1,000,000,000 = 10^9 =1000*1000*1000
  - Example: number of people on Earth (6 billion)
- Trillion= 1,000,000,000,000=10^{12} =1000 billions
  - Example: $ize of American economy

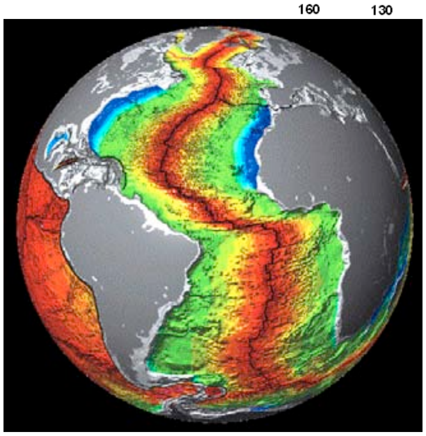
Discrepancy - Age of Earth vs Age of Ocean Floor

- Age of universe about 15 billion years
  - 15 * 1000 * 1,000,000 yrs
- Age of Earth about 4.5 billion years
- Age of oldest ocean floor 150 million years
  - only 4% of age of Earth
- Why?

Seafloor ages

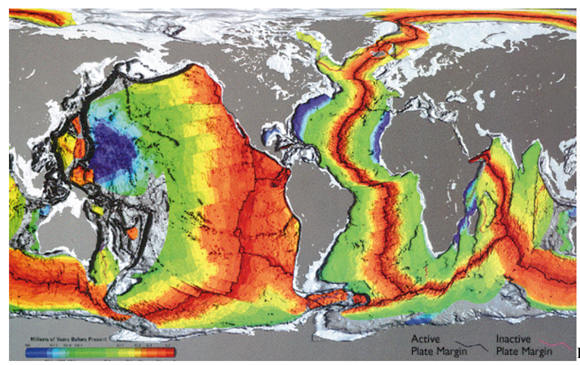
- Ages measured from foraminifera study
  - Single celled ocean creatures
  - Retrieved by drilling to bottom of sediments
- Range from new to 150-200 Mya
  - cms per year created
  - or 40 km per million years
- Seafloor grows old with time until it sinks back into mantle





Atlantic seafloor age

Age of seafloor.
Red young (20 Myr), blue old (150-180 Myr).
Note bands of younger rock in middle of oceans.

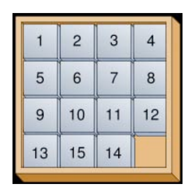


Press 20-11

Distance scales - sizes of continents and oceans

- Centimeter ~ 0.4 in
- Meter (m) ~ 3.3 ft.
  - 100 centimeters (cm) in 1 meter
- Kilometer (km) = 1000 m
  - 1 km = 0.6 mile
- Continent typically several thousands of km across
  - North America is about 4000 km across
  - Atlantic Ocean about 8000 km wide
  - Pacific Ocean about 15,000 km wide

Today's lecture: plate tectonics



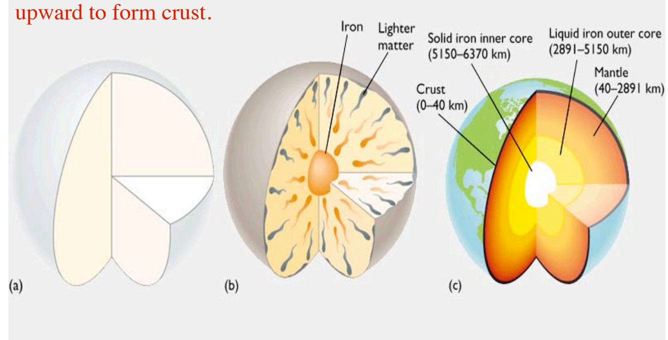
- 0. What are the tectonic plates?
- 1. Reason for plate tectonics, why does it occur?
- 2. Evidence for plate tectonics
  - also history of a supercontinent
- 3. Three types of plate boundaries
- 4. Types of faults, relation to plate boundaries

0. What are “plates”?

- The Earth is layered.
  - crust - rocky (silicate (SiO_4) + light elements(K, Al))
  - mantle - rocky (silicate with more Fe and Mg)
  - core - 90% iron
    - **molten** outer core & **solid** inner core
- Tectonic <u>plates</u> are pieces of the chilled, rigid outermost ~100 km of the Earth (**lithosphere**).
  - like ice on surface of lake, skin on pudding
- Plate interiors are rigid - most deformation occurs at plate margins.

Formation of Earth’s iron core

In process of differentiation iron sank to center, lighter material floated upward to form crust.



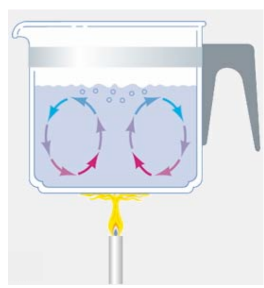
Press 1-6

1. Reason for plate tectonics - mantle convection

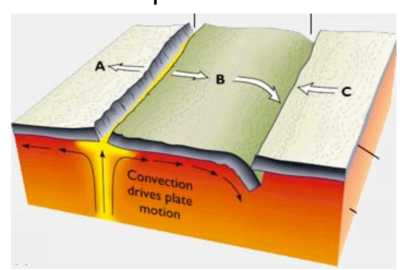
- Heat a liquid from below, cool it on top
  - Hotter material is less dense
    - because rapidly moving atoms occupy more space
  - Cooler material is more dense
- So the warm light liquid on the bottom rises and the cool dense liquid on top sinks
- The liquid continually overturns, like a pot on a stove
- Convection tends to (tries to) homogenize temperatures

Convection in action

- Water on stove

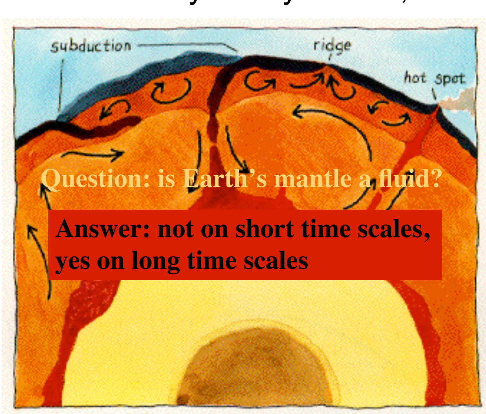


Tectonic plates on mantle



Press, 1-13a, 1-14a

Convection in Earth’s mantle from Scientific American article by M. Wysession, March ‘95

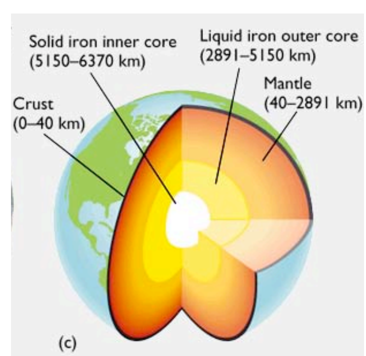


Question: is Earth’s mantle a fluid?

Answer: not on short time scales, yes on long time scales

Classification of Earth’s Layers

- Composition
  - crust - silicate + lighter elements
    - oceanic
    - continental
  - mantle - silicate
  - core - 90% iron
    - fluid outer core
    - solid inner core

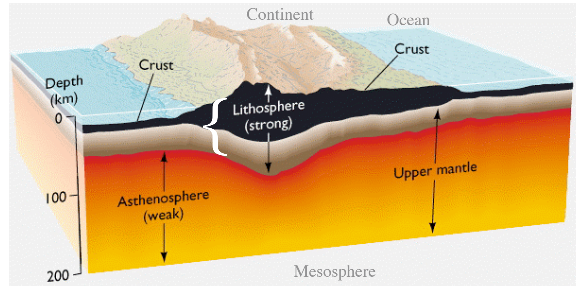


Two Classification Systems of Earth's Layered Structure

- Composition
  - crust
    - oceanic
    - continental
  - mantle
  - core
    - fluid outer core
    - solid inner core
- Strength
  - lithosphere
    - outermost rigid layer
  - asthenosphere
    - weak layer below lithosphere
  - mesosphere
    - lower strong layer

(crust — is part of — lithosphere; mantle } lithosphere, asthenosphere, mesosphere)

Strong layer (lithosphere) slides over weaker layer (asthenosphere)



Press 1-11

Reasons for Plate Tectonics

- Strong lithosphere <u>slides over</u> weaker **asthenosphere** as part of convection of Earth's mantle
- Overall driving process is release of Earth's heat to space
- Force comes from convection
  - **hot rock is less dense and rises**, displacing cooled, denser surface rock which sinks down into mantle

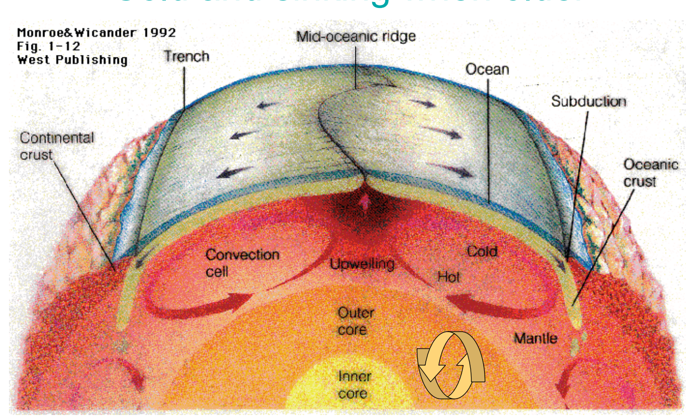
Basics of Plate Tectonics

- There are about 15 major plates.
- Their boundaries are the sites of earthquakes and volcanoes. Why?
- Three types of plate boundaries
  - convergent -> subduction -> destruction of plate (**oceanic** plate)
  - divergent -> sea-floor spreading -> creation of plate (**oceanic** plate)
  - transform -> transform faulting -> conservation of plate

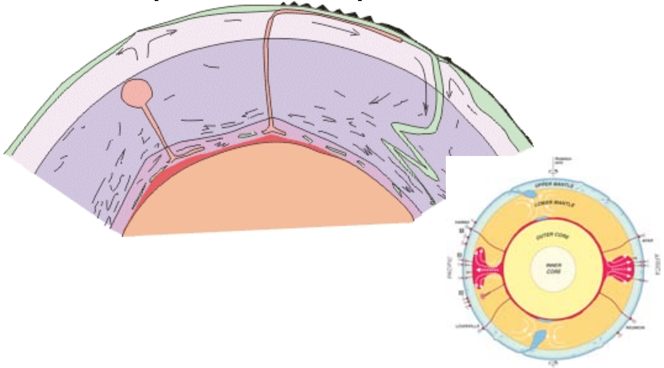
Key points

- Tectonic plates move 1 to 17 cm/year
  - This is about 10 to 170 km (6 to 100 miles) per million years
- The mantle is moving at slightly lower velocities
- It takes about 100-200 million years for the mantle to overturn
- The outer core is a liquid, and it is also convecting, but much faster,
  - creating Earth's magnetic field

Plates move: Hot and buoyant at ridge Cold and sinking when older

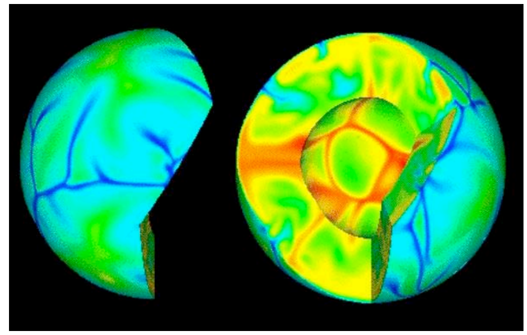


Two modes of convection: plates and plumes



3-D numerical simulations

red - warmer temps blue - cooler



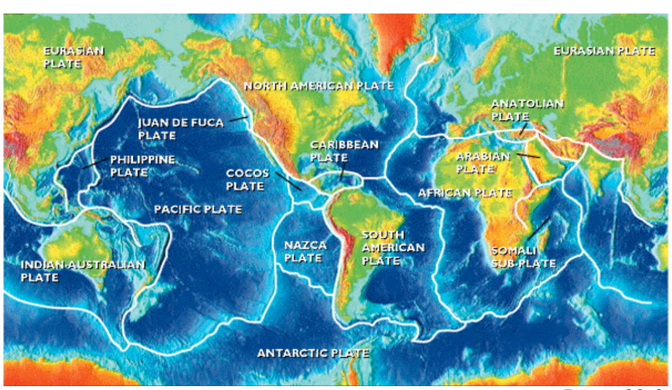
Plates are not continents

- Plate margins need not coincide with continental margins
  - Examples:
  - 1. East coast of US is not plate boundary. North American plate includes continent of North America **and** part of Atlantic Ocean.
  - 2. West part of California on Pacific plate.
  - thus many plates are both continental and oceanic

More points

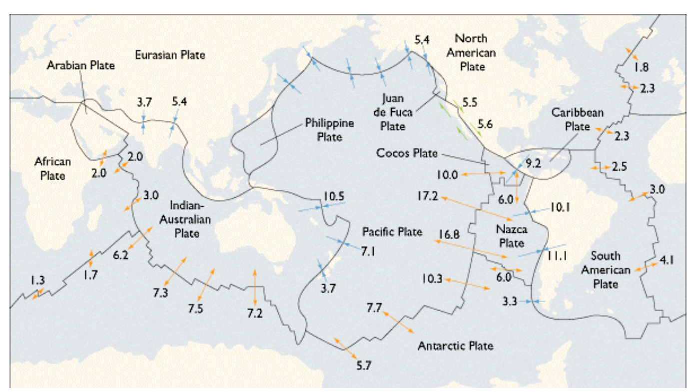
- The boundaries between plates are faults
- Earthquakes are essentially the plates moving past each other jerkily

Map of major plates. Many have continent in the middle, ocean on the edges.



Press, 20-3

Plate speeds range from 1 to 17 cm/yr



Press, 20-12

How far does a plate go?

V - velocity, T - time, D - distance

$V = 1\ cm/yr = 10^{-2}\ m/yr$

T = 1 million years = 10^6 yr

$D = VT = 10^{-2}\ m/yr \times 10^6\ yr = 10^4\ m =$ 10 km

T = 100 million years = 10^8 yr

$D = VT = 10^{-2}\ m/yr \times 10^8\ yr = 10^6\ m =$ 1000 km

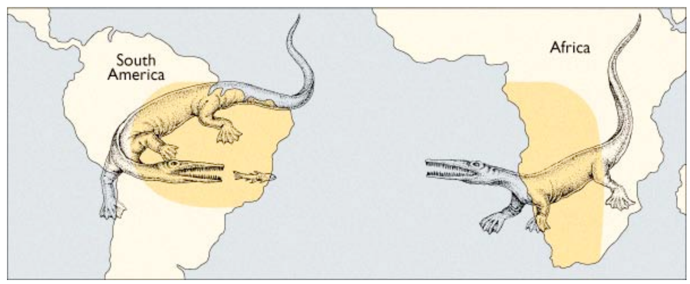
2. Evidence for Plate Tectonics

- Continents fit together
  - like jigsaw puzzle
- Old mountain ranges and rock formations continuous
- Fossils of identical animals found on both sides of Atlantic ocean
- Glacial deposits indicate continents were farther south and next to each other

Continents fit and rock formations match if Atlantic Ocean is closed

Press, 20-1

Matching fossils on opposite sides of Atlantic Ocean



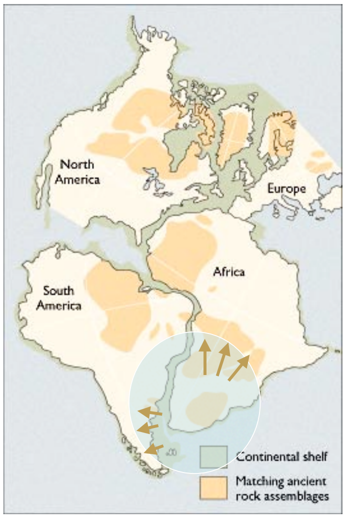
Press, 20-2

Mesosaurus, extinct reptile found only in Africa and South America

Evidence from Glaciation

- Deposits left by glaciers on S. America, Africa, Australia, India
  - indicate these continents were farther south, nearer to South Pole
- Striations (grooves or scratches) in rock show ice flow direction
  - indicate ice flowed **away** from present coastlines
  - imply present-day coastline was ***interior*** of supercontinent

Glacial striations



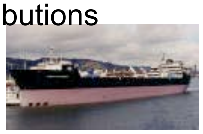
Press, 20-1

A brief history of plate tectonics

- 1660 - Francis Bacon, and probably many others, noticed similarity in coastlines, no idea what it meant
  - Some say he wrote Shakespeare's plays

Then …

- 1912 Alfred Wegener noticed coastal fit and fossil and rock similarities, but very few others believed his theory of continental drift
  - no convection, solid rock can't flow
- 1960's magnetic stripes, seafloor dredging and earthquake distributions convince scientific community



Observations Explained by Plate Tectonics

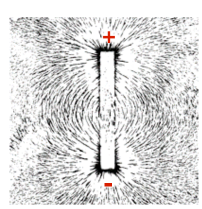
- Relatively young age of the ocean floor
  - Why?
- Earthquakes: locations and types
- Volcanism: locations and types
- Locations of important minerals and energy resources (oil)

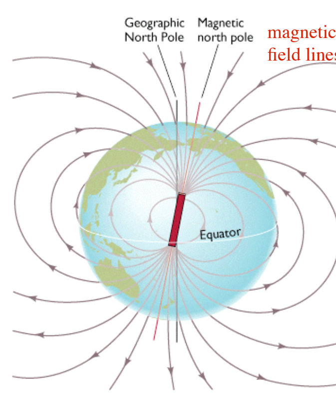
Observations Explained by Plate Tectonics, cont.

- Many aspects of biological evolution - diversity vs. similarity of species
  - About 200 Myr ago continents were joined and many species similar (dinosaurs found on most continents)
  - After Pangea and Gondwana started to split diversity of species greatly increased due to geographical separation of habitats and niches
- Magnetic stripes on ocean floor

Earth's magnetic field
- has dipole form

Iron filings in magnetic field of bar magnet





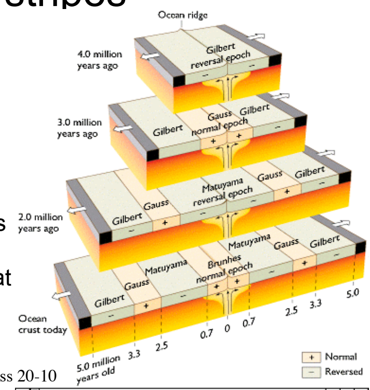
Press 19-12

Earth's magnetic field

- Magnetic field provided key clue to plate tectonics
- Magnetic field has dipole form
  - like magnet with north and south poles
- Field reverses at random intervals
  - ranging from 0.5 Myr to 30 Myr
  - so compasses and magnetic directions in rocks would point toward south pole

Explanation of magnetic "stripes"

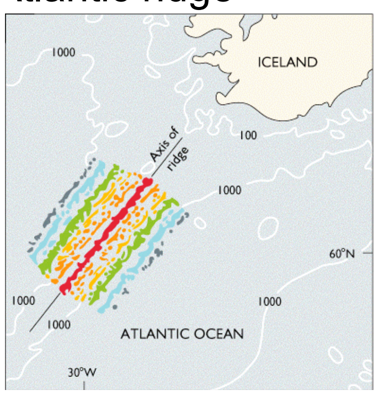
Bands form successively as
- plates spread apart
- magma wells up to form new seafloor
  - which cools and records normal or reversed magnetic field existing at that time



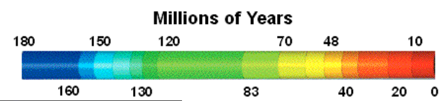
Press 20-10

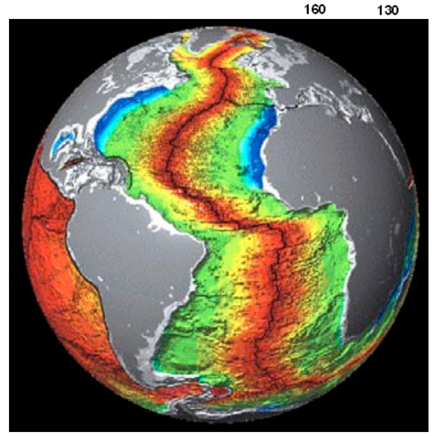
Magnetic "stripes" found on Mid-Atlantic ridge

- Colored bands indicate normal magnetic polarity
- No color indicates reversed polarity
- Symmetric pattern was puzzling to geologists
- Caused by spreading ridges and reversing magnetic field
- Stripes later found in all oceans, give age



Press 20-9





Atlantic seafloor age

Plate reconstructions

- Can trace plate motions well for last 200 million years
  - Since we have oceanic plates up to about that age to reconstruct motions
- Motions less well-known 200-600 Mya
  - No oceanic plates left around to help

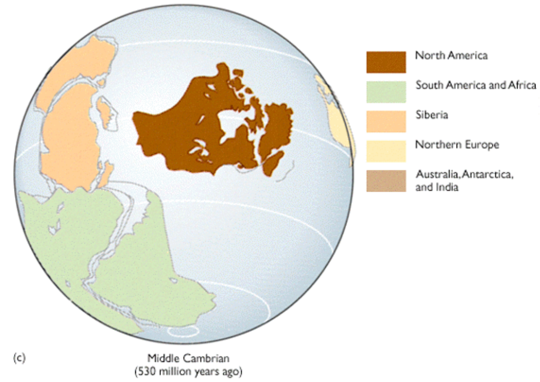
Supercontinents

- **Pangaea** existed ~200 Mya
  - All major continents, N. America near equator
  - Started to rift apart ~175 Mya, dinosaur time
- **Gondwana** is name for supercontinent at about 550 Mya
  - S. America, Africa, India, Antarctica, Australia
  - Near South Pole
  - Re-arranged about 300-200 Mya => **Pangaea**

Super-continent Gondwana

- About 550 Myr ago the following continents were joined together and situated near the South Pole
  - South America
  - Africa
  - India
  - Antarctica
  - Australia
- They started to rift apart ~175 Myr ago.

Gondwanaland - 530 My ago

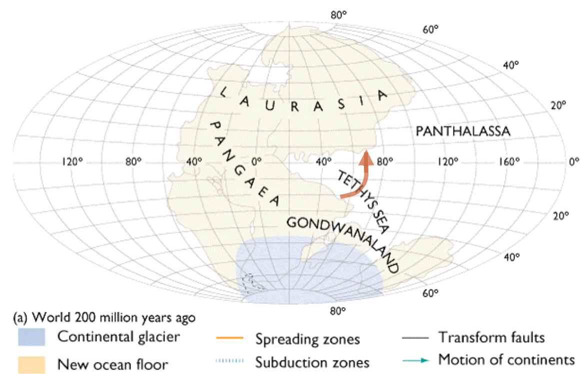


Pangaea ("all lands")

- For a shorter time (~350 - 175 Myr) Gondwana was attached to the Northern continents of
  - North America (Laurentia)
  - Europe
  - Asia
  - Greenland

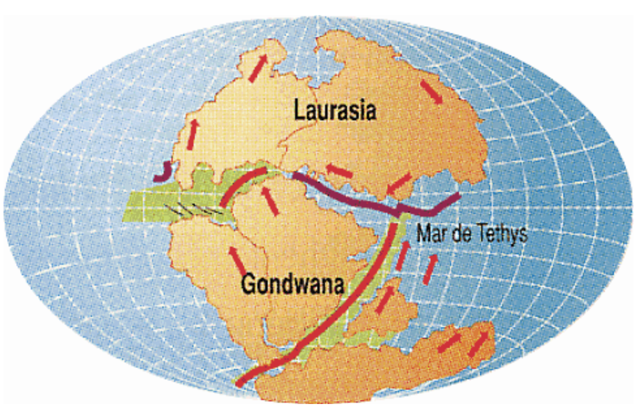
- N. America was situated on the equator
  - Dinosaurs roamed the Earth

Pangaea = Gondwana + Laurasia

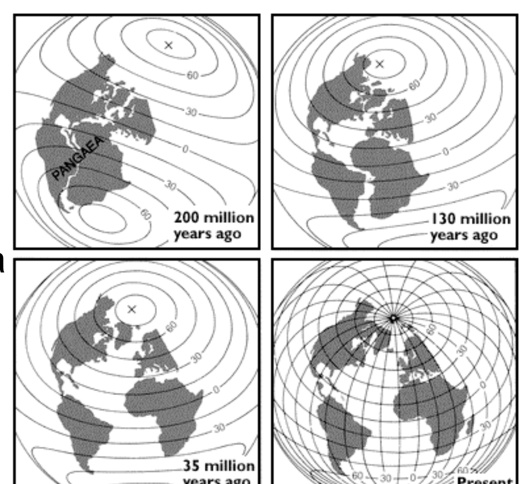


Closure of the Tethys Sea & collision of India with Asia built the Himalayans

Pangaea = Gondwana + Laurasia



The breakup of Pangaea

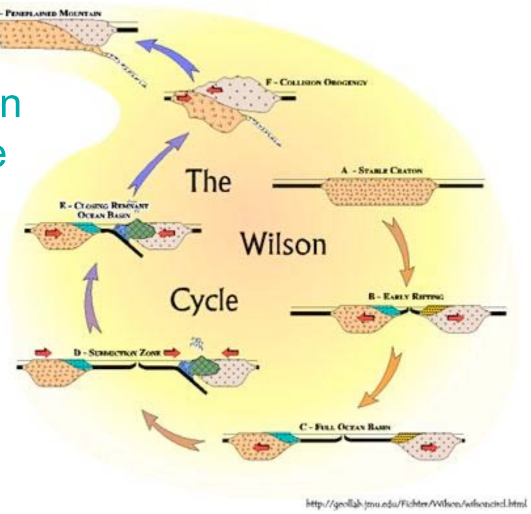


Press, 20-13

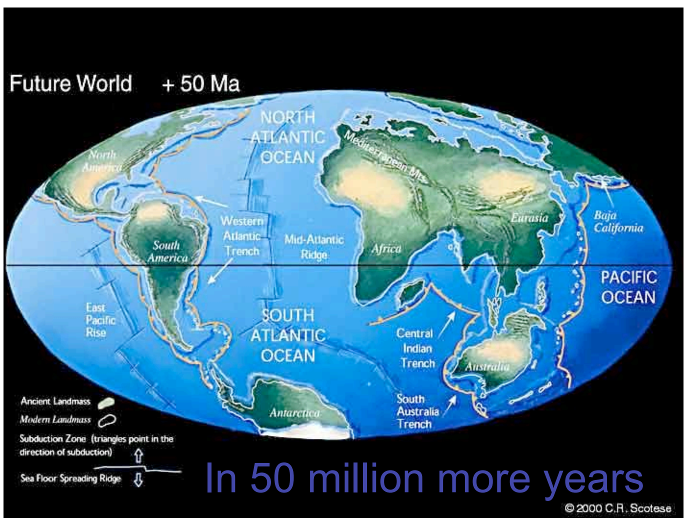
Other Supercontinents

- **Rodinia** formed at 1.3 - 1.0 Gyr and fragmented at 750 - 600 Myr
  - included most of continents in different configuration than Pangaea
- There were probably earlier supercontinents
- Supercontinent “Wilson cycle” of ~500 Mya?
- **Theory** - continents collide, insulate mantle underneath, then separate as mantle gets hot and upwells

Wilson cycle



Movie 05



3. Plate boundaries (edges)

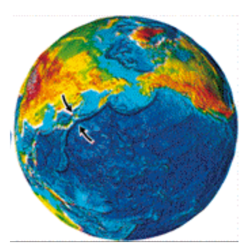
- A plate can shrink, grow, or stay the same
- Three types of boundaries
  - Convergent - plates move towards each other
    - Usually, one plate gets pushed under into the mantle (area shrinks) while the other slides over
  - Divergent - plates move apart
    - Asthenosphere (hot mantle material) rises to fill the space between the separating plates
  - Transform - plates slide past each other
    - Both plates stay on surface and move sideways

Convergent boundaries

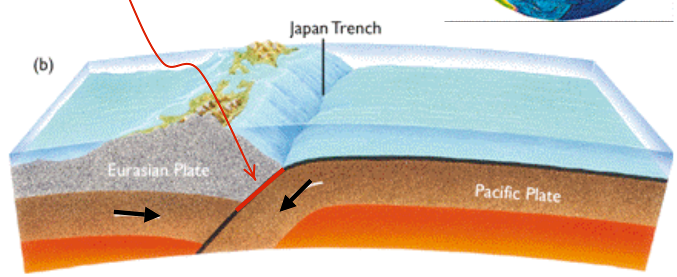
- Subduction zones - common, long-lived
  - oceanic plate over oceanic plate or
  - continental plate over oceanic plate

  } **explosive volcanism!**
- Collision zones
  - occur when continental crust collides, leading to mountain building because
    - **continental crust does not subduct -** It contains a larger proportion of light elements than oceanic crust. Thus, it is not dense enough to subduct.

Oceanic plate over oceanic plate

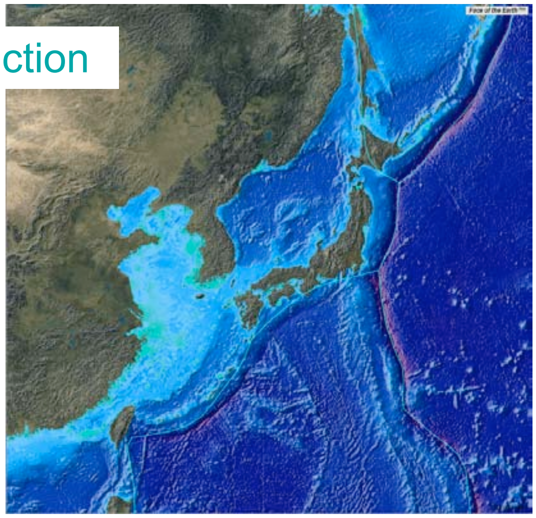


Site of large earthquakes

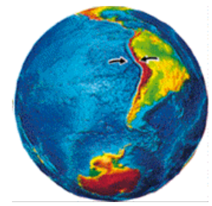


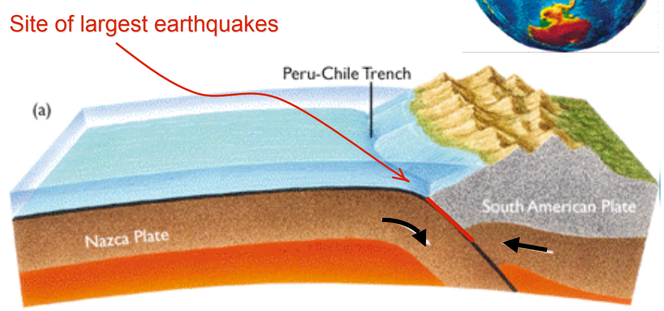
Press, 20-6b

Subduction



Continental plate over oceanic plate





Press, 20-6a

South America

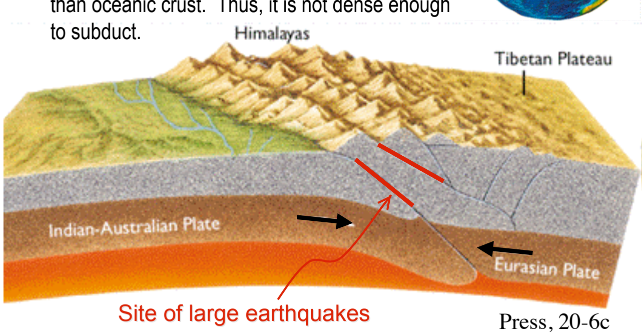
Movie 03

Subduction Zones

- Thrust (reverse) faulting
- **Numerous and large** earthquakes
- Occur from 0 to 700 km depth
  - outline sinking lithospheric slab
  - called Benioff zone, Wadati-Benioff zone
- Examples: Japan, S. America, Latin America, Washington-Oregon

Continent - continent collision

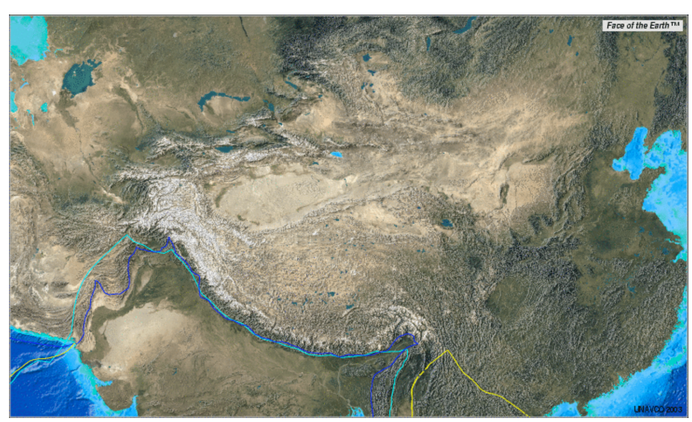
- leads to mountain building because
- continental crust does not subduct
  - it contains a larger proportion of light elements than oceanic crust. Thus, it is not dense enough to subduct.



Press, 20-6c

Himalayas

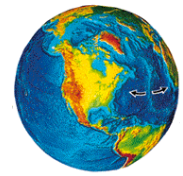
Movie 02

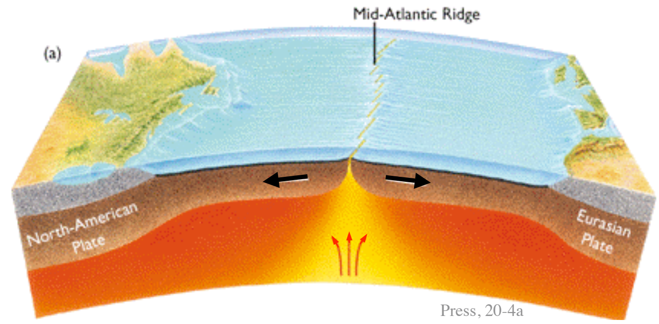


Divergent boundaries

- Most frequently: mid-ocean ridges
  - See figure
  - Examples: mid-Atlantic ridge, many ridges under Pacific and Indian oceans
- Less frequently: rift valleys on land
  - See figure
  - Will turn into mid-ocean ridges once old land has spread far enough apart

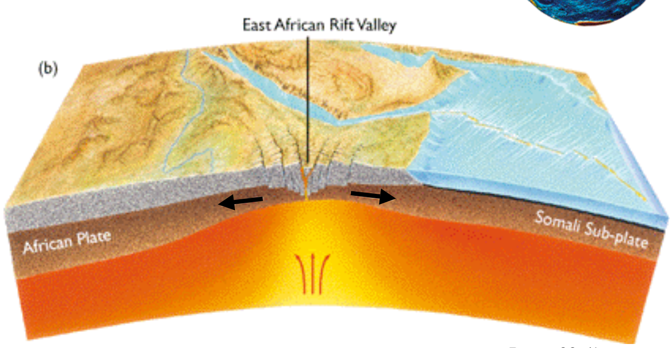
Mid-ocean ridge





Press, 20-4a

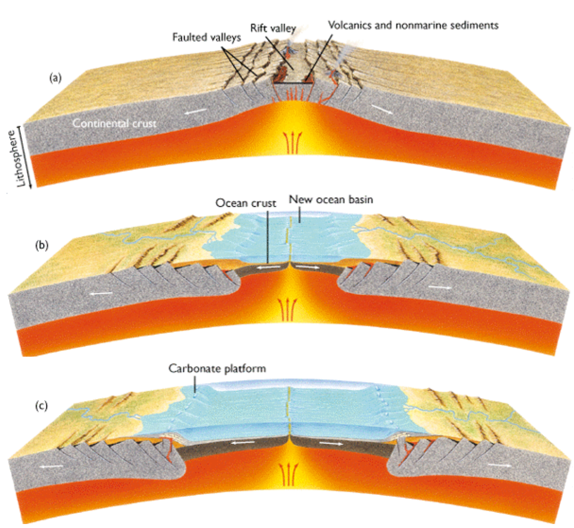
Rift valley



Press, 20-4b

New spreading center in Afar

Movie 01



Plates are created here, therefore destroyed elsewhere

Mid-Ocean Ridge Spreading Centers

- Plates move apart, new plate created
- Normal faulting
- Fewer and smaller earthquakes
- At shallow depths (0-5 km)
- Far from civilization, little damage
  - except in Iceland

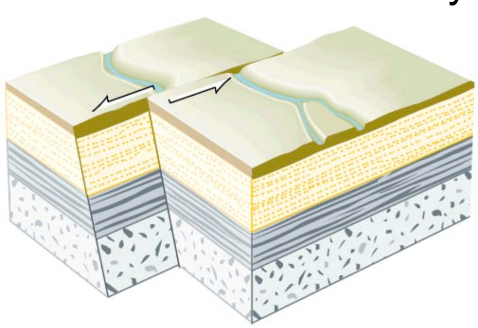
Transform boundaries

- One plate slides sideways past another plate - see figure
  - Can be ocean-ocean contact
  - Or continent-continent contact
    - Like San Andreas fault
- Least common boundary, usually vertical

Transform Boundaries

- Strike-slip faulting
- Intermediate size and number of quakes
- At shallow depths (0-20 km)
- Example: San Andreas Fault

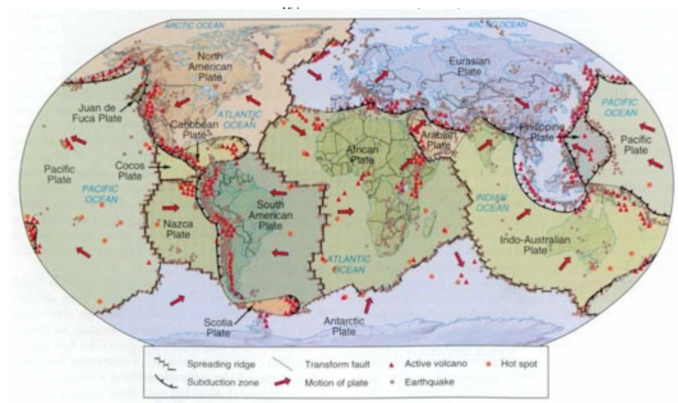
Transform boundary



(c) STRIKE-SLIP FAULT
(left-lateral)

Press, 10-22

Most volcanoes occur near plate boundaries

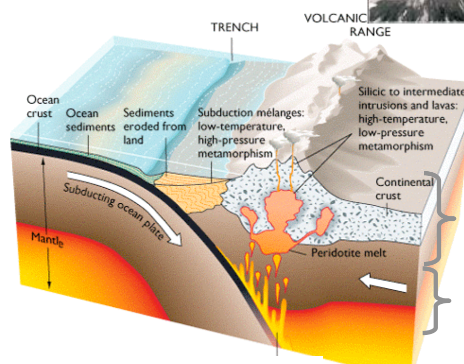


Volcanism at Plate Boundaries

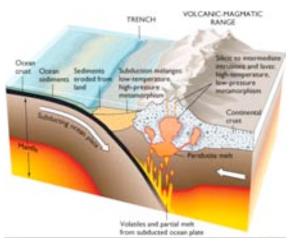
- Mid-Ocean Ridges
  - most abundant, mild (not explosive)
  - located at spreading ridge
- Subduction Zones
  - fairly abundant, explosive
  - located inland from trench, 120 km above top of subducting slab
- Transform Faults
  - rare, somewhat explosive

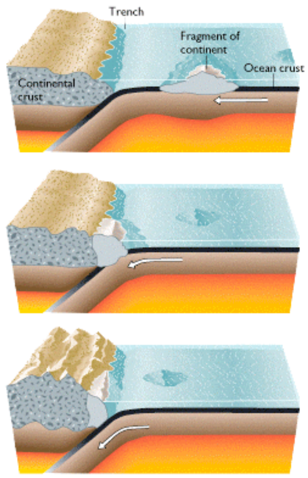
How subduction generates volcanoes

Water released from subducting slab at ~120 km depth, melts overlying rock. Melt pools in magma chambers and erupts to surface.

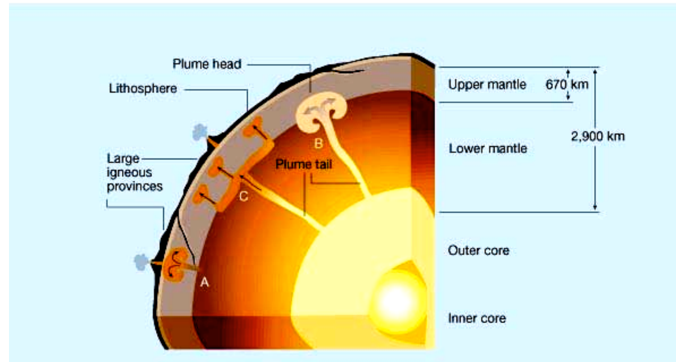


How continental crust grows:
1. Lava and magma chambers
2. Modified oceanic crust or fragments of continental crust are accreted to continental crust.

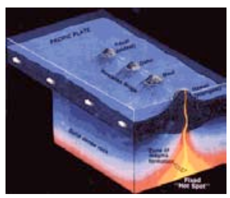




Plumes from core-mantle boundary create “hotspots”

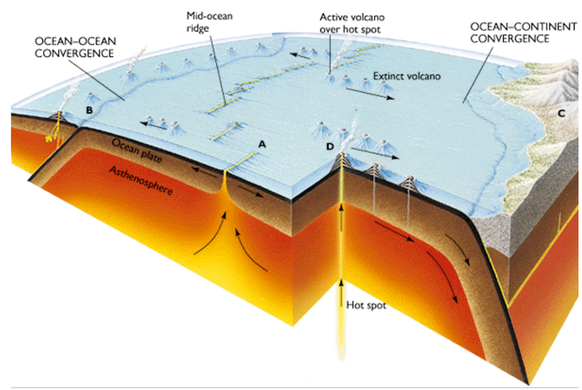


Volcanism in Plate Interiors



- Produced by hot spots, narrow plumes of rising, hot, partially-molten rock
  - originate from deep in mantle, probably core-mantle boundary
  - don’t move much wrt each other or mantle
- Volcanoes form long chains as plate moves over hot spot
  - as in Hawaiian Islands
  - another example: Yellowstone

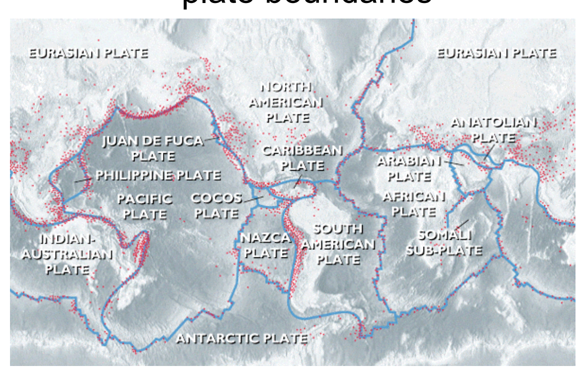
Different tectonic settings of volcanism - rifting, convergence, hotspot



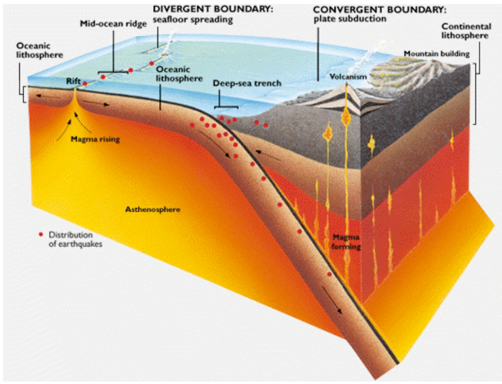
4. Types of Faults and Relation to Plate Tectonics

- Earthquakes occur at all plate boundaries, with differing intensity
- From details of earthquake wave, can determine
  - orientation of the fault plane
  - direction of slip
- Different types and numbers of earthquakes occur at the three different types of boundaries

Most, not all, seismicity occurs near plate boundaries



Quakes occur at all plate boundaries

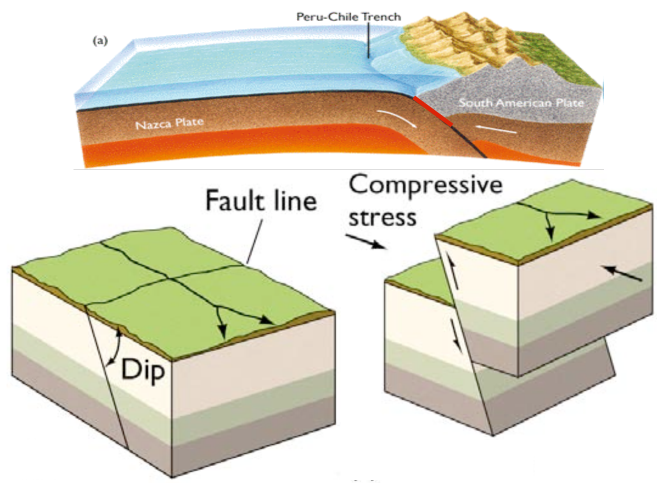


Types of Earthquakes/Faulting

- Thrust (reverse)
- Normal
- Strike-slip
  - Right-lateral
  - Left-lateral

Faulting at plate boundaries

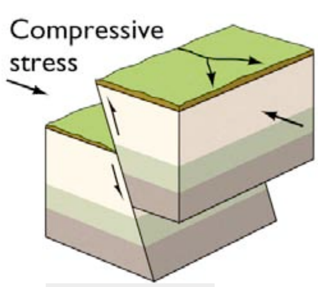
- Three main types of faults
  - Normal faults - common at spreading ridges
  - Thrust faults - common in subduction zones
  - Strike-slip faults - common on transform zones
- There is also distributed deformation
  - Folds, stretching, shearing
  - Occurs smoothly, not seismic



Press, 18-12a,c

Convergent zones

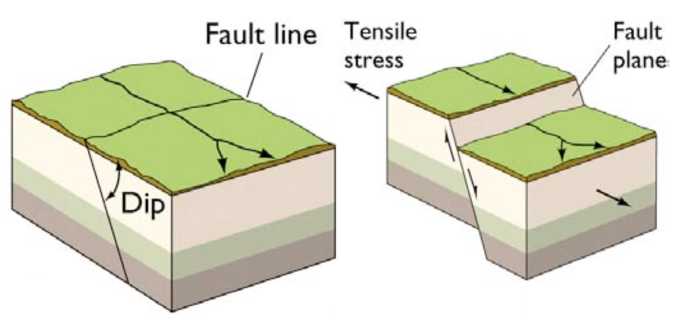
- Collision zones
  - India-Asia
- Subduction zones
  - Around Pacific Rim
  - Earthquakes, volcanoes, tsunamis, landslides
    - "Ring of Fire"
  - Also by Indonesia



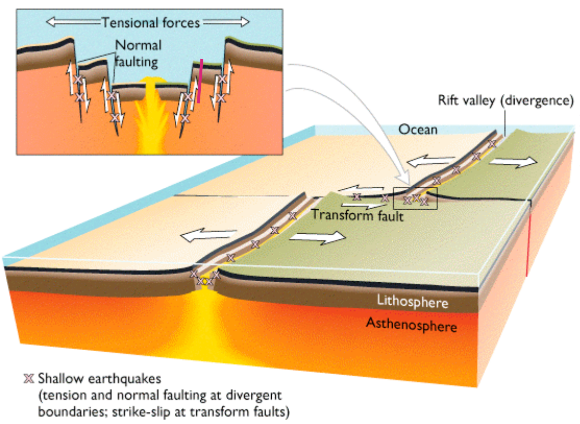
Thrust faults

Press, 18-12b

Normal fault - divergence

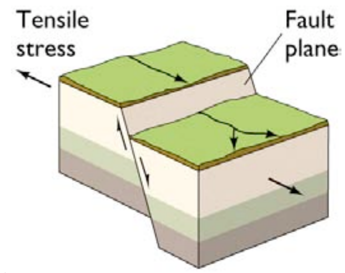


Press, 18-12a,b



Normal fault - divergence

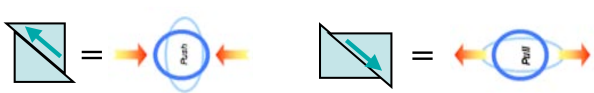
- Mid-ocean ridges
  - Atlantic Ocean
  - Pacific Ocean
  - Indian Ocean
- Rift zones
  - Baikal Rift
  - Basin and Range
  - East African Rift zone



Press, 18-12b

To distinguish normal from thrust faults

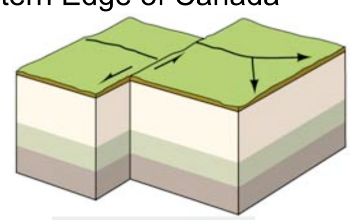
- Imagine a vertical line through the fault. The crust above the intersection of the line with the fault is called the hanging wall, the crust below the intersection is called the footwall.
- If the hanging wall is moving up, the fault is a **thrust** (reverse) fault.
- If the hanging wall is moving down, the fault is a **normal** fault.



Strike-slip fault - Transform

- Less common
- California, Western Edge of Canada
- New Zealand

Movie 04



Strike-slip fault

Press, 18-12d

Press, 10-6

Ways to deform rock