Introduction to Oceanography

Lecture 4: Plate Tectonics

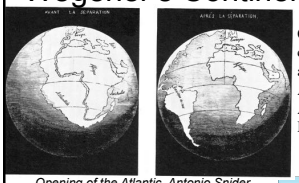
Geologic map of Iceland, USGS image, Public Domain

Thingvellir and the Mid-Atlantic axial rift. Photo by Someone35, Creative Commons Attribution-Share Alike 3.0 Unported https://commons.wikimedia.org/wiki/File:Thingvellir,_Iceland_landscape.jpg

Check lab exercise key outside 3820 Geology.

1st lab quizzes this week!

Wegener's Continental Jigsaw Puzzle

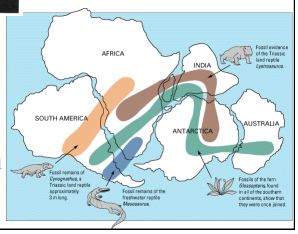


Observation: 1. The coastlines of the continents around the Atlantic Ocean appear to fit together (particularly South America and Africa). Australia, India, Antartica and Madagascar also seem to fit together.

Opening of the Atlantic, Antonio Snider-Pellegrini, 1858, Public Domain

Observation 2: When the continents are fit together, many geologic features line up across the boundaries.

Examples include mountain belts, types of fossils, belts of ~200 million year old and older rocks)



Gondwanaland image: USGS, http://pubs.usgs.gov/gip/dynamic/continents.html, Public Domain

The Scientific Method

- 3) **Experiments** test if hypothesis is valid
  - Can the hypothesis predict the results for related phenomena?
    - Wegener's hypothesis is incomplete:

If continents drift and oceans close, what happens to the rocks in the ocean crust?

- In 1910's little was known about the ocean floor and Earth's interior. Few instruments to make measurements.
- BUT - from 1930's through 1950's much was learned about Earth structure, the age of rocks, and the seafloor.

USS Sea Owl, Navy image, Public Domain

  - WWII and Cold war ocean surveys, global satellite gravity surveys & global seismometer stations provide the necessary clues

Probing the Earth with Seismology

- Cold, brittle crust
- Energy radiates out as seismic waves
- Like a flash bulb inside the Earth

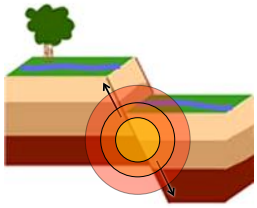
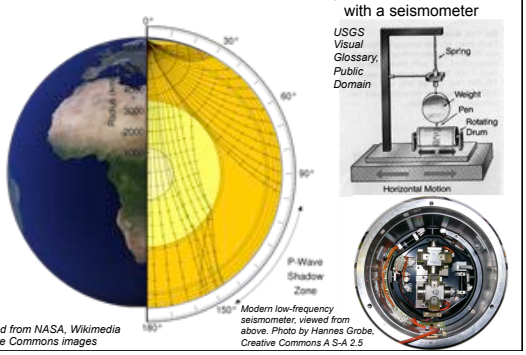


Figure by E. Schauble, modified from a USGS image, Public Domain.

Probing the Earth with Seismology

Earthquake waves are detected with a seismometer



Modified from NASA, Wikimedia Creative Commons images

USGS Visual Glossary, Public Domain

Modern low-frequency seismometer, viewed from above. Photo by Hannes Grobe, Creative Commons A S-A 2.5

Large Earthquakes, 2000-2008

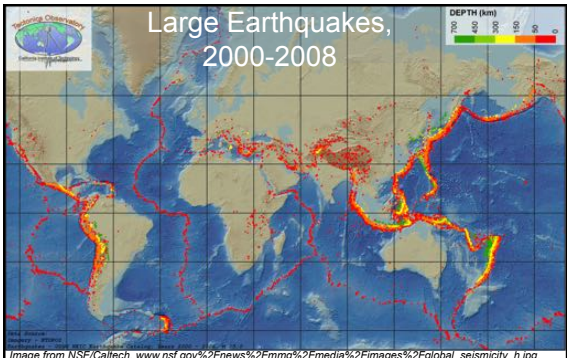
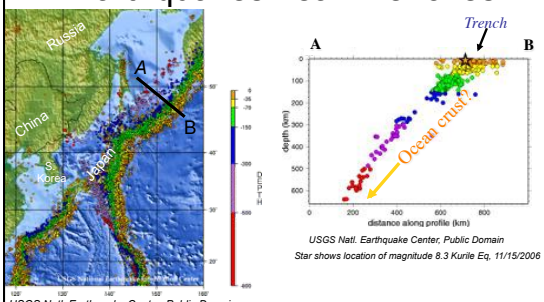


Image from NSF/Caltech, www.nsf.gov%2Fnews%2Fmmg%2Fmedia%2Fimages%2Fglobal_seismicity_h.jpg, Public Domain

Observation 3: Earthquakes are concentrated in a few "strips" or lines near the Earth's surface. This suggests "cracks" or boundaries between rigid areas.

Earthquakes near Trenches



USGS Natl. Earthquake Center, Public Domain

USGS Natl. Earthquake Center, Public Domain

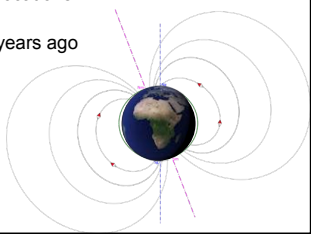
Star shows location of magnitude 8.3 Kurile Eq, 11/15/2006

USGS Natl. Earthquake Center, Public Domain

Observation 4: At trenches (e.g., NE. of Japan) earthquakes get deeper with distance. Earthquakes happen in rocks that are cold & break rather than flow. Deep earthquakes suggest a slab of cold material that was recently at the Earth's surface.

Records of Earth's magnetic field

- Convection in outer core generates the Earth's magnetic field
  - Dominantly dipolar magnetic field
    - like a bar magnet aligned near the rotation axis
  - Magnetic poles reverse locations ~1/250,000 years
  - Last reversal ~780,000 years ago

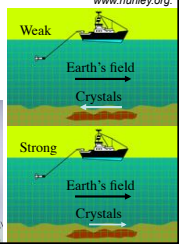


E. Schauble, modified from images by NASA and JrPol (Public Domain & Creative Commons Share Alike

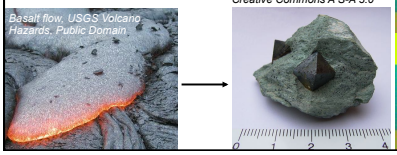
Dating rocks with magnetism

- At volcanoes, molten rock erupts and cools. As it cools crystals form (it solidifies).
- Some crystals with iron in them are magnetic. They tend to line up with the Earth's magnetic field when they cool down.
- If the Earth's magnetic field reverses, the crystal magnets stay put -- they are frozen in place.
- A magnetometer towed behind a boat will pick up a weak field if the crystal magnets point the opposite direction from the Earth's field. (They partly cancel each other out).
- A magnetometer will pick up a strong field if the crystals point the same direction and the Earth's magnetic field.

Modified by E. Schauble, from image at www.hunley.org.

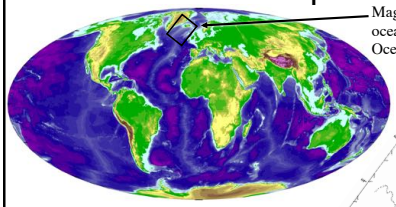


Magnetite, photo by Density, Creative Commons A S-A 3.0

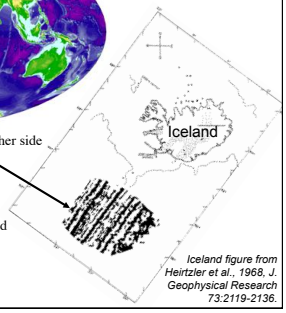


Basalt flow, USGS Volcano Hazards, Public Domain

The oceanic "tape recorder"



Magnetic survey of a mid-ocean ridge in the Atlantic Ocean near Iceland.



Areas of strong and weak magnetism on either side of the mid-ocean ridge are mirror-images

The crest of the ridge has strong magnetism (I.e. crystals and Earth aligned.)

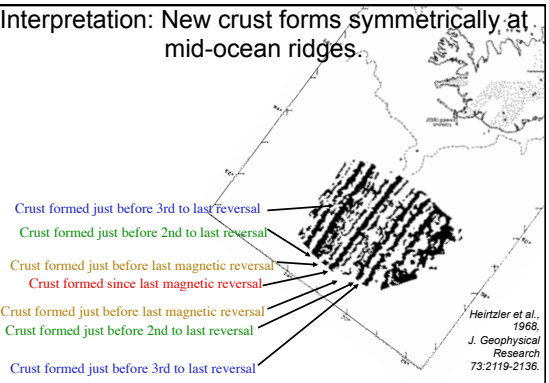
Farther away weaker magnetism (Crystals formed when the Earth's field was reversed),

Many oscillations from strong to weak.

Globe image by Plumbago, Wikimedia Commons, Creative Commons A S-A 3.0

Iceland figure from Heirtzler et al., 1968, J. Geophysical Research 73:2119-2136.

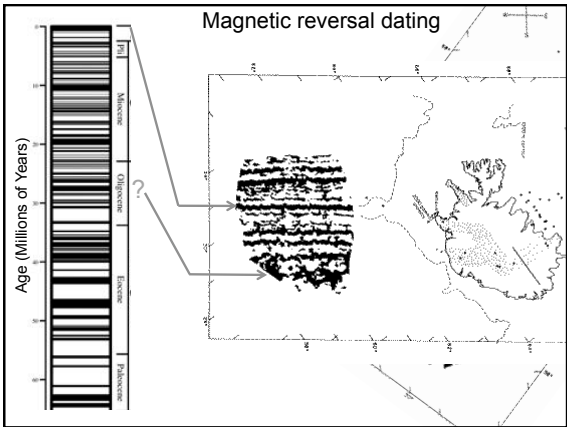
Interpretation: New crust forms symmetrically at mid-ocean ridges.



Heirtzler et al., 1968, J. Geophysical Research 73:2119-2136.

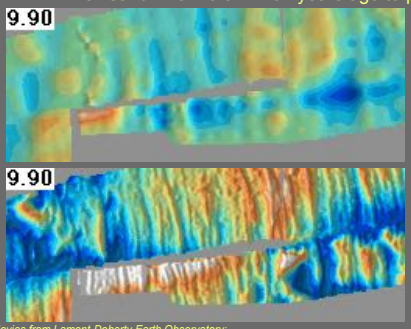
This interpretation is confirmed by the age of sediments and volcanic rocks on the seafloor (youngest at the top of the ridge).

Magnetic reversal dating



Seafloor-spreading movies!

Movies run from 9.9 million years ago to present



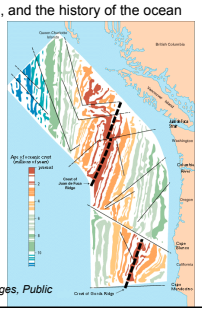
Magnetic "stripes"

Depth white=shallow blue=deep

Movies from Lamont-Doherty Earth Observatory:
http://ocean-ridge.ldeo.columbia.edu/Other_stuff/PAR_Movie/parmovie.html

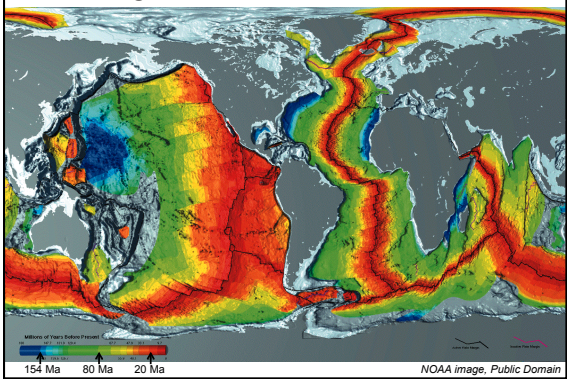
Magnetic stripes not just found in Atlantic!

Faults, sediments complicate interpretation of magnetic patterns on the seafloor, but they are the best high-resolution record of ancient plate motions, and the history of the ocean basins.



USGS and NOAA images, Public Domain

Age of the Ocean Floor



NOAA image, Public Domain

The Scientific Method

- 3) **Experiments** test if hypothesis is valid
  - Can hypothesis predict the results for related phenomena?
    - Too little known about the ocean floor and Earth's interior.
    - Hypothesis incomplete because it doesn't address the oceans themselves.
    - BUT - from 1930's through 1950's much was learned about Earth structure, the age of rocks, and the seafloor.
    - Newer measurements showed that oceanic crust is created at mid-ocean ridges, and appears to sink into the mantle at deep-sea trenches.
- 4) Repetition by independent groups
  - Magnetic surveys and sediment sampling in all the world's oceans confirm results.
- 6) **Modification** of original hypothesis: Plate Tectonics.
  - Includes life-cycle of oceanic crust and continental drift

Certainty and the Scientific Method

- What is scientific certainty?
  - Tempered by scientific method
    - Observations often reveal limitations to the most well-established ideas
  - No **measurement** is perfect
    - This injects formal uncertainty into all reported quantities, & ultimately theories.
      - Example 1: Rates of plate motion (very slow)
      - Example 2: Average yearly global surface temperature (local/regional temperatures are highly variable)

Scientific Terminology

- Scientific Theory: A theory represents a hypothesis that has been confirmed by repeated independent experimental tests.
  - Example: Evolution by Natural Selection is a well-tested theory.
    - No theory can be proven to be true, only disproven; future tests can conflict with a theory.
      - Ptolemy's Earth-centered universe was destroyed by Galileo's observations of Jupiter's moons
      - Flat-Earth concept (re)invalidated by oceanic explorations
      - Newtonian mechanics and gravity modified by Einstein's relativity
      - Experimental error always puts limitations on the validity of any theory--i.e., only valid within experimental limitations
  - ***Another Example: Plate Tectonics!***
    - ***Comprehensive explanation of seismology, volcanoes, ages of the seafloor, shapes of the continents.***

Questions?

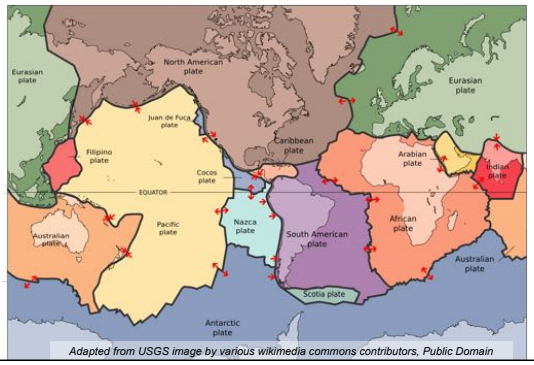


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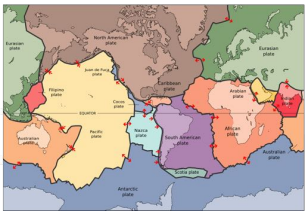
Plate Tectonics: The Basics

- Lithosphere
  - Broken into ~15 major plates
    - ~ 50 plates total
  - Plates are thin: ~100km thick
  - Internally rigid
    - Deformation & seismic activity at edges
  - In motion: ~ 2-15 cm/yr
- Oceanic Crust and Lithosphere *Recycle*
  - New oceanic lithosphere generated at mid-ocean ridges
  - Ancient oceanic lithosphere consumed at deep sea trenches



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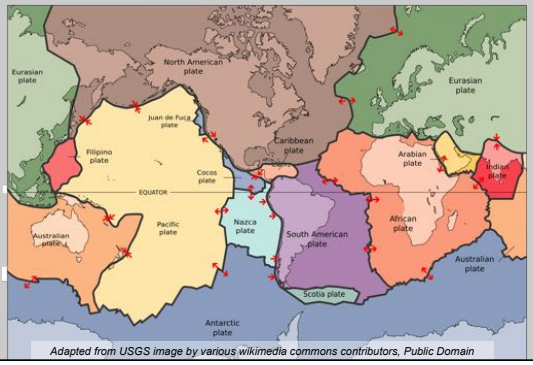
Schematic of 15 Largest Plates



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Plates, Volcanoes & Earthquakes

Figure by Eric Gaba, Wikimedia Commons, Creative Commons A S-A 2.5, http://en.wikipedia.org/wiki/File:Tectonic_plates_boundaries_detailed-en.svg, adapted from map by P. Bird (UCLA)

Lithospheric Recycling

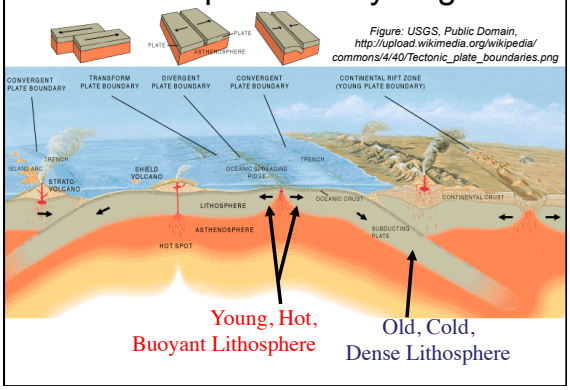


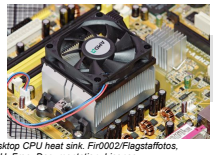
Figure: USGS, Public Domain, http://upload.wikimedia.org/wikipedia/commons/4/40/Tectonic_plate_boundaries.png

What is Convection?

- Modes of heat transfer

Radiative
Fireplace, the Sun, glowing lava

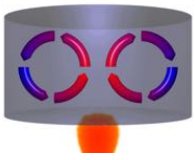
Kilauea lava, photo by Greg Smith, Creative Commons A 2.0 Generic.



Conductive
Direct transfer: touching a hot stove, cool metal against a hot CPU

Desktop CPU heat sink. Fir0002/Flagstaffotos, GNU_Free_Documentation_License http://en.wikipedia.org/wiki/File:AMD_heatsink_and_fan.jpg

Convective
Heat transfer by moving "fluid".
Water on the stove



Movie by Oni Lukos, GDFL, Creative Commons-BY-SA-2.5. http://commons.wikimedia.org/wiki/File:Convection.gif

Wien's law: $\lambda_{peak} \approx 2898\ K \cdot \mu m / T \approx 2\ \mu m$
(visible light is 0.4-0.8μm)

Stefan-Boltzmann law: $j \approx (5.67 \times 10^{-8}) T^4 \approx 27$ Watts/cm^2
(full tropical sunlight is 0.11 Watts/cm^2)

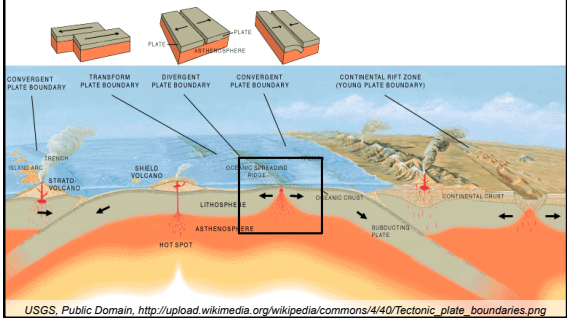
Most of the radiation is invisible!

QUESTIONS?

Movie by Jenny Wysocki, Robert Wysocki, Syracuse University Lava Project (C) 2014

Divergent plate boundaries

- Mid-Ocean Ridges: Spreading Centers
  - Local pressure-release melting → magma → new crust



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Divergent Boundaries

- Map View of divergent margin

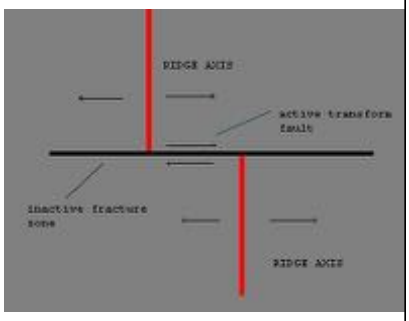
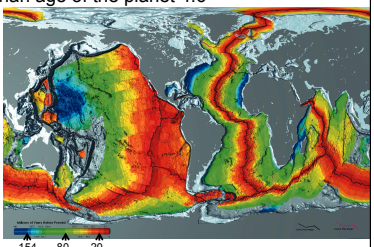


Figure by Erimus, Wikimedia Commons, Public Domain, http://en.wikipedia.org/wiki/File:Fracturezone.jpg

Age of the Ocean Floor

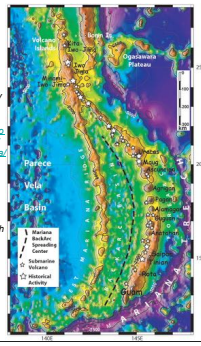
- Crust increases in age and thickness with distance from ridge axis
- Oldest oceanic crust ~200 m.y. old
  - MUCH younger than age of the planet 4.6 billion years old
  - And oldest continental rocks
- Spreading rates agree with magnetic stripe estimates:
  - Atlantic: 2-3cm/yr
  - Pacific: 10-15 cm/yr



NOAA image, Public Domain

Types of Convergent Boundaries

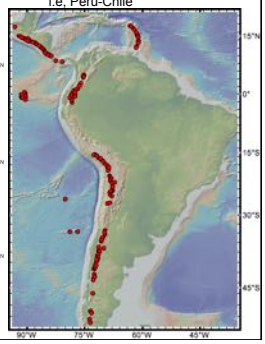
Ocean-Ocean: volcanic island arcs
Oceanic lithosphere subducts under ocean
i.e.,
Aleutians
Marianas



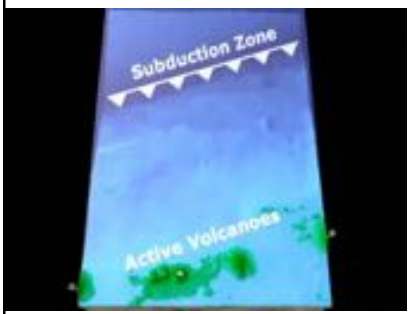
Marianas bathymetry from Sandwell and Smith (1997), courtesy NOAA, http://oceanexplorer.noaa.gov/explorations/03fire/background/plan/media/marianas.html, Public Domain

Right fig., South America bathymetry & volcanoes, created with GeoMapApp, Creative Commons A S-A 3.0, http://www.geomapapp.org/

Ocean-Continent: Mountain + arc
Ocean subducts under continent
i.e, Peru-Chile



Volcanism at convergent boundaries

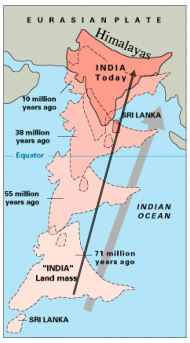


Water-rich fluid released by descending slab fluxes
(i.e., lowers melting temperature of) the overlying mantle

Movie from NOAA, Public Domain, http://oceanexplorer.noaa.gov/explorations/03fire/logs/subduction_320.mov

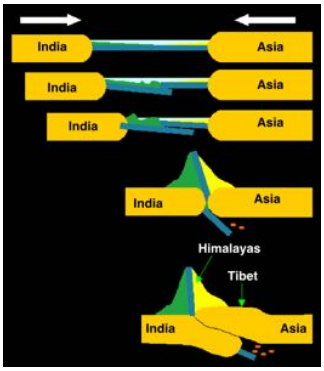
Continent-Continent Convergence

- India-Asia collision
- Himalayas
- Continental crust is too buoyant to subduct, crumples and thickens at the surface.
- Extra-thick continental crust ---> BIG mountains.



USGS image, Public Domain, http://commons.wikimedia.org/wiki/File:Himalaya-formation.gif

Continent-Continent Convergence



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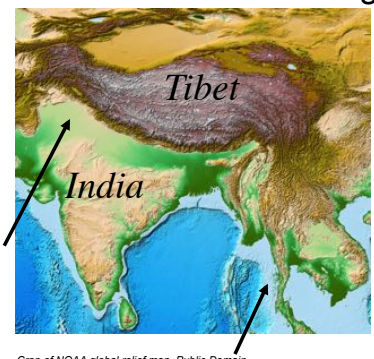
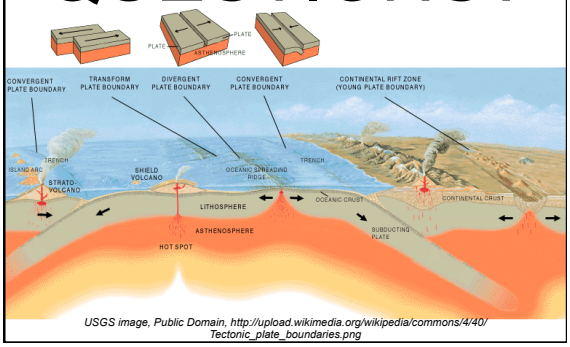
Continent-Continent Convergence



Crop of NOAA global relief map, Public Domain

QUESTIONS?



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Transform Boundaries

Two plates sliding past each other horizontally

Example: San Andreas Fault

Transform portion: Seismically active part of Fracture Zone

Usually between offset ridge segments

Plates move parallel to plate margin

San Andreas Fault, Carrizo Plain, CA. Wikimedia Commons. Photo by Ian Kluft Creative Commons A S-A 3.0, http://commons.wikimedia.org/wiki/File:Kluft-photo-Carrizo-Plain-Nov-2007-Img_0327.jpg

Transform Boundaries

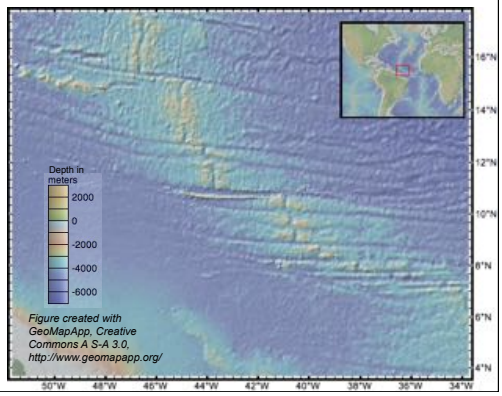


Figure created with GeoMapApp, Creative Commons A S-A 3.0, http://www.geomapapp.org/

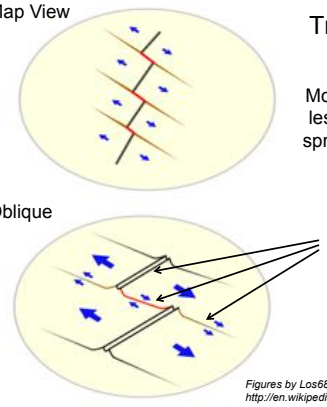
Map View

Transform Boundaries

Most common as more-or-less right-angle offsets of spreading segments along the mid-ocean ridge.

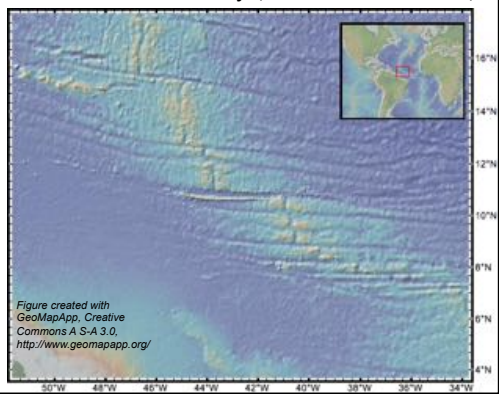
Oblique

Where do you expect to see earthquakes?



Figures by Los688, Wikimedia Commons, Public Domain, http://en.wikipedia.org/wiki/File:Transform_fault-1.svg

Transforms and seismicity (Mw > 5.0, 1973-2009)



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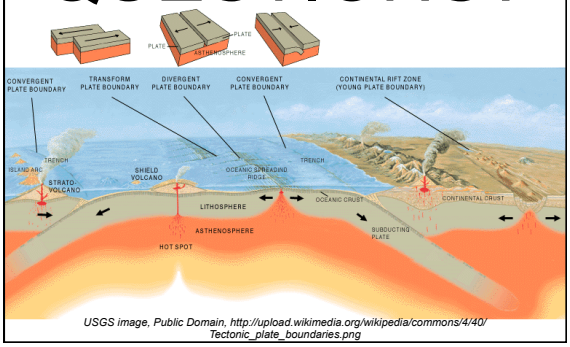
QUESTIONS?

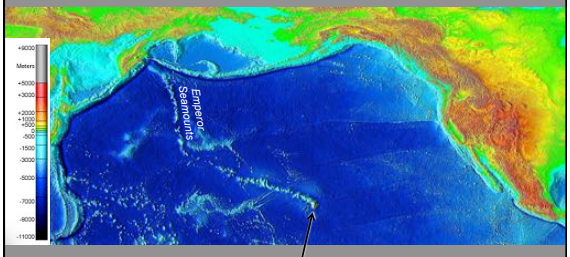


USGS image, Public Domain, http://upload.wikimedia.org/wikipedia/commons/4/40/Tectonic_plate_boundaries.png

Hotspots & Mantle Plumes

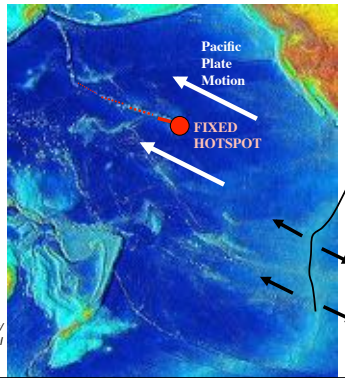
- Stationary volcanic sources in mantle
  - Persist for ≥ $1x10^7$ years
- Ocean Crust ~ 10% generated at hotspots
- Heat transfer: ~10-30% of mantle heat flux
  - May transport heat directly from the core
- Hotspot Island Chains
  - Hawaii-Emperor Chain
  - Stationary heat source tracks plate motions

Hawaii-Emperor Seamount Chain Traces Past Plate Motion



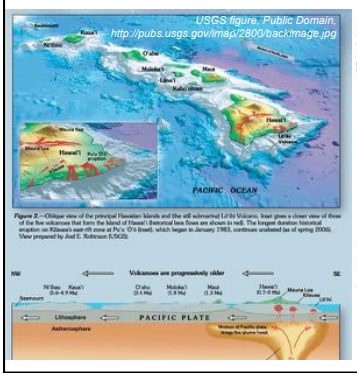
NOAA image, using ETOPO2v2 Database, Public Domain, http://www.ngdc.noaa.gov/mgg/image/2minrelief.html

Hotspots & Mantle Plumes

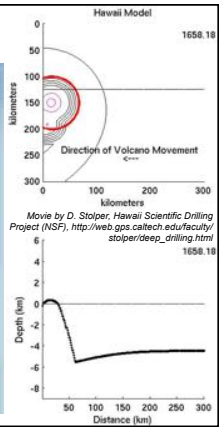


NOAA image, using ETOPO2v2 Database, Public Domain, e.g., http://www.ngdc.noaa.gov/mgg/image/2minrelief.html

Hotspots & Mantle Plumes



USGS figure, Public Domain, http://pubs.usgs.gov/imap/2800/backImage.jpg



Movie by D. Stolper, Hawaii Scientific Drilling Project (NSF), http://web.gps.caltech.edu/faculty/stolper/deep_drilling.html

Tectonic Evolution of Ocean Basins

Oceanic life cycles (Wilson Cycle):
~200-500 million years to open and close

African Rift Valley: An embryonic ocean?

Ol Doinyo Lengai, photo by Clem23, Wikimedia Commons Creative Commons A S-A 3.0, http://commons.wikimedia.org/wiki/File:NgareSero.jpg

Tectonic Evolution of Ocean Basins

Oldest oceanic crust is less than 200 million years old – oceans are created and destroyed repeatedly.

Embryonic – linear rift valleys

Juvenile – narrow seaway

Mature – broad ocean, well-developed passive margins

Declining/terminal – active margins, narrowing or irregular basin

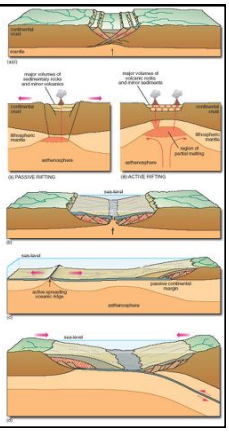


Figure from Open University Learning Space, "Geological processes in the British Isles", Creative Commons A S-A 2.0, http://dspace.jorum.ac.uk/xmlui/download/bitstream/handle/123456789/993/Items/SXR260_1_006i.jpg?sequence=33

Questions?

GPS-determined Plate Velocity Map by Michael B. Heflin, JPL/ NASA, Public Domain