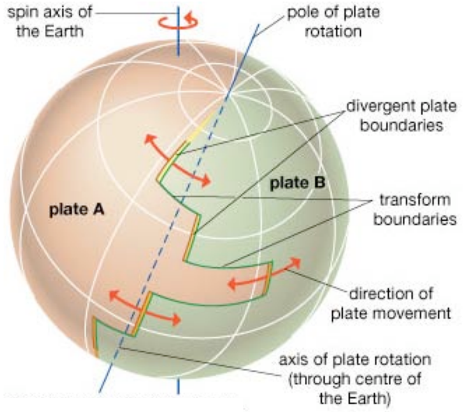
Planet Earth:
Plate Tectonics



Recommended Books:

An Introduction to **Our Dynamic Planet** (**ODP**), 2007, Rogers, N. et al. (Eds.), Cambridge University Press, 390 pp.

An Introduction to **Global Geophysics** (**GG**), 2004, C. R. M. Fowler, Cambridge University Press, 472 pp.

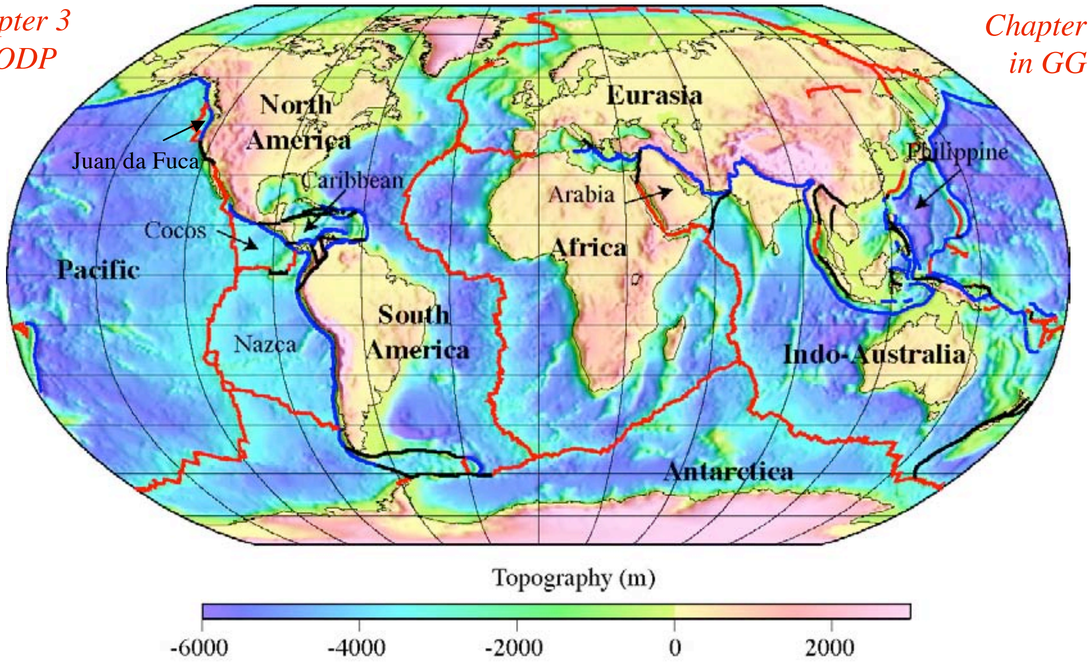
Weblearn:

Lecture pps files, Reading lists, Problem sets etc

Lecture 1: Plate Mechanics and Kinematics

Chapter 3 in ODP

Chapter 2 in GG

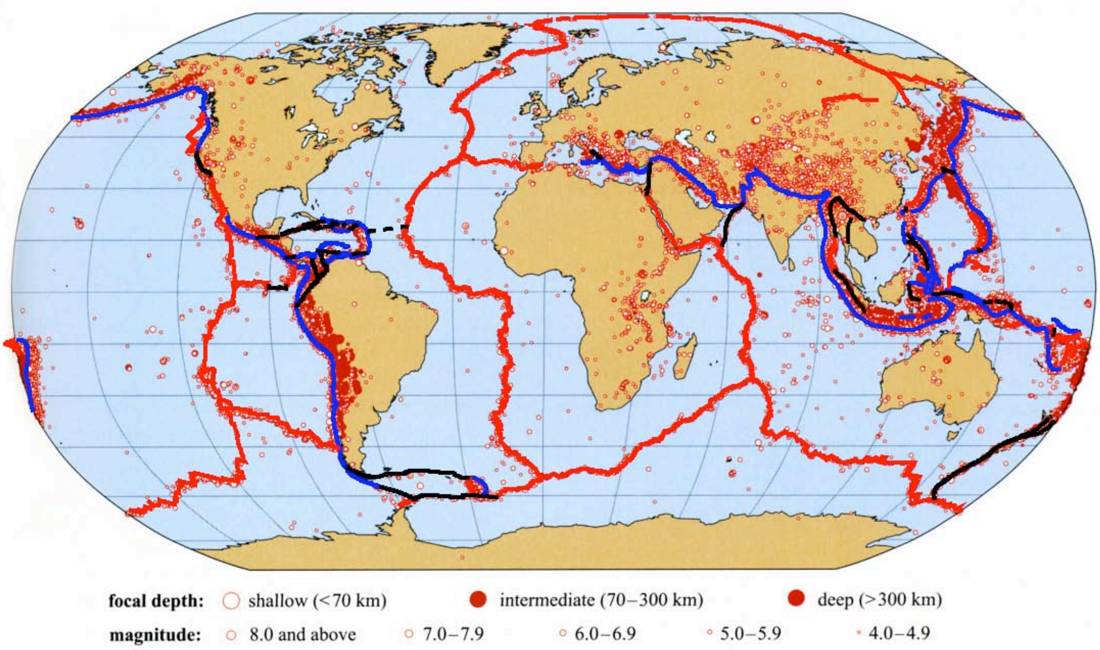


The Earth comprises 7 major plates and a number of smaller plates

Plate boundaries:

— Convergent — Divergent — Transform

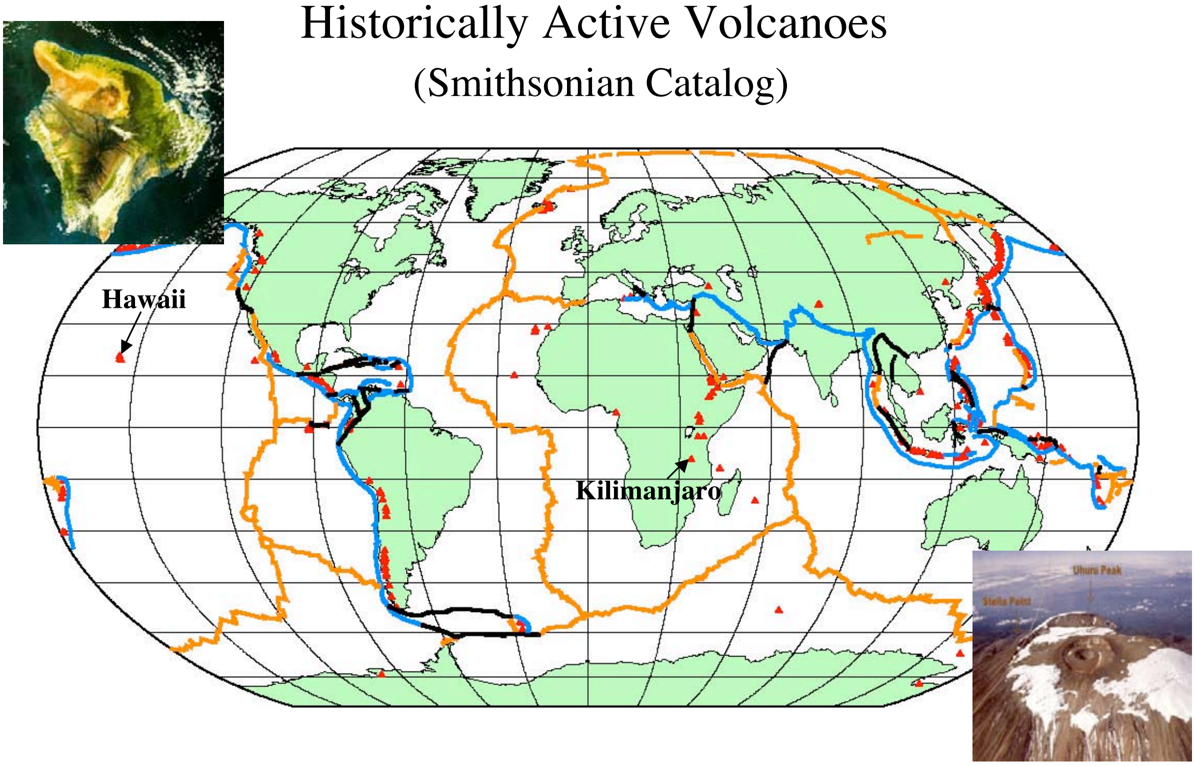
Global earthquake epicentres between 1980 and 1996



Plates are rigid and deformation (e.g. during an earthquake) is limited to the plate boundaries. The main exceptions are in the continents where deformation is more distributed.

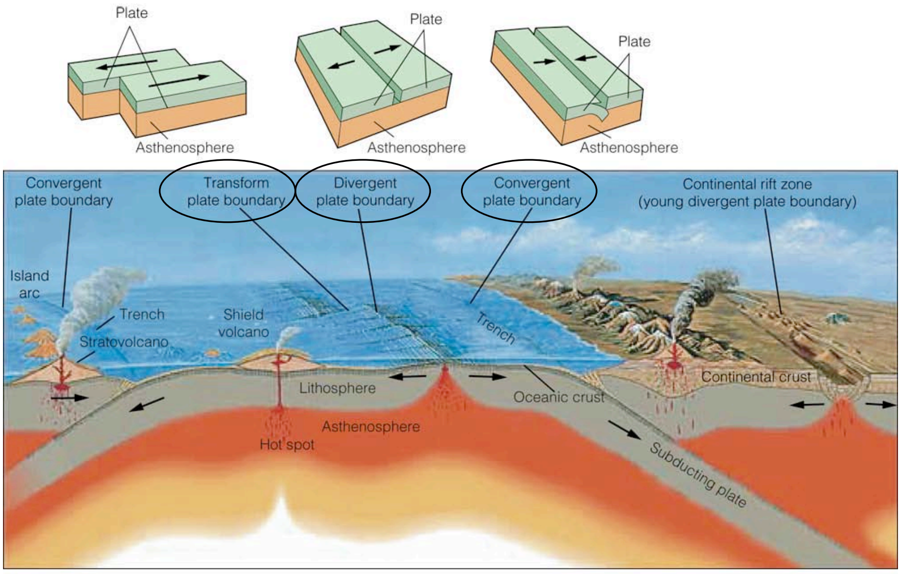
Historically Active Volcanoes

(Smithsonian Catalog)



Volcanic activity is also limited to plate boundaries. However, there are a number of prominent active volcanoes in the plate interiors (e.g. Kilimanjaro, Hawaii).

The different types of plate boundaries

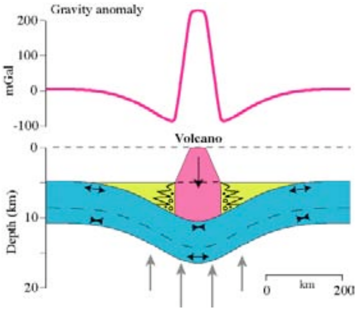


© 2006 Brooks/Cole - Thomson

There are 3 main types of plate boundary: divergent (e.g. Mid-Ocean Ridge), transform (e.g. Transform Fault, Strike-slip Fault), and convergent (e.g. Deep-Sea Trench).

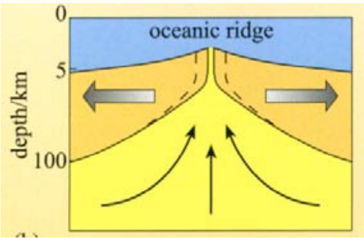
How do we know the plates are rigid?

- ***Gravity*** anomaly data which show that the outer layers of the Earth support large loads such as volcanoes, ice and sediment for long periods of geological time ($>10^5$ a).



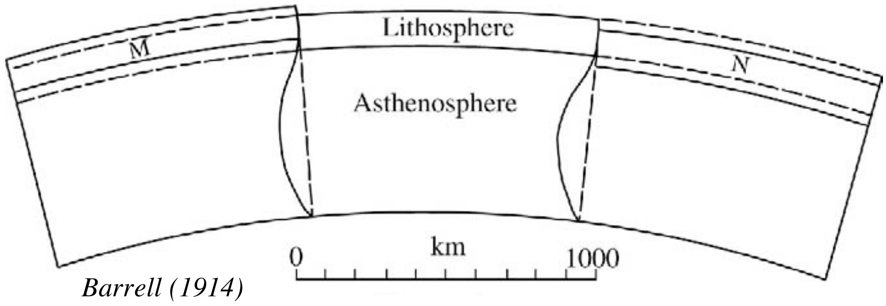
- Controlled and passive (e.g. earthquake) source ***seismology*** which show that the Earth has a strong mechanical "lid" with relatively high P-wave and S-wave velocities.

- Surface ***topography*** and ***heat flow*** data which shows that the outer layers of the Earth behave as a thermal boundary layer which looses its heat by conduction.



Lithosphere and asthenosphere

The strong, cool, outer layer of the Earth is called the **lithosphere** and the weak, hot, underlying layer the **asthenosphere**.



Barrell (1914)

We define the thickness of the lithosphere in the following way:

Mechanical

The **elastic thickness**, T_e, is the thickness of the lithosphere that supports long-term ($>10^5$ a) geological loads. $0 < T_e < 40$ km (oceans). $0 < T_e <\sim 100$ km (continents)

The **seismic thickness**, T_s, is the high seismic velocity LID that overlies the low-velocity zone. $T_s \sim 10\text{-}80$ km (oceans). 250 km. $T_s > 200$ km (cratons).

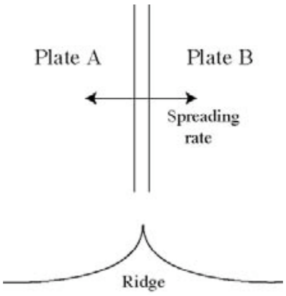
Thermal

The **thermal thickness**, T_h, is the thickness of thermal boundary layer that is loosing heat conductively. $T_h \sim 125$ km (oceans).

Plate interactions

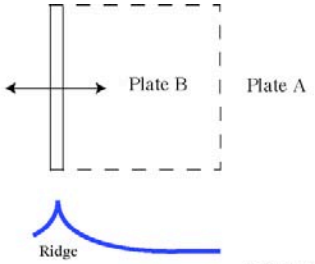
Two-plate system

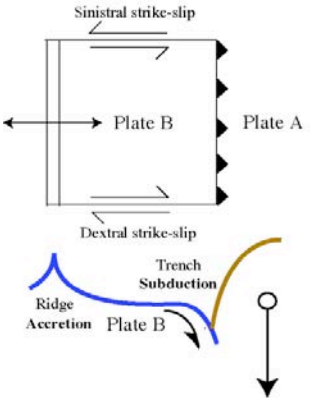
The velocity of plate B with respect to plate A = ${}_A\mathbf{V}_B$



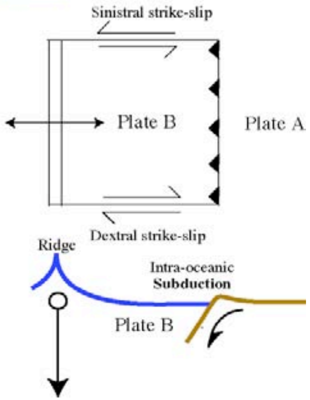
At a ridge, ${}_A\mathbf{V}_B$ is called the **plate separation rate**. The **spreading rate** is half the separation rate = ${}_A\mathbf{V}_B/2$

Let the spreading rate = 2 cm/yr





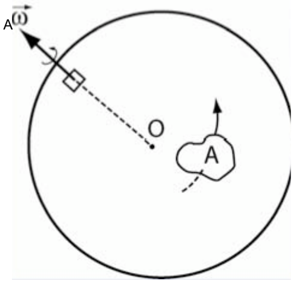
${}_A\mathbf{V}_B$ = 4 cm/yr
Plate B is destroyed



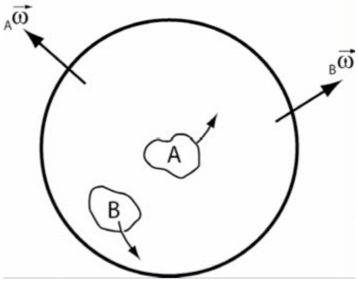
${}_B\mathbf{V}_A$ = 4 cm/yr
Plate B grows

The (elastic) lithosphere is "forever", but plates morph and shrink and grow

Relative plate motions on a sphere



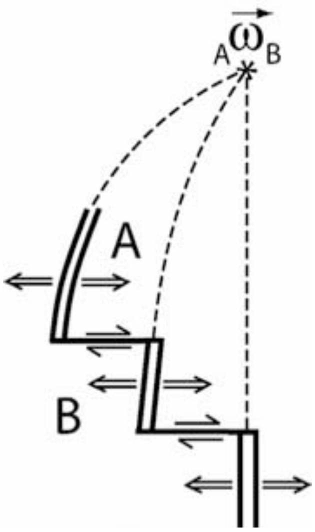
Euler's theorem: motion of any spherical plate can be explained by a single rotation about a suitably chosen axis which passes through the centre of the Earth.



Motion of Plate A can be described by rotation about $_A\omega$ and Plate B by $_B\omega$

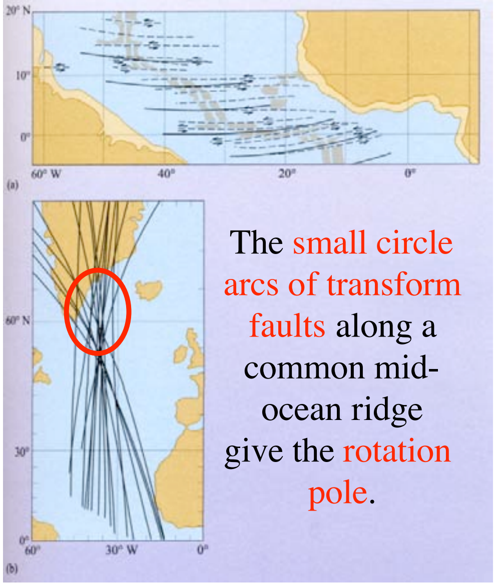
The relative motion between plate A and B is $_A\omega_B$. The pole of rotation is described by a latitude, longitude and rate in deg/yr

$$_A\omega_B = {}_A\omega - {}_B\omega$$



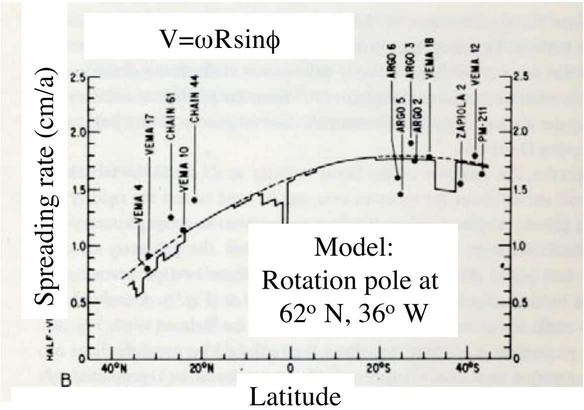
In a three-plate system, A, B and C, if $_A\omega_B$ and $_B\omega_C$ are known then $_C\omega_A$ can be found. See GG p23-24.

Measuring relative plate motions



The small circle arcs of transform faults along a common mid-ocean ridge give the rotation pole.

The spreading rate along a mid-ocean ridge can also be used to find the rotation pole.



$V=\omega R\sin\phi$

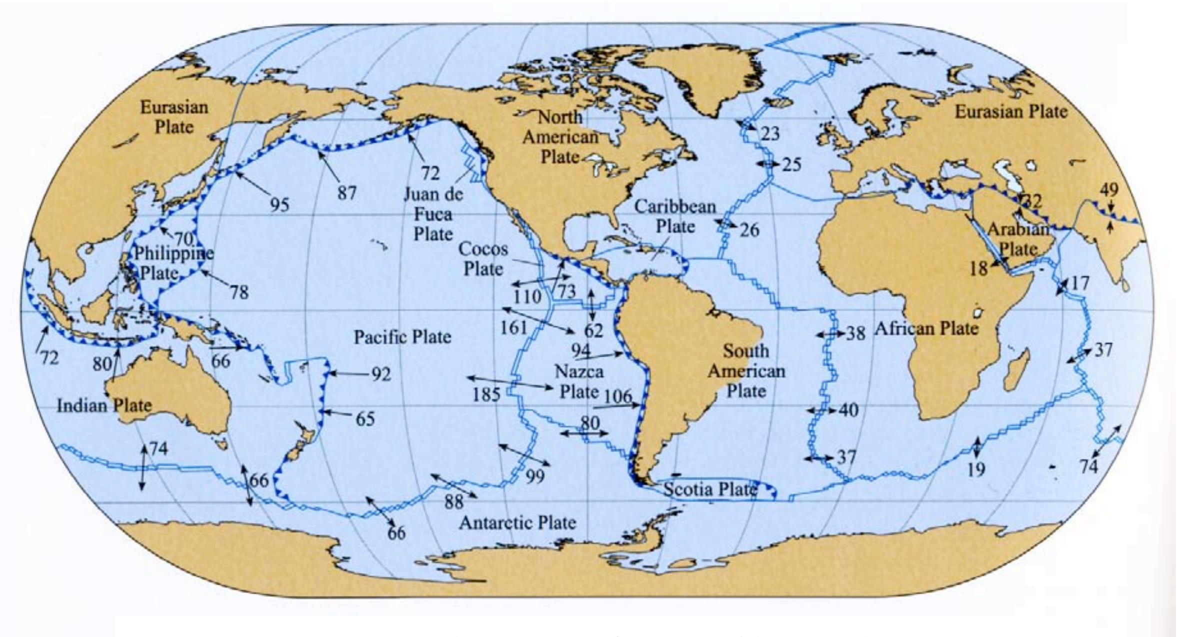
Model: Rotation pole at 62° N, 36° W

Present-day plate motions can be measured in real time using satellite technology (e.g. satellite laser ranging techniques + the Global Positioning System). See *Stein & Wysession* (2003) and *Burbank & Anderson* (2001).

Also, **fault plane solutions** (focal mechanisms) of earthquakes. Gives direction of relative motion only. See GG p130-136.

Relative plate motion

Plate separation rates (mm/yr)

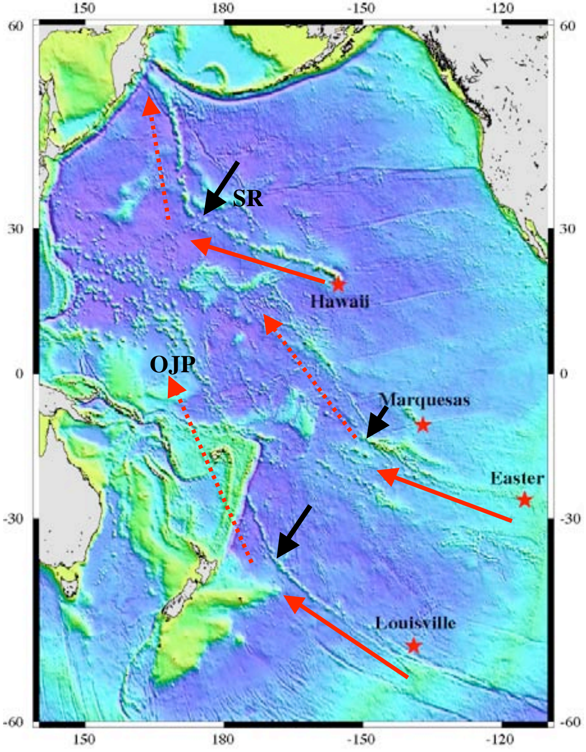


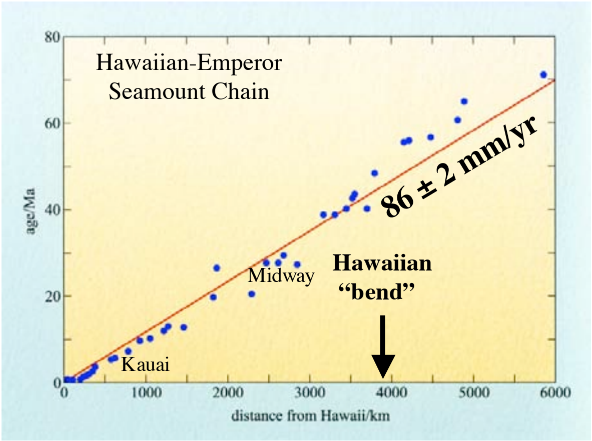
Fastest: Pacific/Nazca, Slowest: Africa/Arabia

Note: the African plate is separated from the South American and Indo-Australian plates by a divergent plate boundary. So, as it grows in size at least one of these boundaries must move.

Absolute Plate Motion

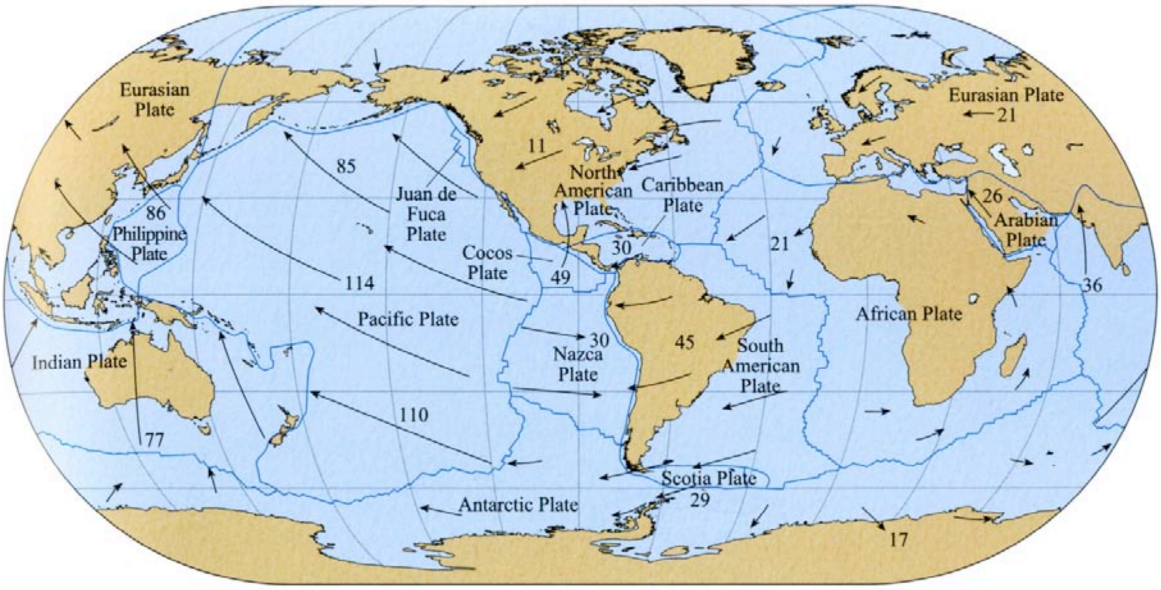
The "hotspot" Reference Frame





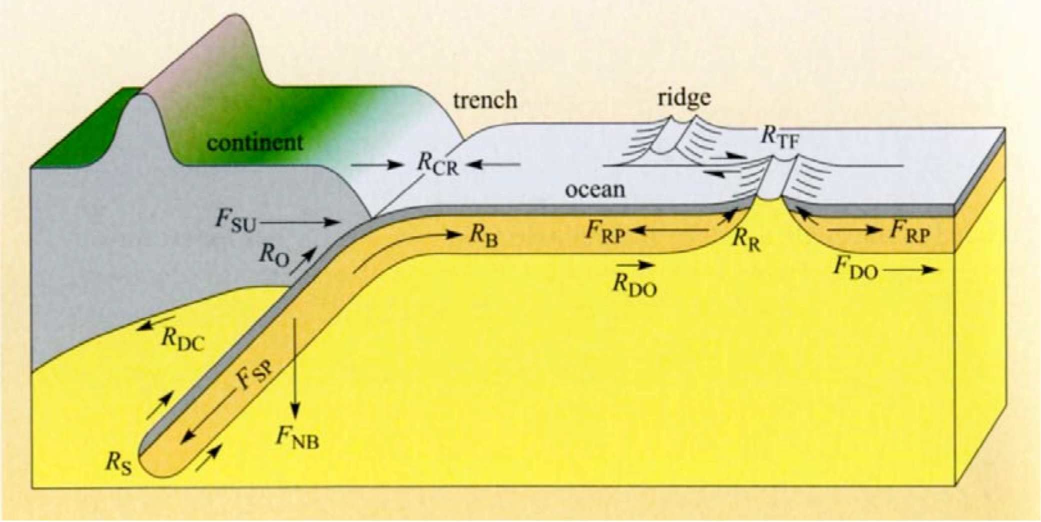
There are 4 main long-lived (>70 Myr) hotspots in the Pacific, 2 of which can be backtracked to an oceanic plateau. OJP = Ontong-Java Plateau, SR = Shatsky Rise.

Absolute plate motions (mm/yr)
Arrow length = amount of movement over past 50 Myr



Fastest moving plate = Pacific, Slowest moving plate = African. There is a net westward "drift" of the lithospheric plates. But, the fixivity of hotspots has been questioned.

Forces acting on the lithospheric plates



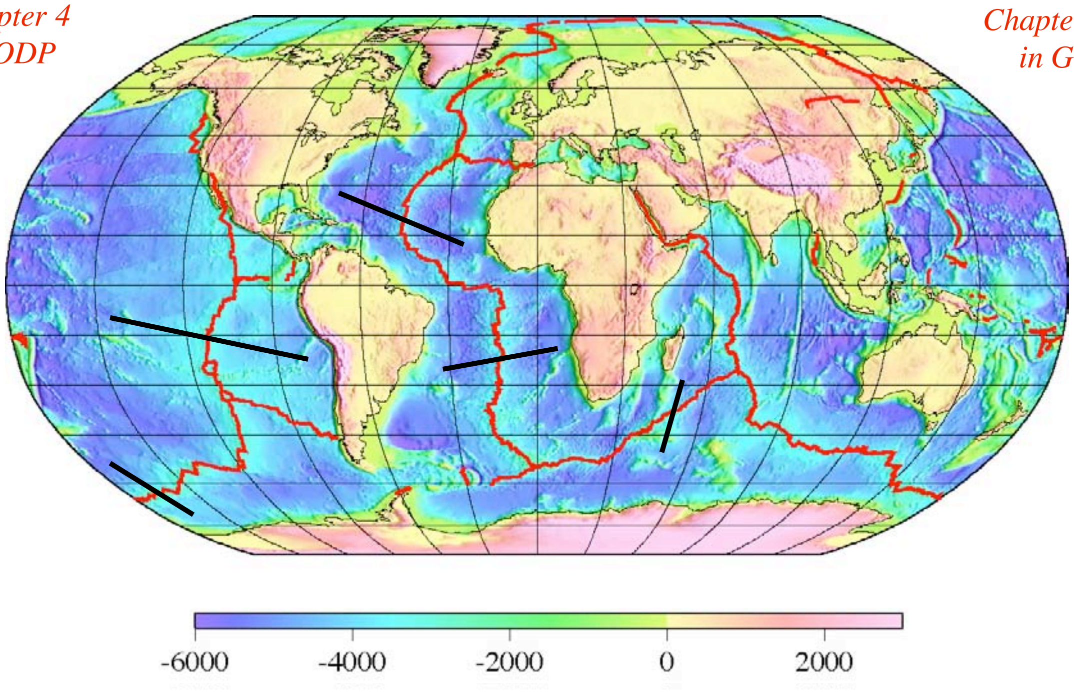
F = driving forces
F_{RP}=ridge push, F_{SP}=slab pull, F_{SU}=trench suction force,
F_{NB}=slab negative buoyancy
R = resistive forces (e.g. oceanic and continental drag)

Fastest moving plate (Pacific) has the longest slab (and the least continental area) $\rightarrow F_{SP}$
Slowest moving plate (Africa) has the greatest continental area $\rightarrow R_{DC}$
The interiors of most plates are dominated by compression $\rightarrow F_{RP}$

Lecture 2:
Mid-ocean ridges and constructive plate boundaries

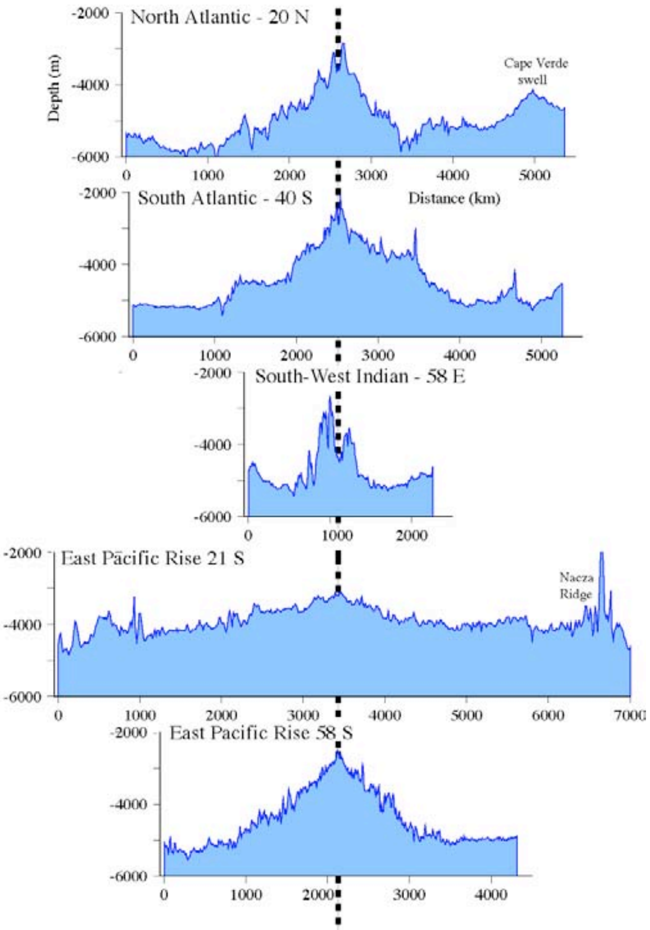
Chapter 4
in ODP

Chapter 9.3
in GG



A 65,000 km long zone of extension and crustal production

Bathymetry of the mid-ocean ridge

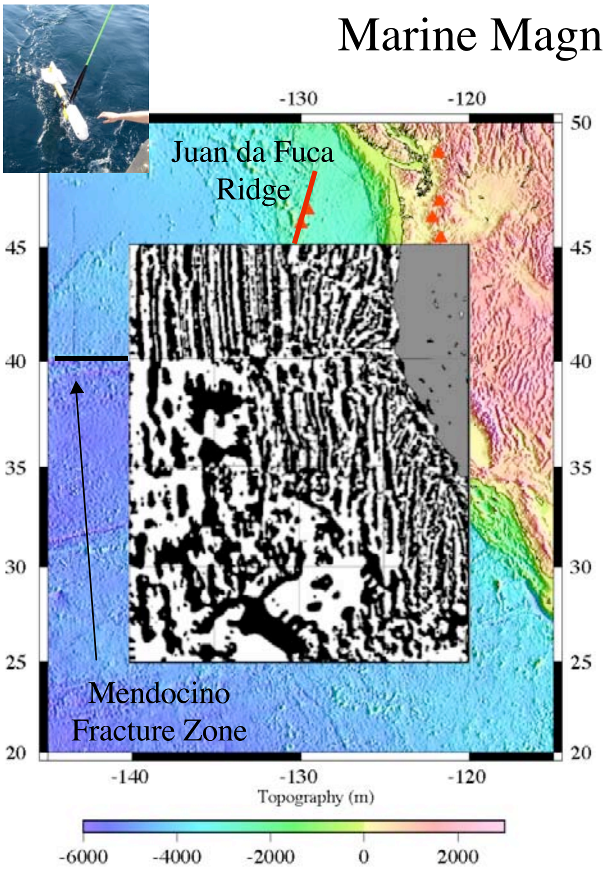


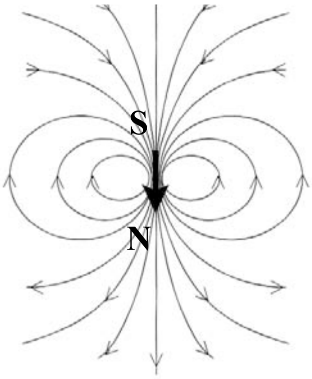
Ridge crest depths are generally similar (~2500-2900 m).

Widths vary - narrow (North Atlantic - slow spreading), wide (East Pacific Rise - fast spreading).

Bathymetry is generally smoother on the East Pacific Rise than it is on the North and South Atlantic and South-West Indian ridges.

Marine Magnetic Anomalies



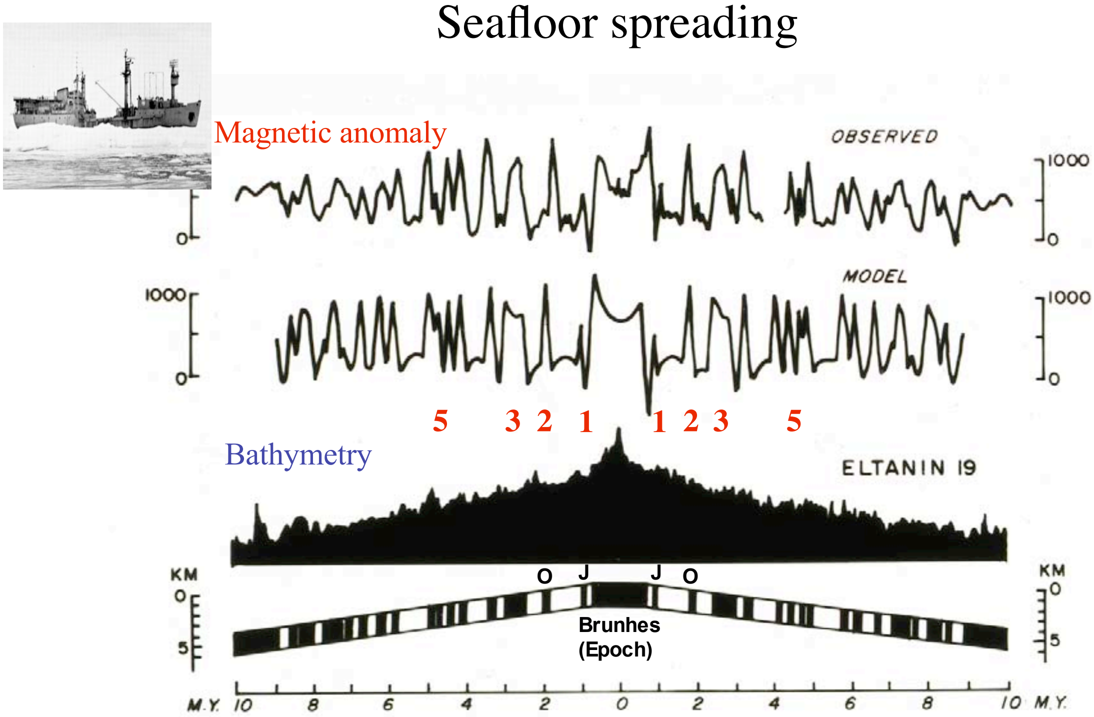


The Earth's magnetic field approximates that of a magnetic dipole

Magnetic anomaly "stripes" run parallel with a mid-ocean ridge and are offset by fracture zones.

They are caused by the rapid cooling of basalt in a magnetic field (remanent magnetisation) which changes its polarity with time.

Seafloor spreading

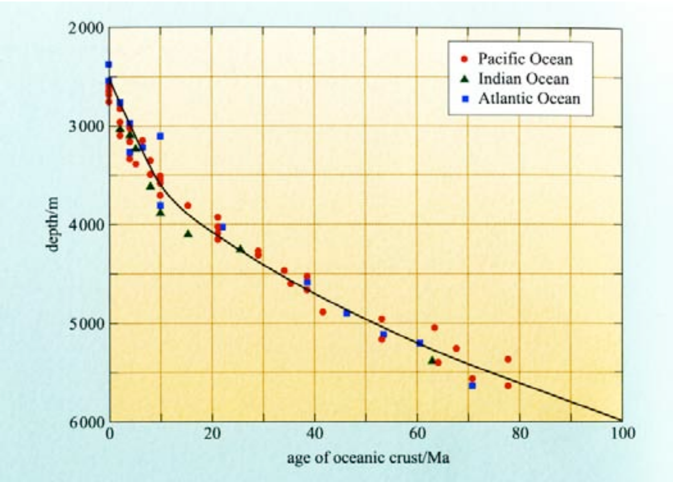


Black blocks represent periods of normal polarity and white blocks periods of reverse polarity

The geomagnetic polarity time-scale derived from marine magnetic anomalies has been confirmed by deep-sea drilling (age of oldest sediment).

Depth Vs. Age

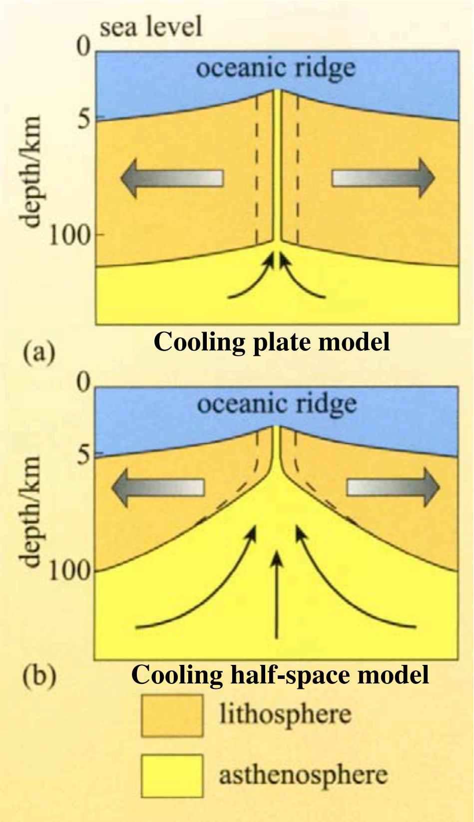
Oceanic crust systematically increases its depth away from a mid-ocean ridge as it cools, contracts and subsides with age



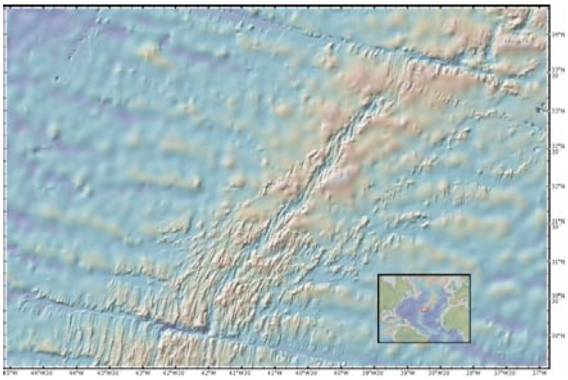
$d(t) = 2500 + 350t^{1/2}$ m, $0 < t < 70$ Ma

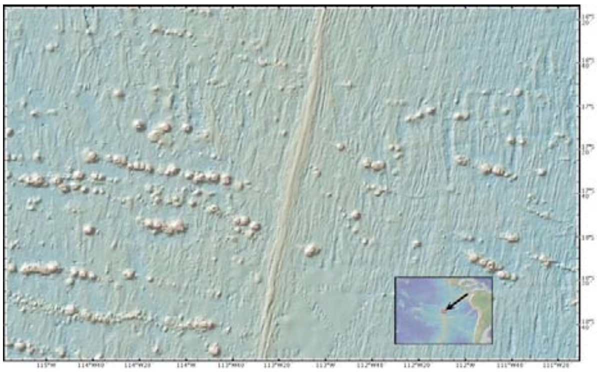
$d(t) = 6400 - 3200{*}(e^{-t/62.8})$ m, $t > 20$ Ma

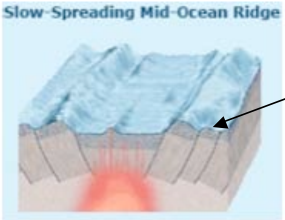
Parsons & Sclater (1977), Chapter 4 in GG



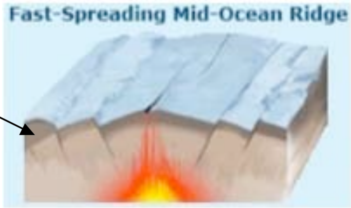
Ridge morphology







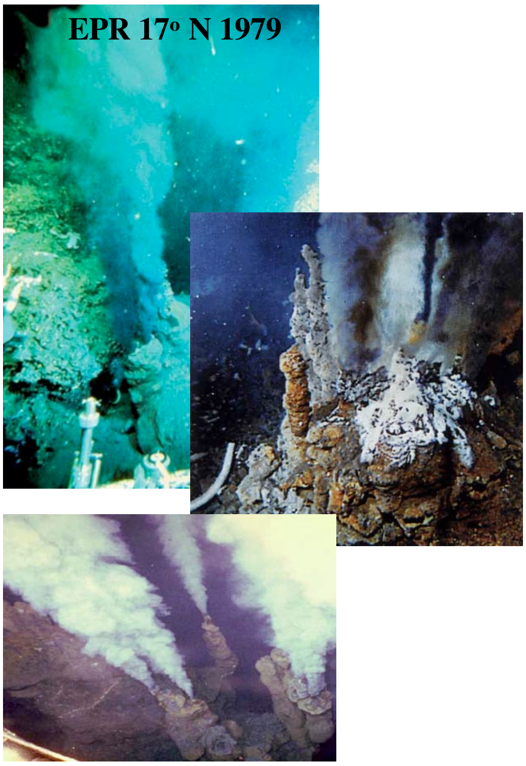
Fissures

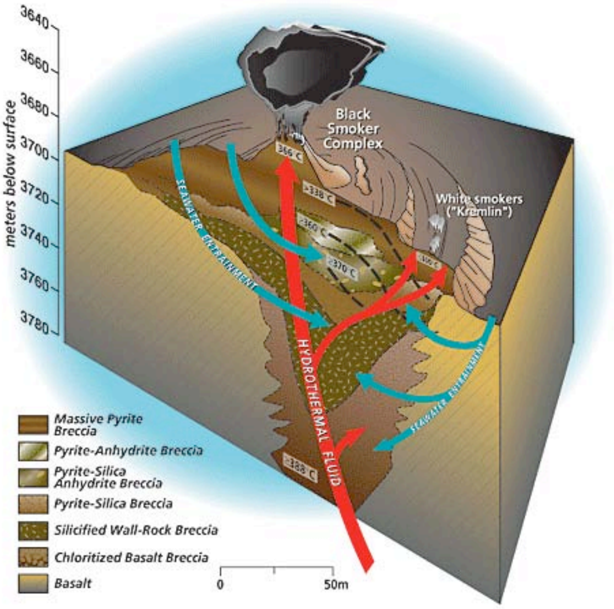


Spreading rates - 20 mm/yr
(e.g. N. and S. Atlantic)
Axial rift, rough flank topography

Spreading rates - 80-120 mm/yr
(e.g. East Pacific Rise)
Axial horst, smooth flank topography

Black, grey and white smokers and mineral mounds



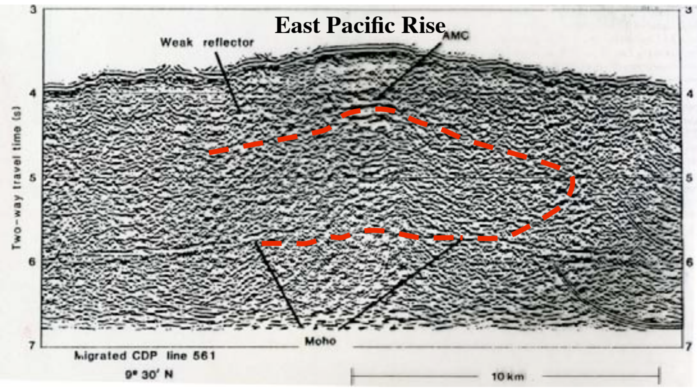


Hydrothermal activity: seawater flows through the crust and is discharged through one or more vents on the seafloor

Vent faunas

Vents are associated with unique (chemosynthetic) ecosystems that comprise tube worms, giant clams, crabs and gastropods. See (e.g. Grassle, 1985).

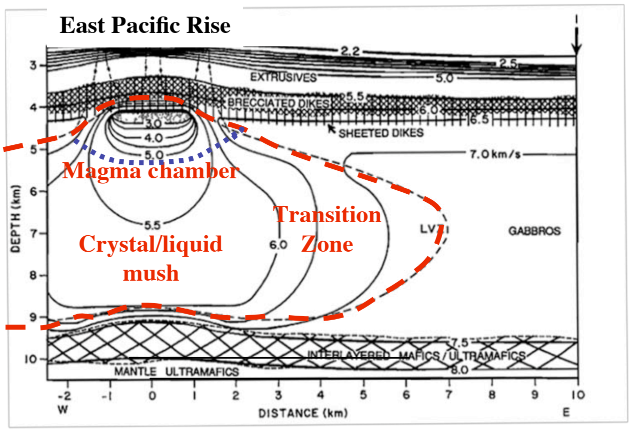
Seismic structure of the crust



Oceanic crust - and Moho - are formed within ~2 km of a mid-ocean ridge crest.

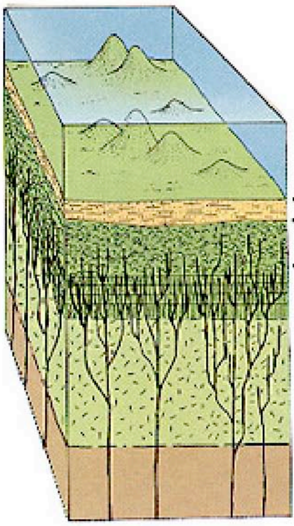
Vera et al (1999)

The East Pacific Rise has a low velocity zone (LVZ), the top of which is marked by a strong reflector which is interpreted as the top of a magma chamber.



The LVZ comprises the magma chamber, crystal/liquid mush and a transition between mush and solid hot rock

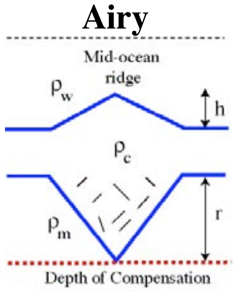
Oceanic crust: Composition, Thickness and seismic attributes

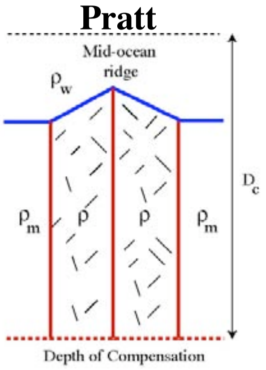


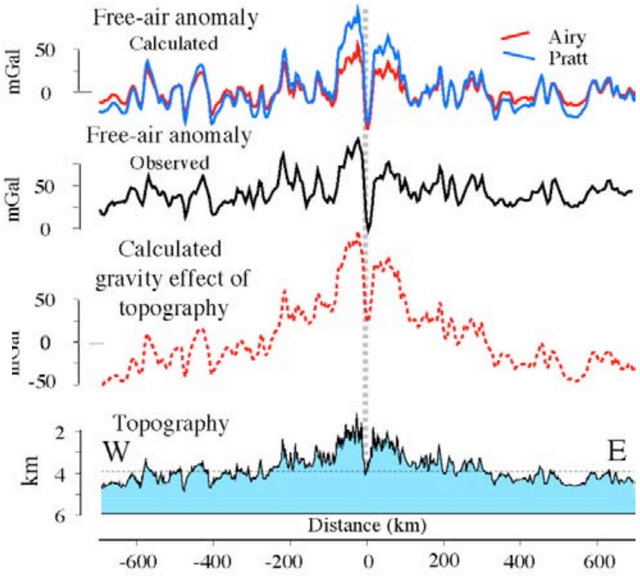
			Velocity	*Gradient*
Sediment	Layer 1			
Pillow Basalt	Layer 2A	0.5 km	3.5 km/s	1-2 km/s
Basalt Dikes	Layer 2B	1.5 km	4.8-6.2 km/s	
GABBRO	Layer 3	5.0 km	6.5-6.9 km/s	0.1 km/s
	Seismic Moho			
Petrologic Moho				
Peridotite (Upper Mantle)	Layer 4		>~ 7.6 km/s	

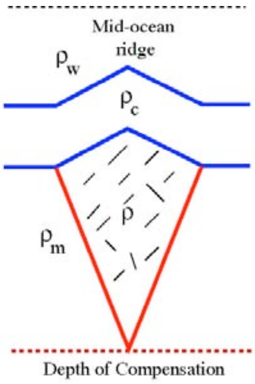
The "normal" thickness of oceanic crust is ~7 km: it is thicker at aseismic ridges (e.g. oceanic plateaus) and thinner at fracture zones. Oceanic crust is homogeneous on horizontal length scales of up to several hundred km.

Gravity anomalies



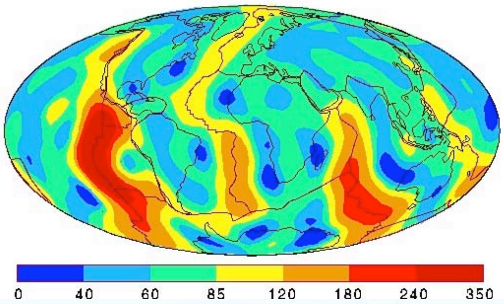


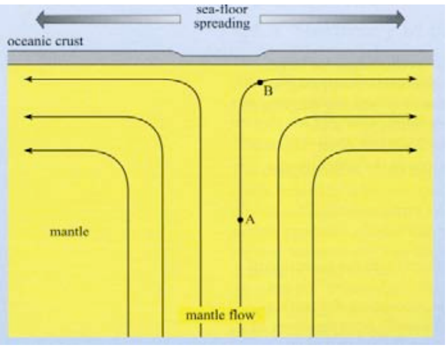


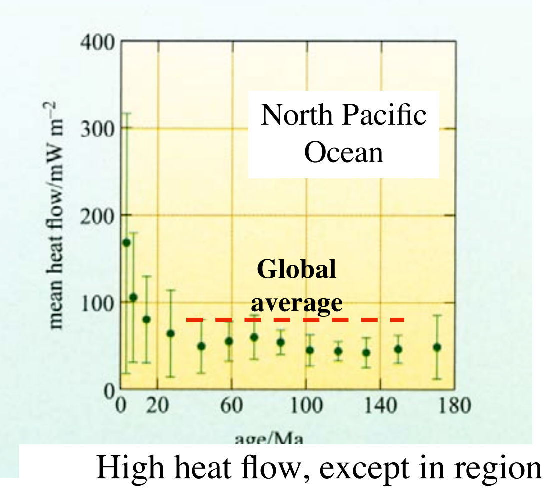


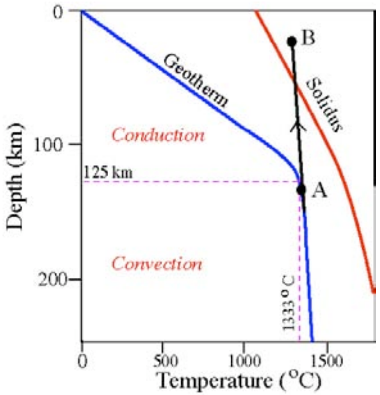
The small-amplitude free-air anomalies suggest that mid-ocean ridges are isostatically compensated at depth. Gravity modeling suggest that the oceanic crust at a mid-ocean ridge is underlain by low density mantle

Heat flow, hydrothermal circulation and melting







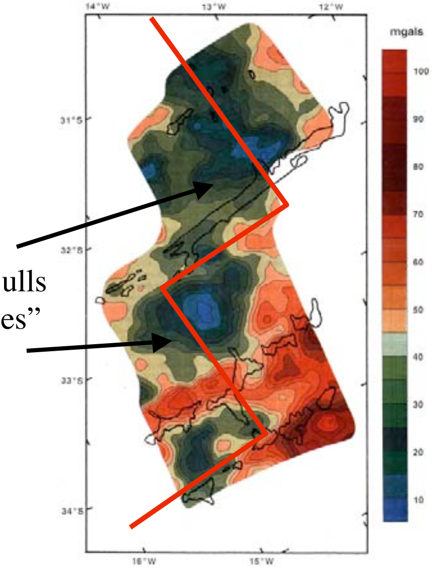


Langmuir & Forsyth (2007)

High heat flow, except in regions of hydrothermal circulation. Suggests hot upwelling and decompression melting

Segmentation and melt delivery

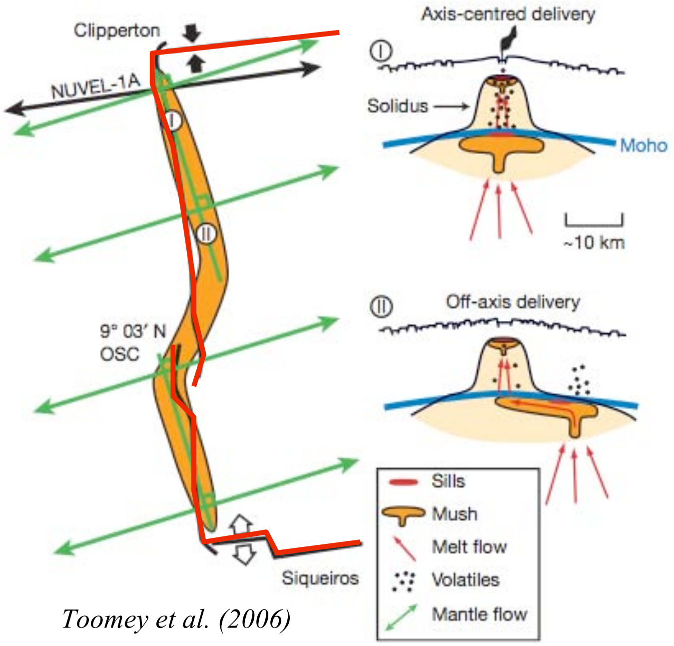
Mantle Bouguer Anomalies (MBA) = Free-air Anomalies corrected for topography and uniform crustal thickness



"Bulls eyes"

Kuo & Forsyth (1988)

MBA "bulls eyes" suggest focused melt delivery

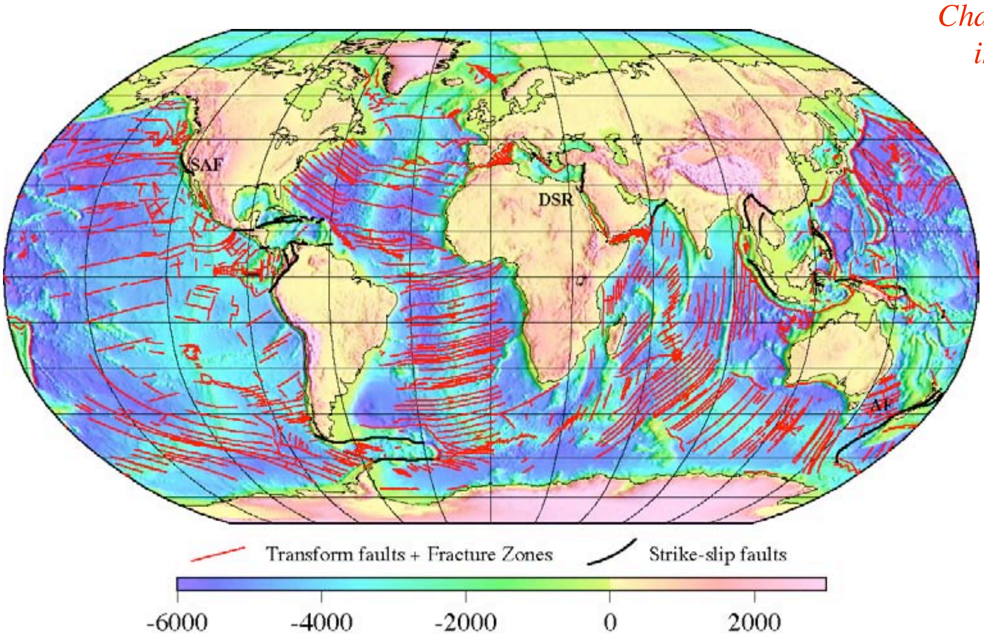


Toomey et al. (2006)

Low mantle P wave velocities (7.3-7.5 km/s) suggest an asymmetric focusing?

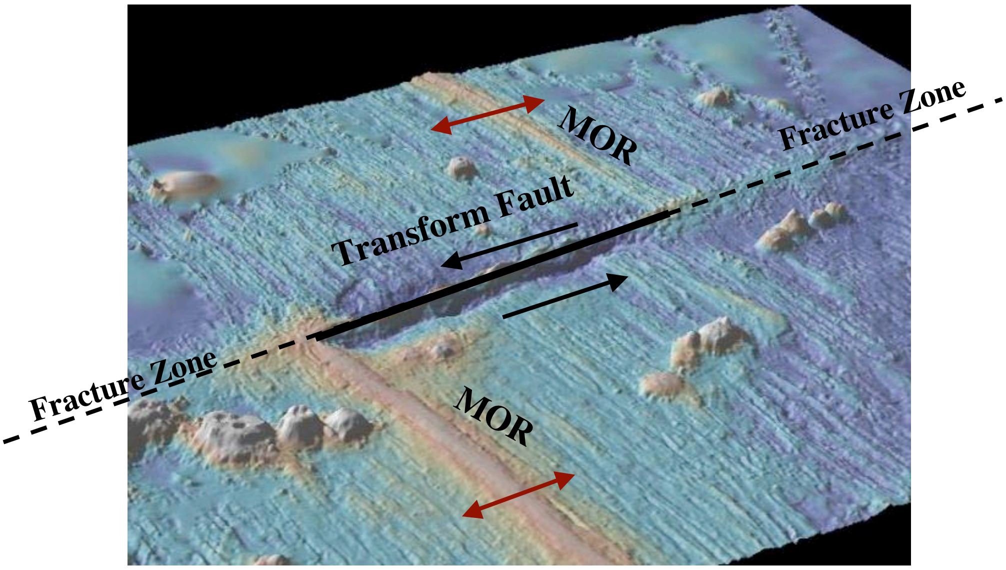
Lecture 3:
Transform faults, fracture zones and strike-slip faults

Chapter 9.5 in GG



SAF = San Andreas Fault, DSR = Dead Sea Rift

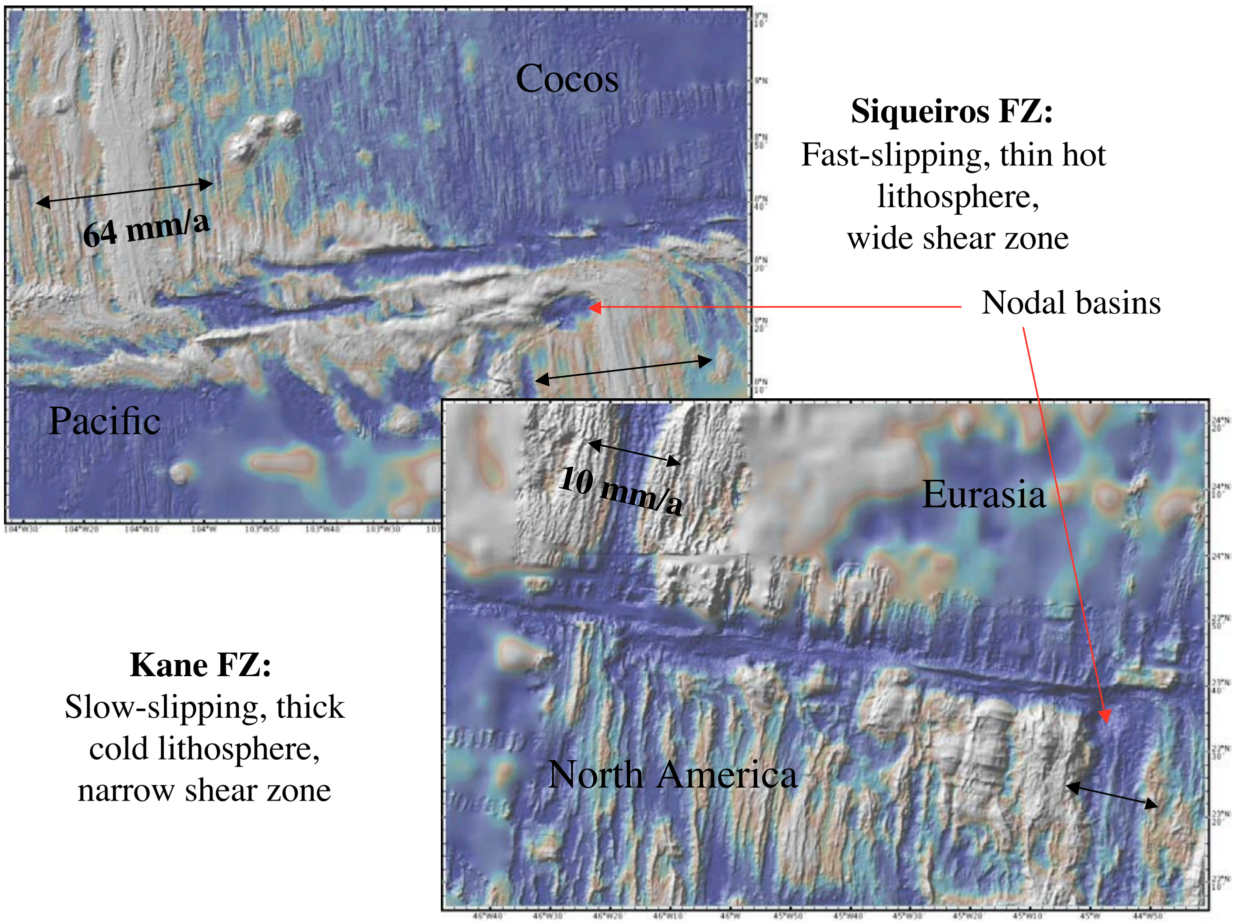
Transform Faults and Fracture Zones



Clipperton Fracture Zone (EPR - 9º N) *Pockalny* (1997)

Offset = 85 km (~1.5 Myr age offset), Slip Rate ~107 mm/a

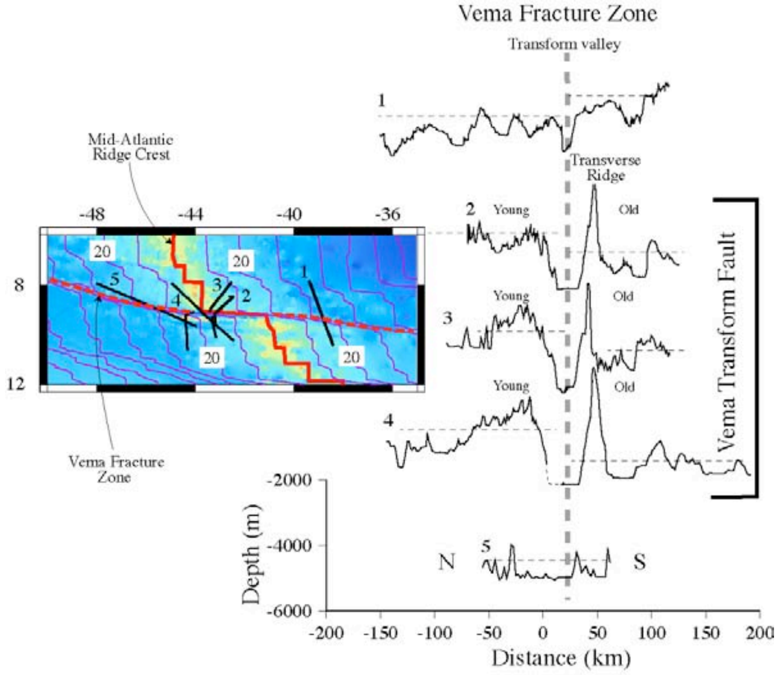
Transform faults are offsets that separate two segments of an actively spreading Mid-Ocean Ridge (MOR). They are sites where two plates are slipping past each other. Fracture zones are fossil transform faults. They extend for hundreds of km away from a ridge.

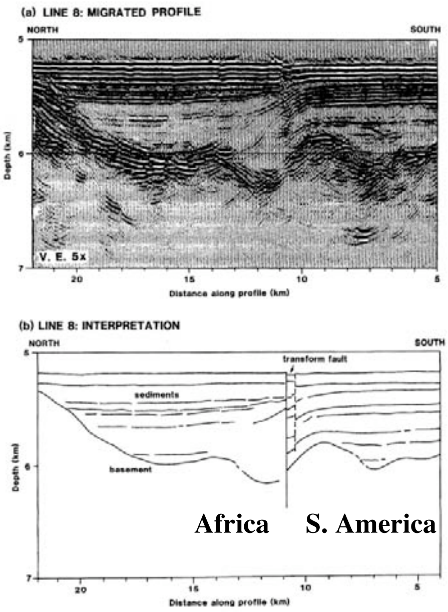


Siqueiros FZ:
Fast-slipping, thin hot
lithosphere,
wide shear zone

Kane FZ:
Slow-slipping, thick
cold lithosphere,
narrow shear zone

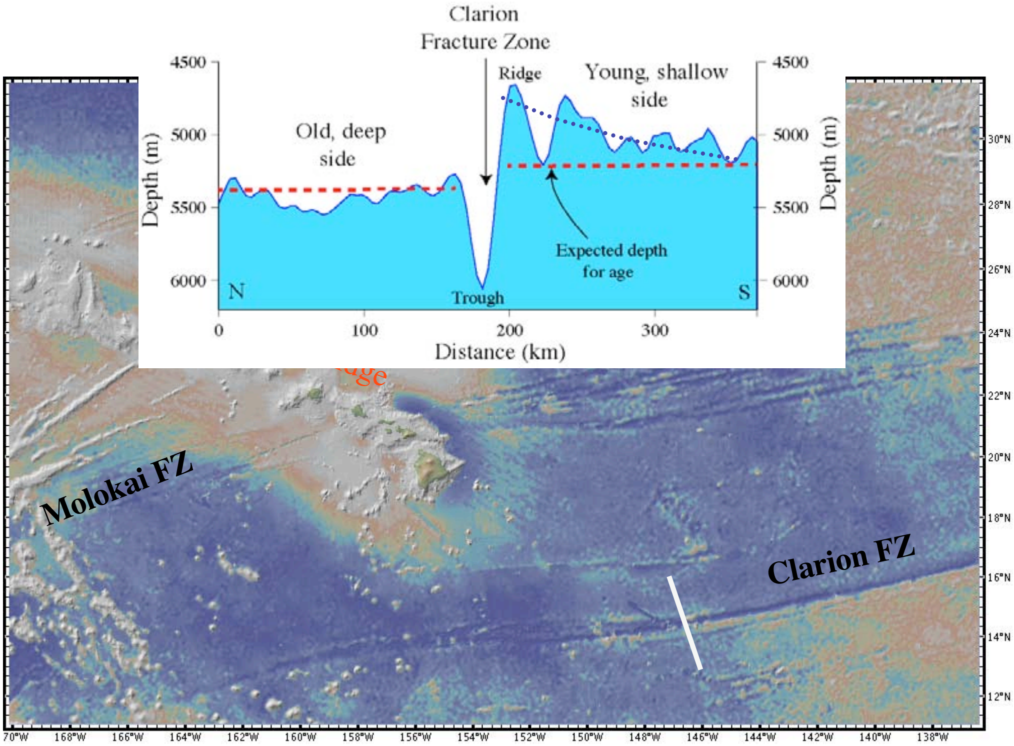
Transform fault topography





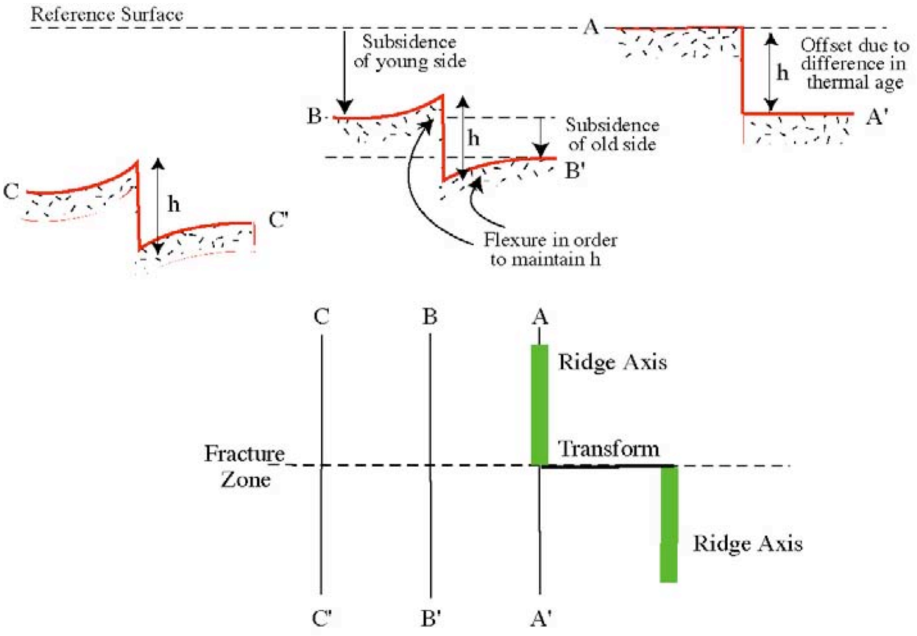
Transform faults are associated with deep troughs, steep-sided (transverse) ridges, thick sediments and a regional bathymetric offset that reflects differences in the age of oceanic crust.

Fracture Zone topography



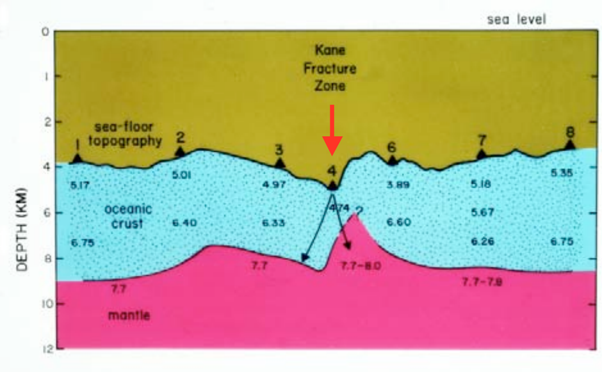
Fracture zone topography is similar to transform faults, except that the young side sometimes has a rim uplift and the old side a hanging valley

Subsidence and flexure



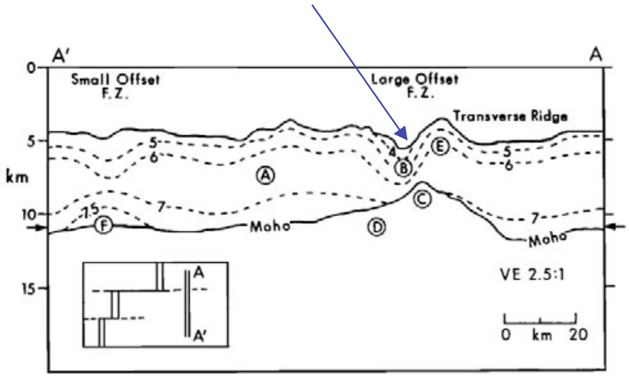
Unlike a transform fault, there is no slip across a fracture zone. Fracture zones evolve by differential subsidence and flexure, forming a rim uplift on the young side and a hanging wall on the old side. The trough may be infilled by in excess of 3 km of sediment.

Fracture Zone Crustal structure



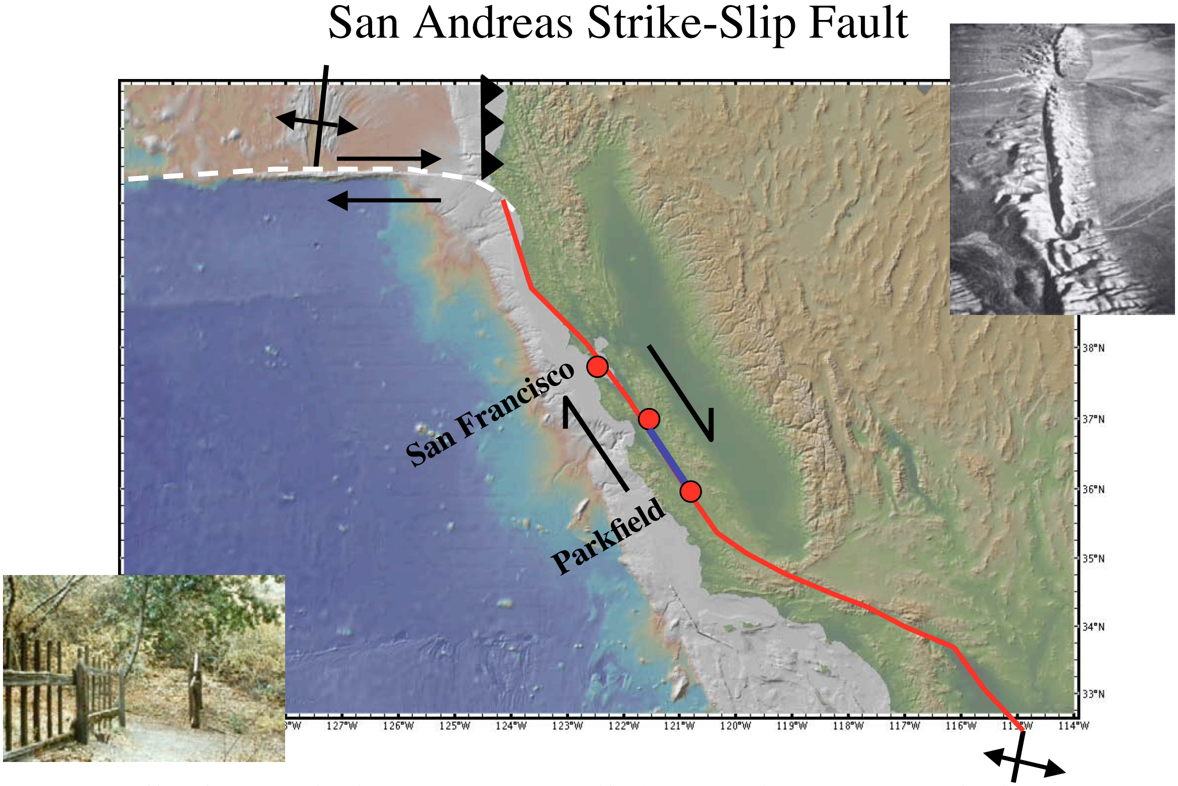
Detrick et al (1993)

Dredge rocks include basalts, metabasalts, gabbros, metagabbros and serpentinised ultramafics.



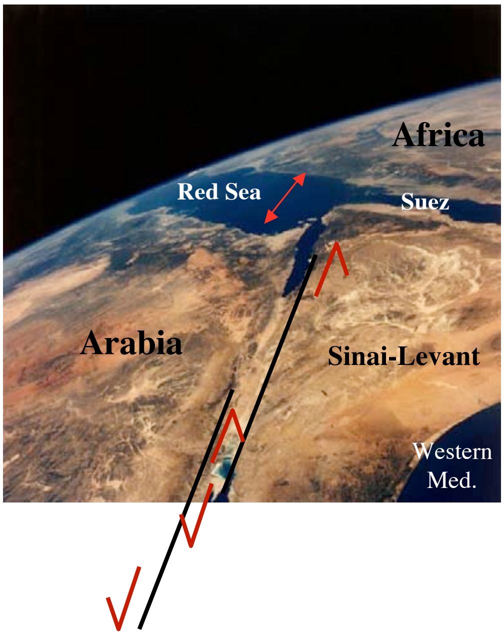
Fracture zones are typically associated with a thin crust, anomalously low velocities and the absence of an oceanic layer 3. The velocities may reflect an intensely fractured, highly altered, basaltic crust that is overlain by a serpentinised mantle while the thin crust is indicative of a reduced magma supply.

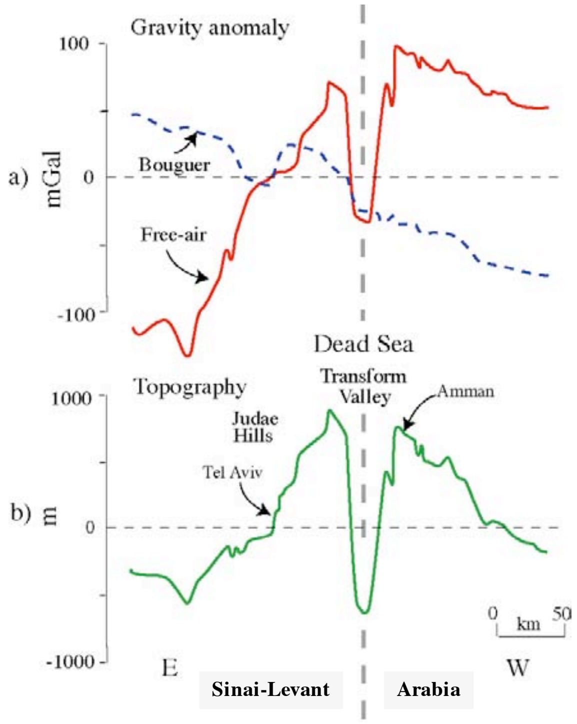
San Andreas Strike-Slip Fault



Laterally slipping faults onshore are called strike-slip or wrench faults. The San Andreas is an example of right-lateral strike-slip fault. The creeping section (in blue) is slipping (aseismically) at ~32 mm/yr.

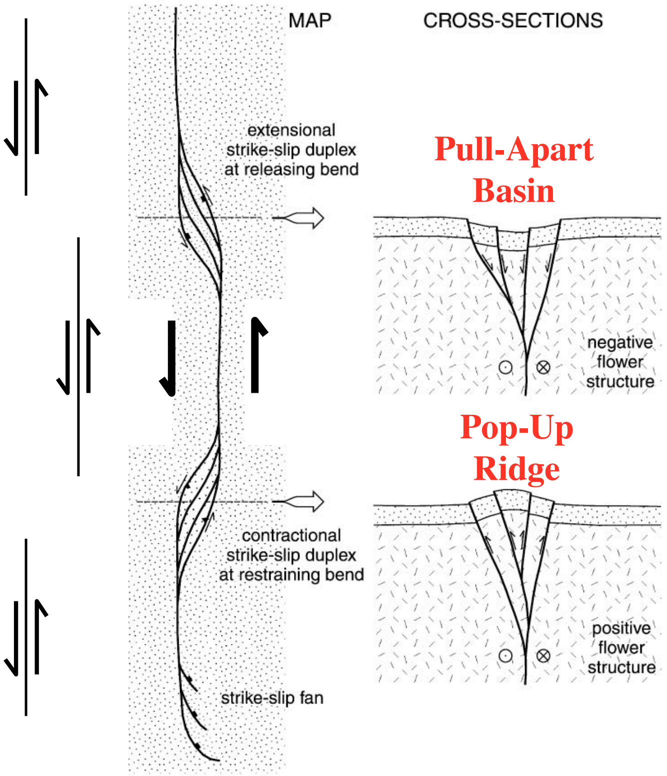
The Dead Sea Rift

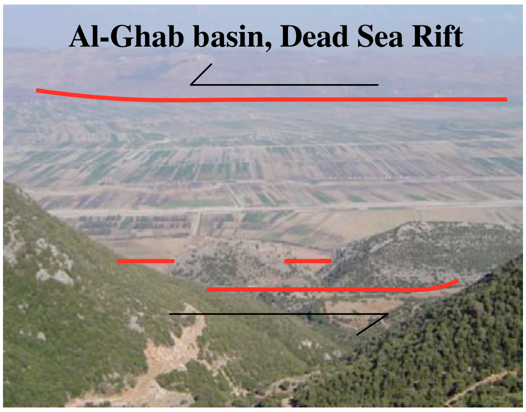


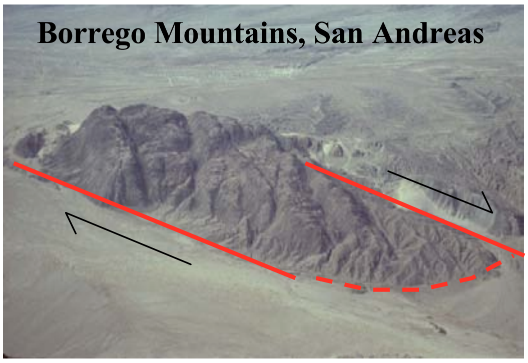


The Dead Sea is an example of left-lateral strike-slip fault. There is no evidence from the Bouguer anomaly that Moho is involved.

Strike-slip faults, pull-apart basins and pop-up ridges



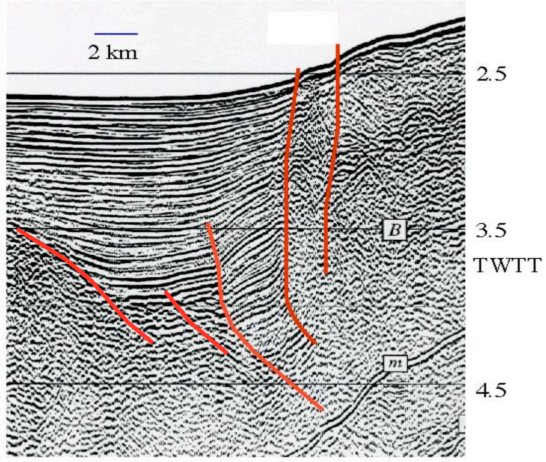




Flower structures

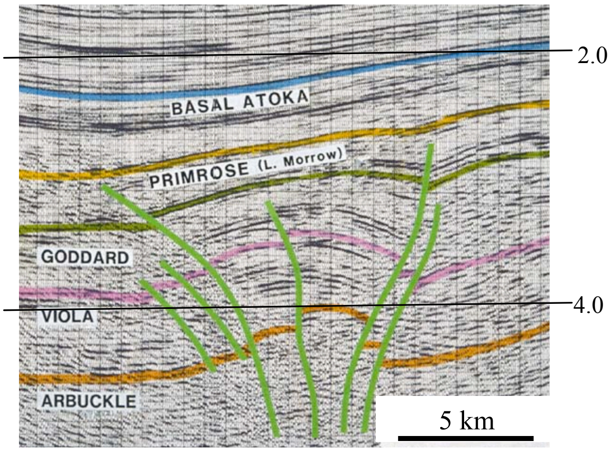
Pull-apart basins and pop-up ridges develop along with the strike-slip displacement on the main border faults. This displacement is believed to extend downwards to a detachment surface that separates the brittle upper crust from the ductile lower crust.

Petrunin & Sobolev (2006)



e.g. Yusuf basin - Alboran Sea

Negative flower structure



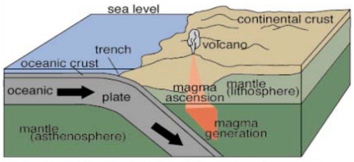
e.g. Ardmore basin - Oklahoma

Positive flower structure

Lecture 4:
Deep-sea trenches and destructive plate boundaries

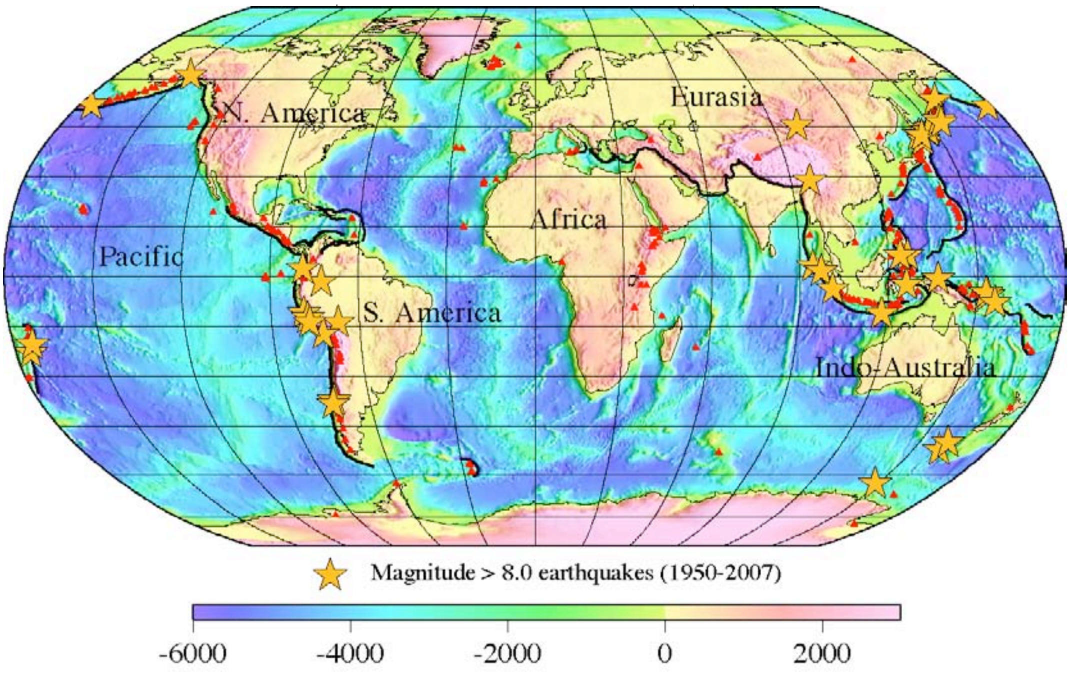
Chapter 5 in ODP

Ocean/continent
Ocean/ocean
→ Trench

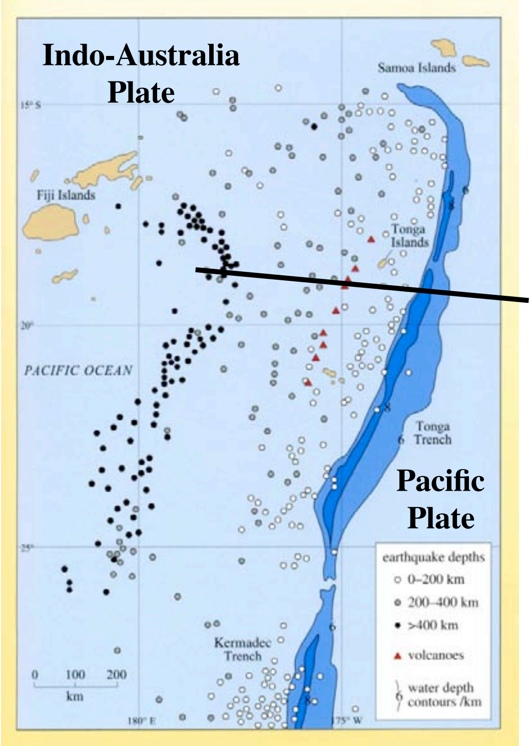


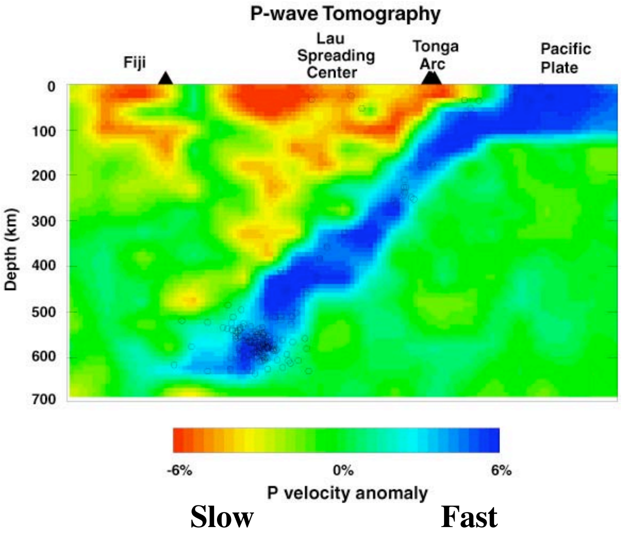
Continent/continent
→ Foredeep or
Foreland basin

Chapter 9.6 in GG



Earthquakes: Benioff Zone

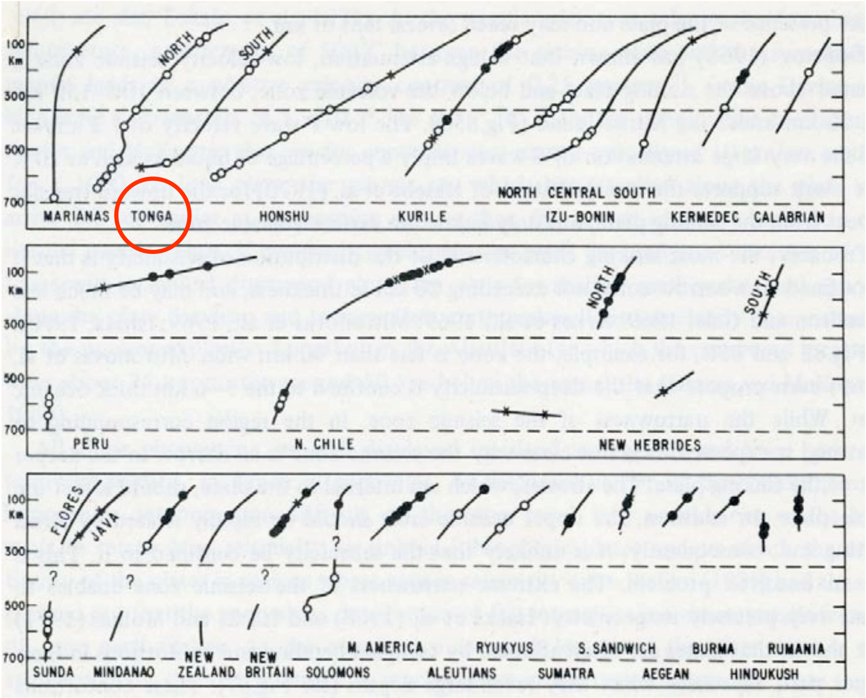




Zhao et al. (1997)

Earthquakes and fast P-wave velocities down to > 600 km. Define a 50-100 km thick, dense, sinking lithospheric "slab". Slow P-wave velocities suggest partial melting in the mantle "wedge" above the slab and beneath the arc.

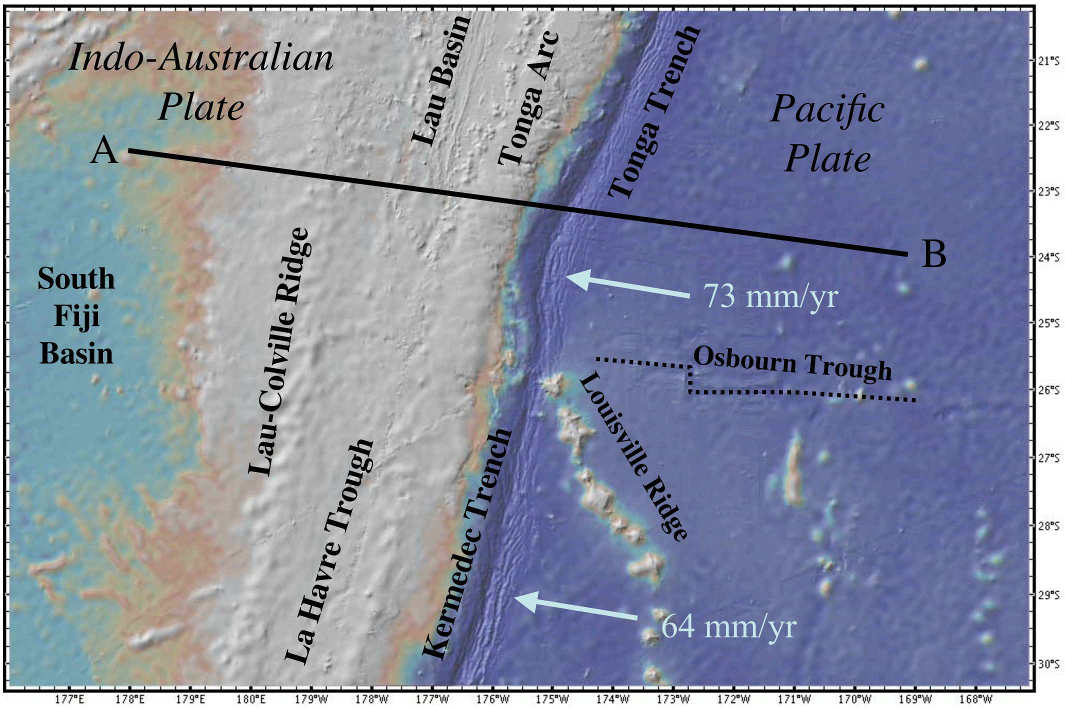
Slab dip and stress state



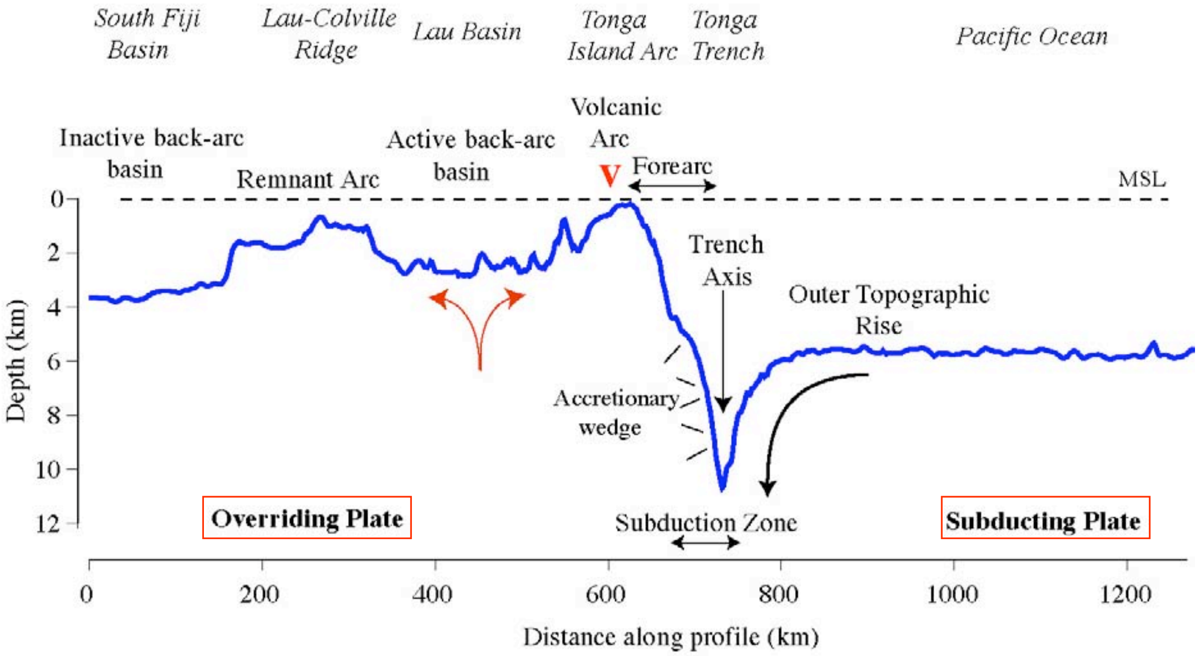
○ = downdip compression ● = downdip tension

Isacks & Molnar (1967)

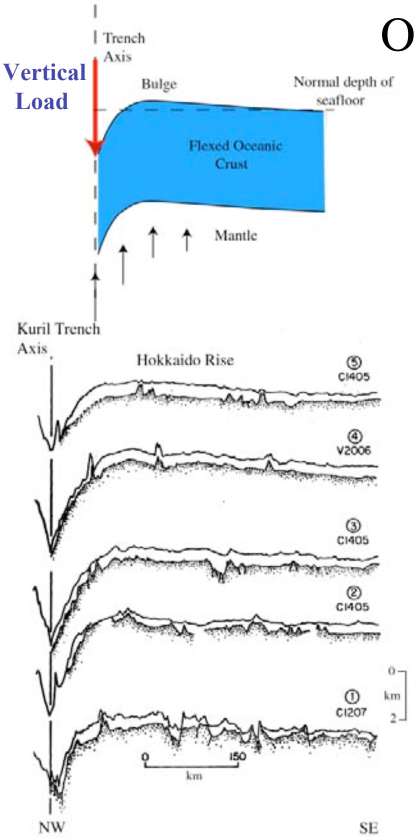
Bathymetry

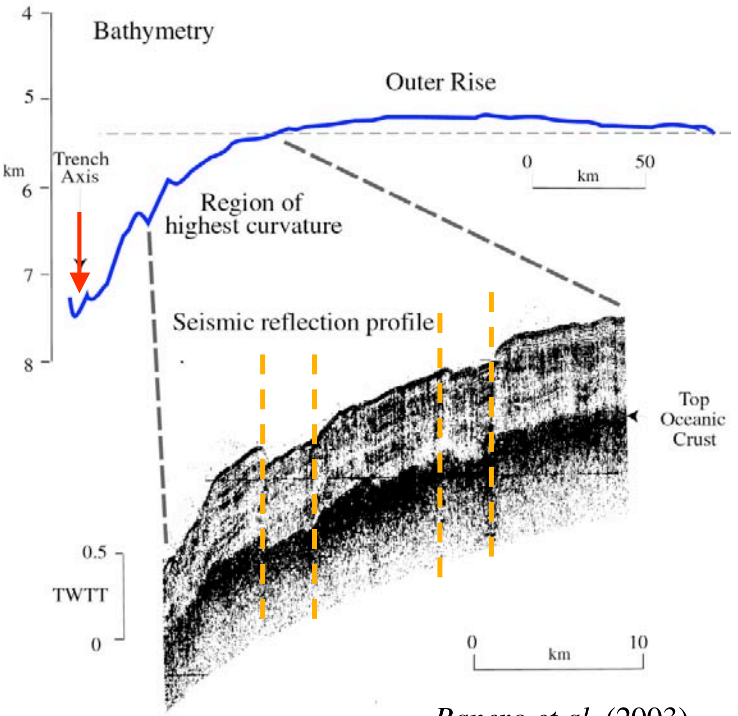


The Tonga-Kermadec Island Arc - Trench is the most seismically active, fastest converging and linear subduction zone system in the world.



Outer Topographic Rise



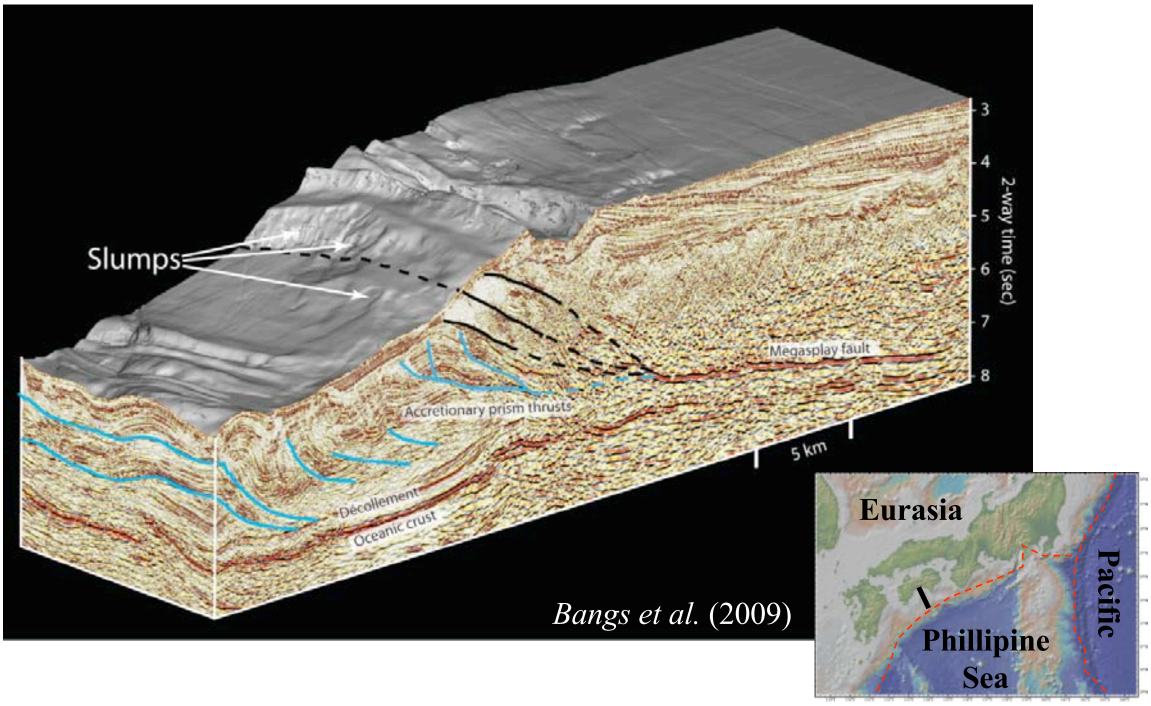


Ranero et al. (2003)

Elastic plate bending and breaking, horst and graben structures and mantle hydration seaward of the trench.

Forearc

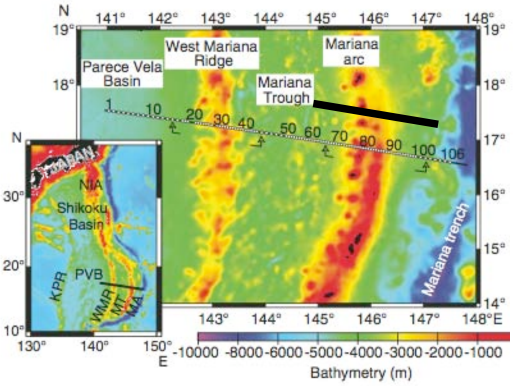
3D Seismic Reflection Profile data - Nankai Trough, Phillipine Sea



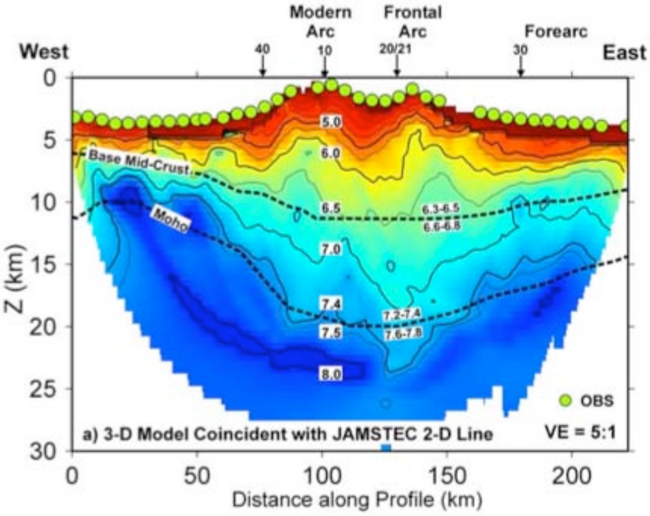
Bangs et al. (2009)

Accretionary wedge thrusts, “Megasplay” faults, detachment surfaces and submarine slides and slumps

Volcanic (Island) Arc

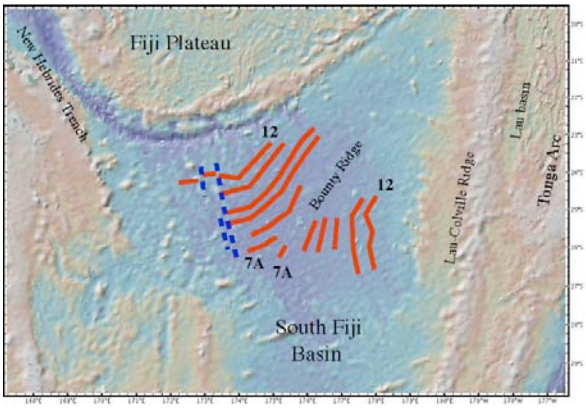


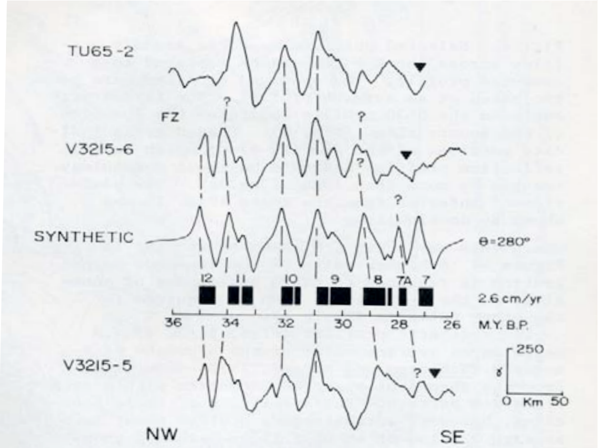
Calvert et al. (2008)



Arc crust is thicker (~20 km) than normal oceanic crust. The velocity structure suggests an upper basaltic layer, a middle quartz-rich (i.e. andesitic) gabbroic layer and a lower quartz-poor gabbroic layer.

Back-arc basin





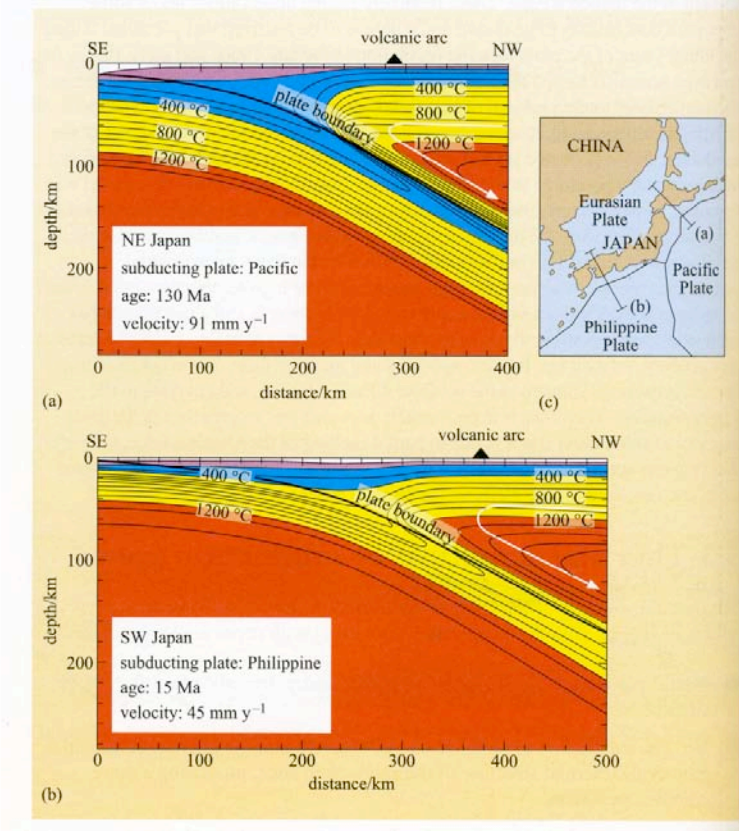
Magnetic anomalies can be correlated with the geomagnetic polarity time-scale and resemble those generated at a mid-ocean ridge

Back-arc basin sea-floor spreading is generally short in duration (~10 Myr). Some basins are active (e.g. Lau basin) while others are inactive (e.g. Japan Sea).

Geochemical data suggest that basaltic lavas from back-arc basins are a mix of arc-like and mid-ocean ridge sources.

Taylor & Martinez (2003)

The thermal structure of subduction zones



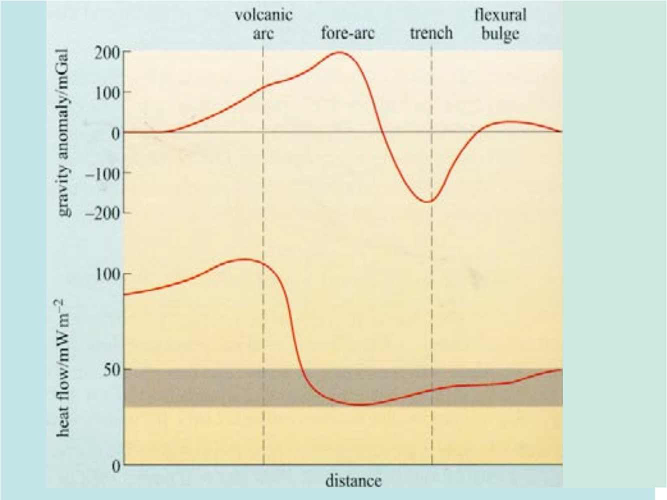
The thermal structure of a downgoing slab depends on the age of the subducting plate and the convergence rate.

As the slab subducts, it cools the overlying mantle wedge, pulling hot mantle down and inducing a corner flow.

The thermal structure determines where in the slab "wet" oceanic crust dehydrates and basalt changes phase to eclogite. Both processes may generate earthquakes

Hacker et al. (2003)

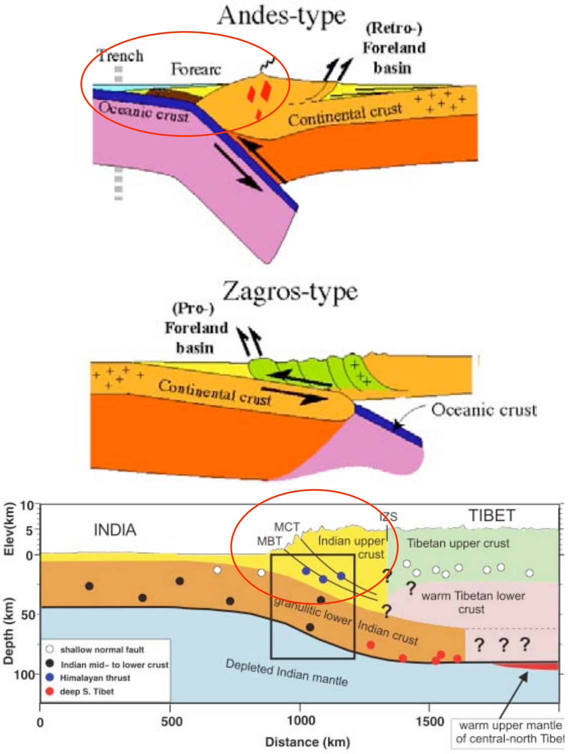
Heat flow and gravity anomalies

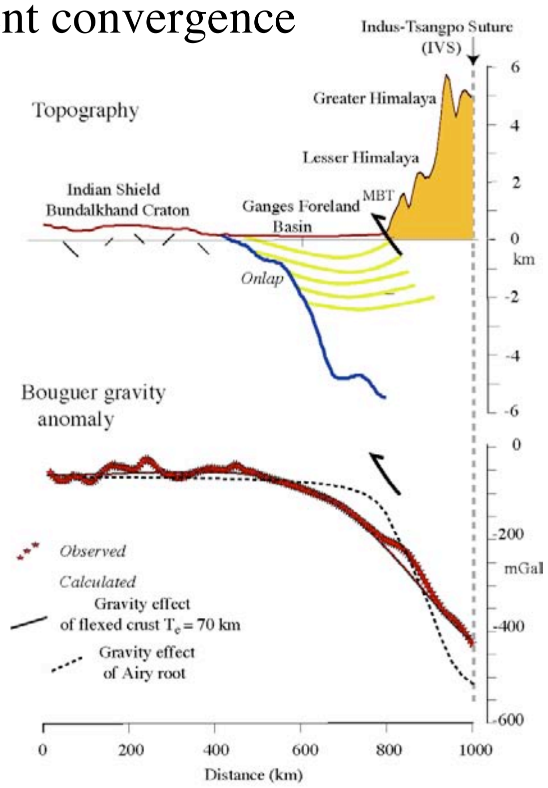


Free-air gravity anomaly comprises a high over the forearc, a low over the trench and a high over the outer rise. Reflects the build up mass in the accretionary wedge, the depression of the oceanic crust below its "normal" depth and the upward flexure of the oceanic plate seaward of a trench.

Heat flow comprises a high over the volcanic arc and a low over the forearc. Reflects the presence of hot magma at shallow depth in the volcanic arc and the subduction of a cold sinking slab.

Continent/Continent convergence



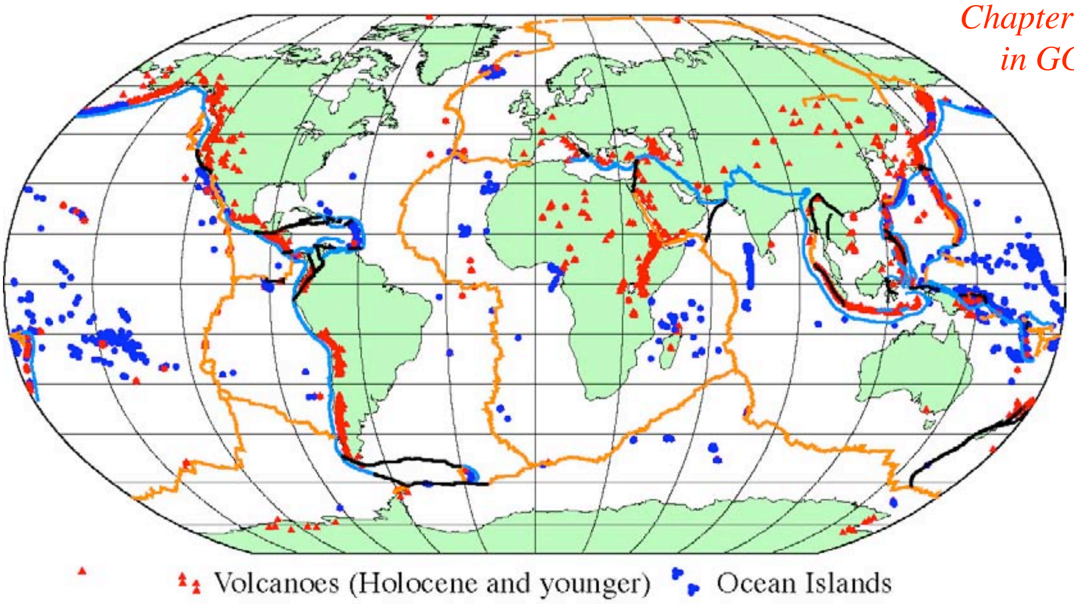


Bouguer gravity anomaly "lows" and wide (up to 350 km) and deep (up to 6 km) foreland basins that develop in front of migrating fold and thrust loads

Please remember to bring along your Western USA and Eastern Pacific problem set and figures tomorrow pm!

Lecture 5:
Ocean islands, seamounts, mid-plate swells and mantle plumes

Chapter 8.7 in GG



There are 1770 ocean islands, the majority of which are volcanoes.

Pacific Ocean Islands

Main types

- Volcanoes
- Volcanoes with a fringing coral reef
- Volcanoes with a lagoon and barrier reef
- **Atolls** (lagoon and barrier reef)
- Continental/oceanic crust

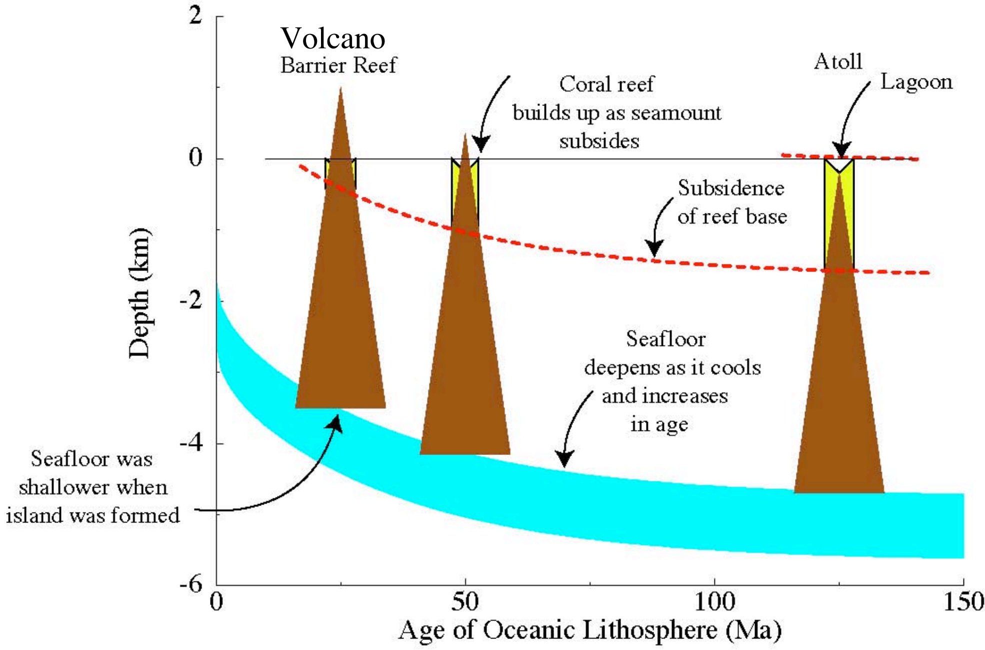
Moorea
(Society Islands)
1.5 Ma

Bora Bora
(Society Islands)
3.3 Ma

Aratika
(Tuamotu Islands - 42-47 Ma)

Origin of atolls

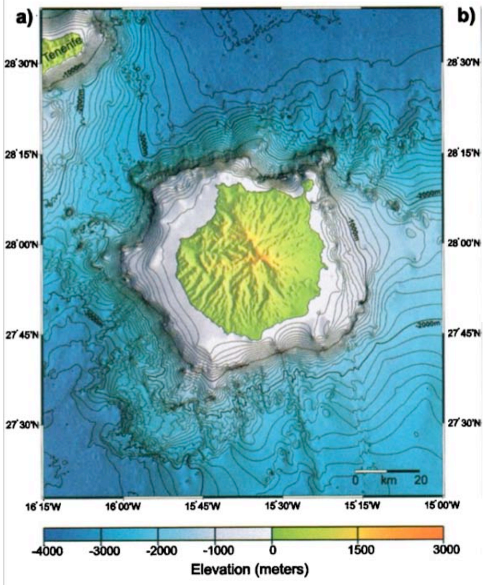
(Theory of Darwin)



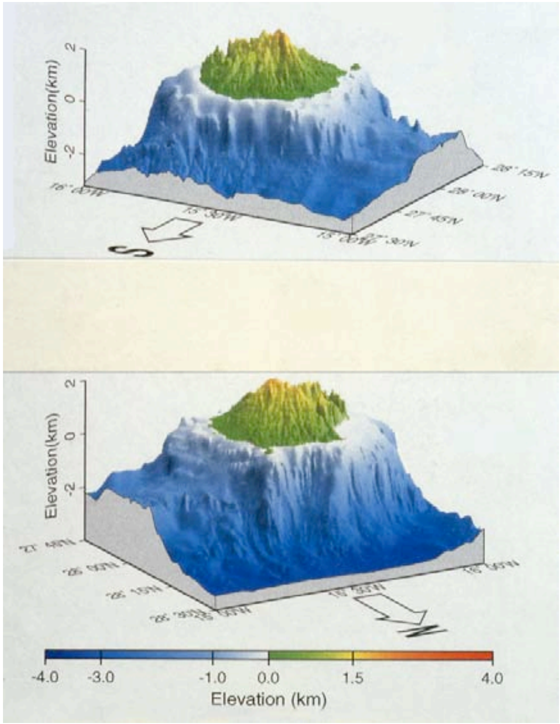
Atolls are barrier coral reefs that develop on a submarine volcano that is subsiding with age.

Reefless Islands

Some islands have no coral reef
and are in the process
of being truncated by wave action

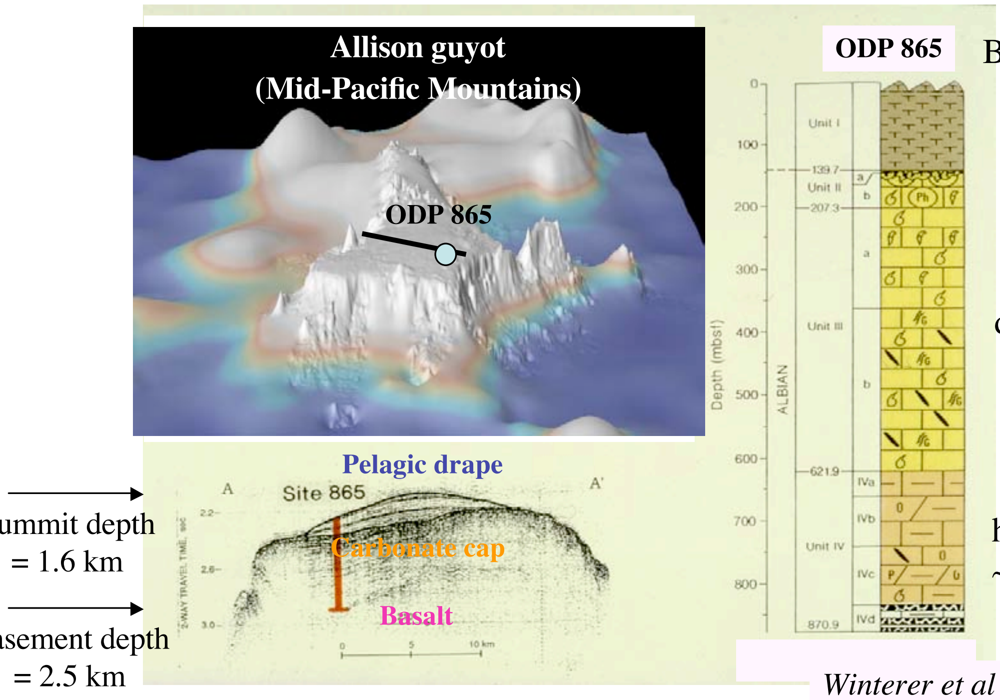


e.g. Gran Canaria, Canary Islands
(~13 Ma)



Funck & Schminke (1996)

Guyots



Summit depth = 1.6 km

Basement depth = 2.5 km

Winterer et al (1995)

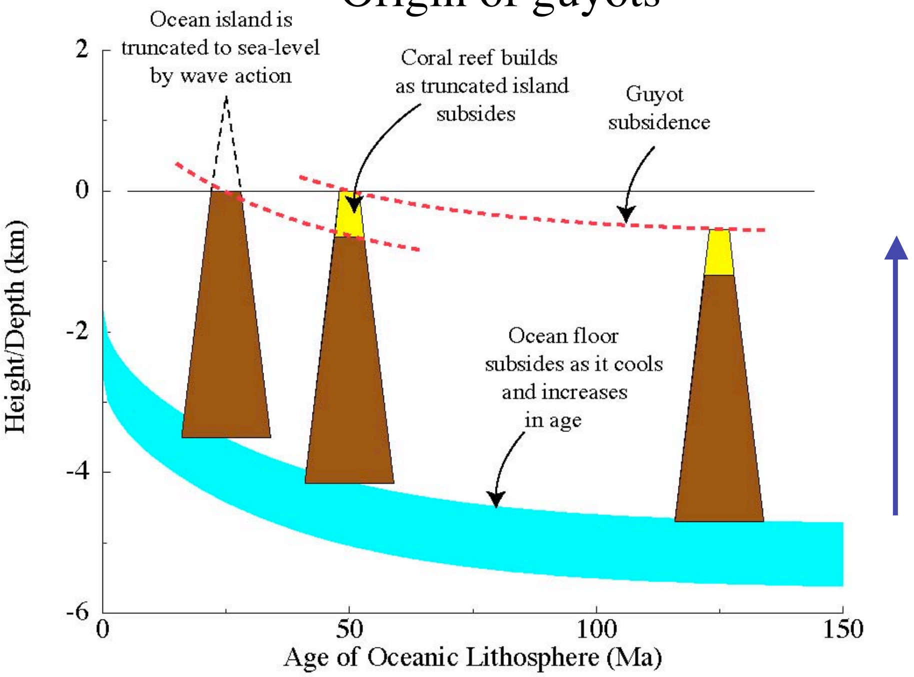
Basalt ~111 Ma.

Underlying seafloor ~124 Ma

(Use depth Vs. age equations in Lecture 2 to show that guyot should have subsided ~2.2 km since 111 Ma)

Guyots are flat-topped submarine volcanoes. Some guyots (mostly equatorial ones) are capped by carbonates and a pelagic drape.

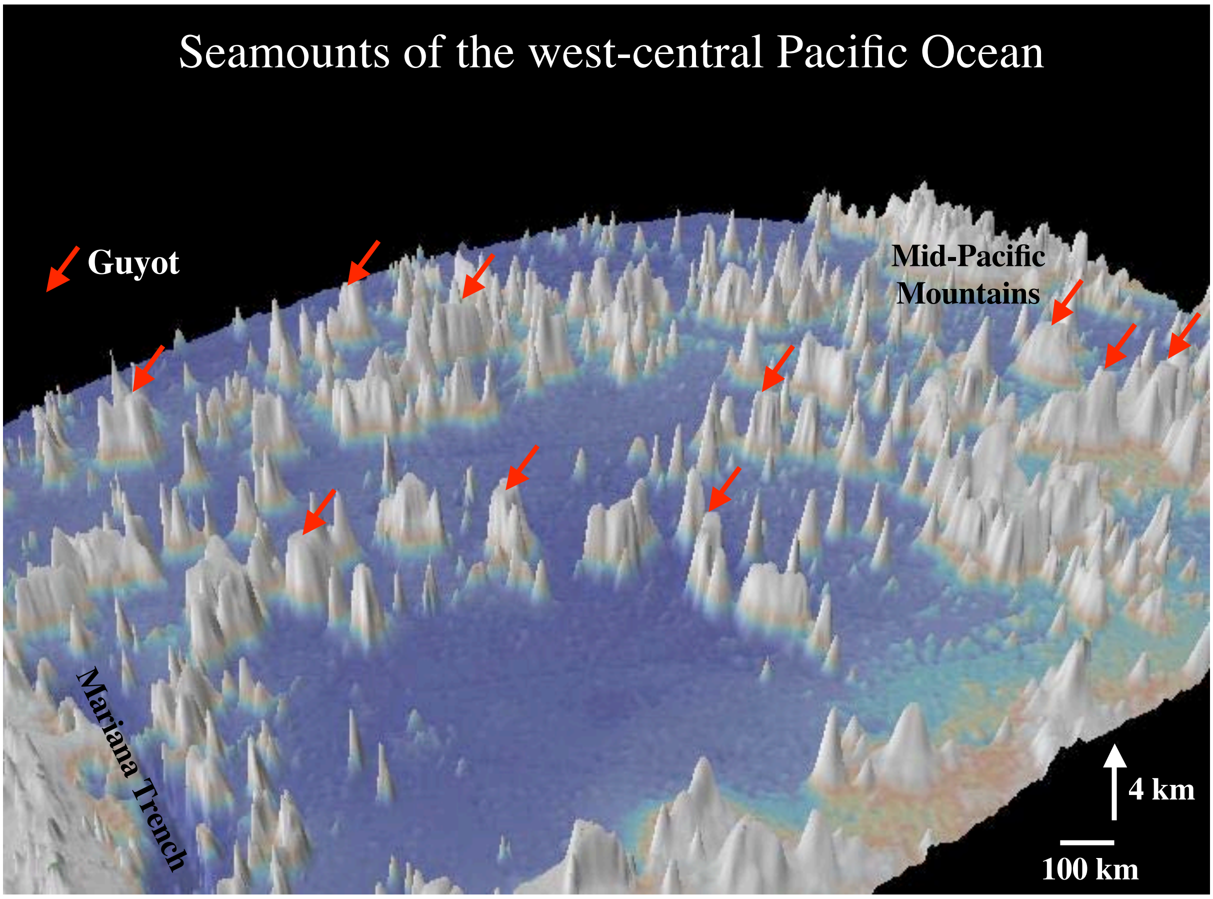
Origin of guyots



Pedestal height = Depth of seafloor when volcano formed

Guyots: Volcanoes that were wave-trimmed at sea-level and are now subsiding with age.

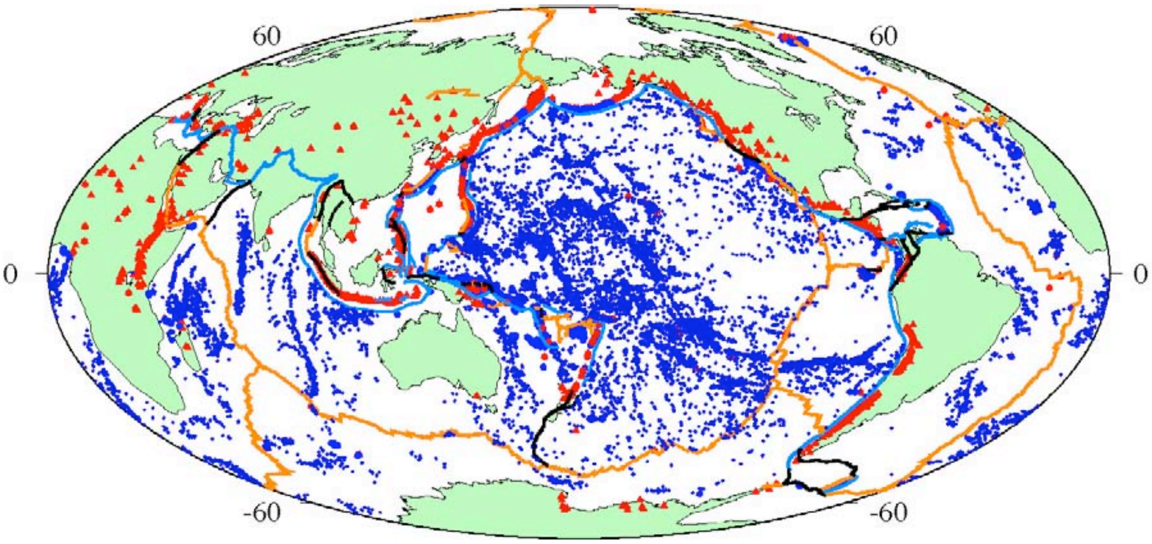
Atolls and guyots suggest that the seafloor should be littered with volcanoes (seamounts) some of which are growing up to become islands and others that were once islands and are now sinking.



Global distribution of volcanoes

Smithsonian Institute - Global Volcanism Program

?Holocene-Historical: Total: 1,684 (Historical: 568). Mean height = 1915.6 m, RMS = 1403.2 m

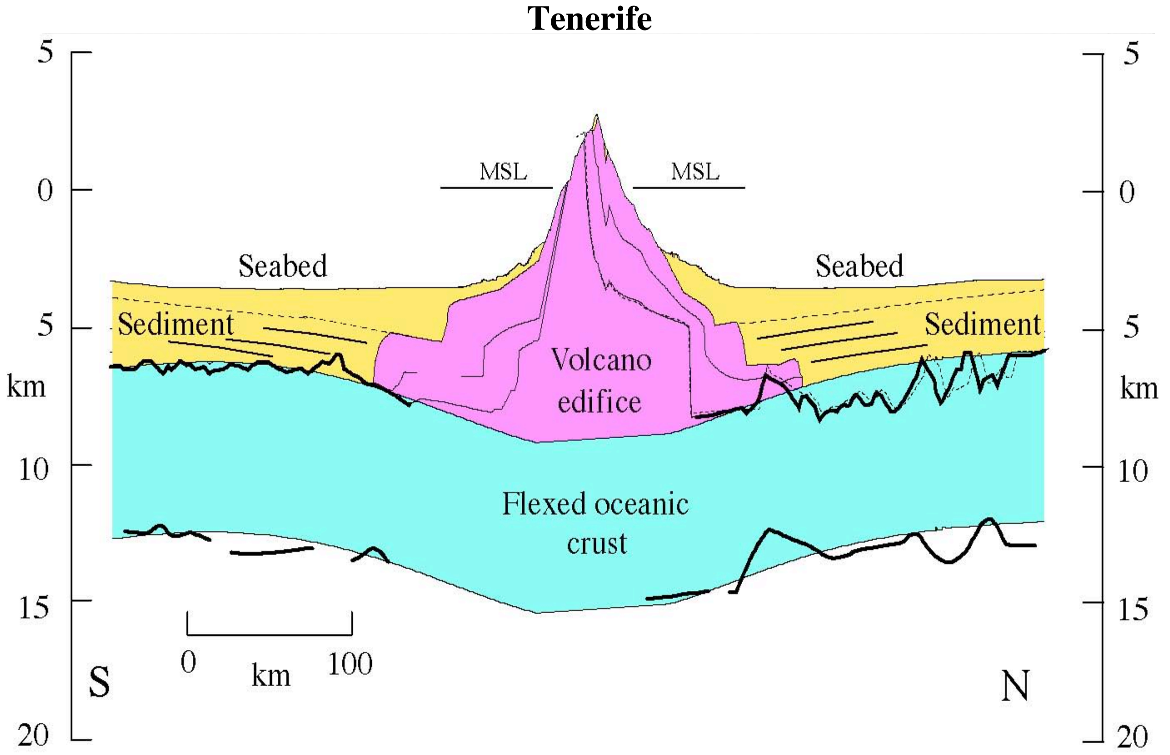


Seamounts (define): 512.4 m < h < 3318.8 m, N = 12,786

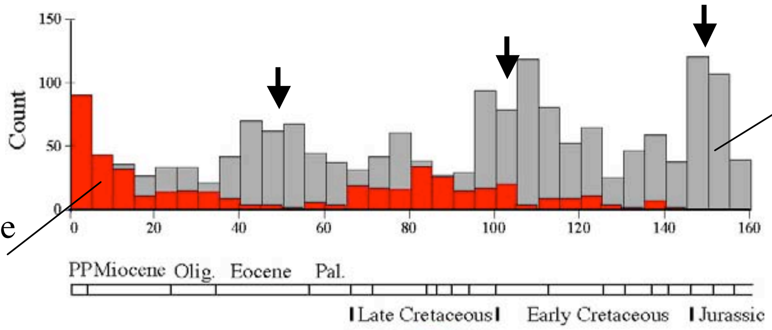
Historical: 4,313??

The structure of ocean islands

(from deep seismic sounding)

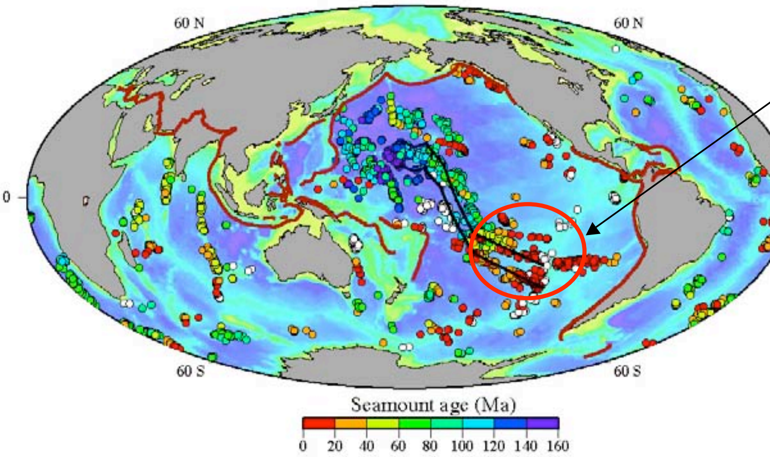


How old are seamounts?

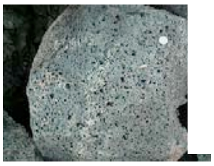


Estimated Ages

Sample ages



SOuth Pacific Isotopic and Thermal Anomaly (SOPITA)

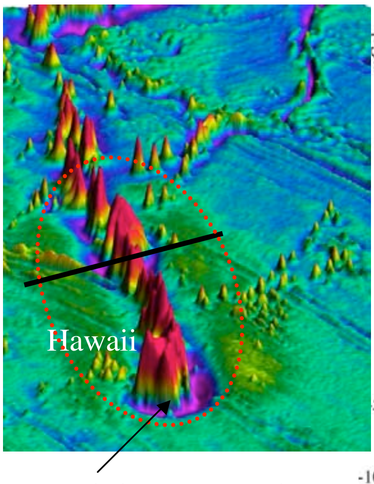


Tenerife, Canary

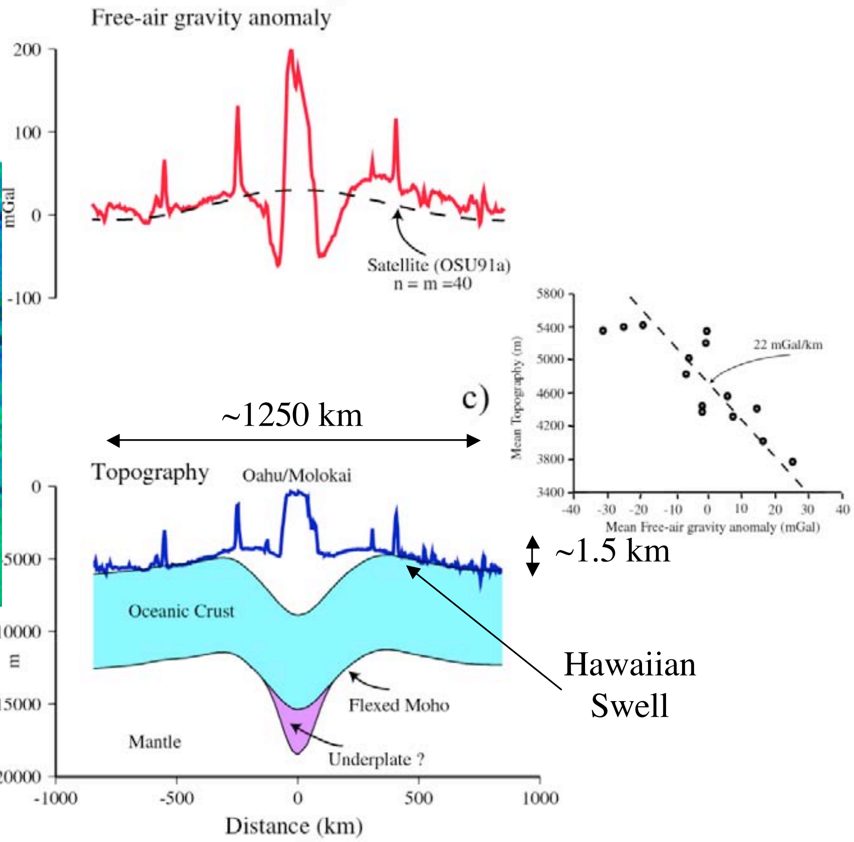
Loihi, Hawaii

The Hawaiian hotspot (mid-plate) swell

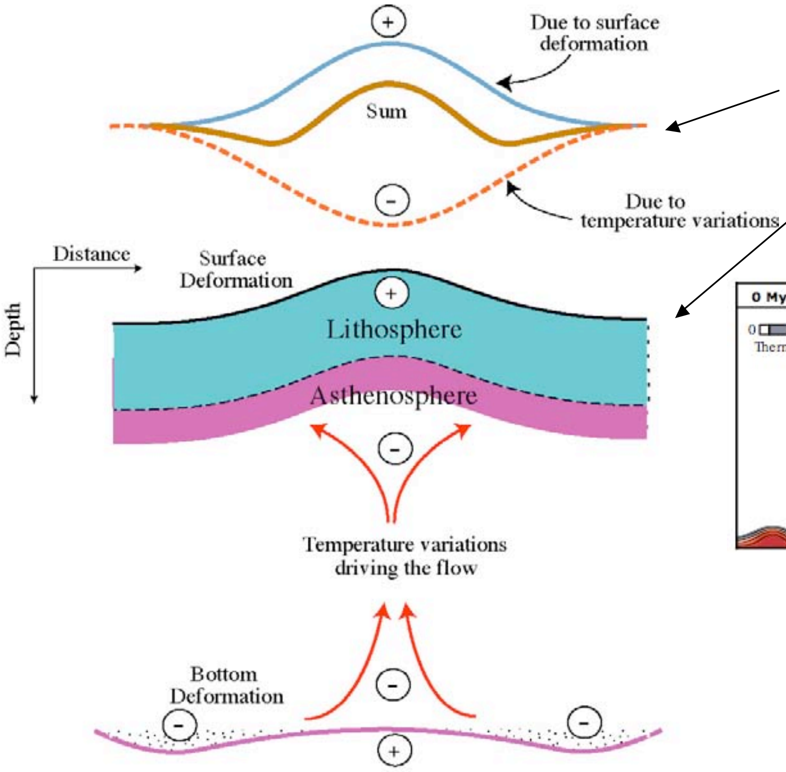
Swell “swept” upstream by plate motions



Loihi - present day location of the Hawaiian hotspot

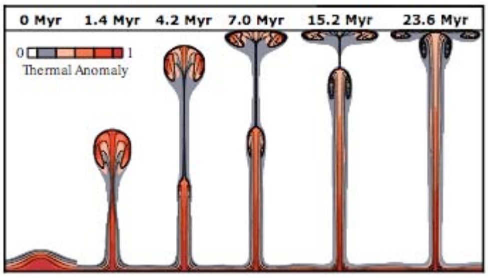


Gravity anomalies, swells and upwelling mantle plumes



Strong correlation between (free-air) gravity anomaly and topography.

Davies & Davies (2009)



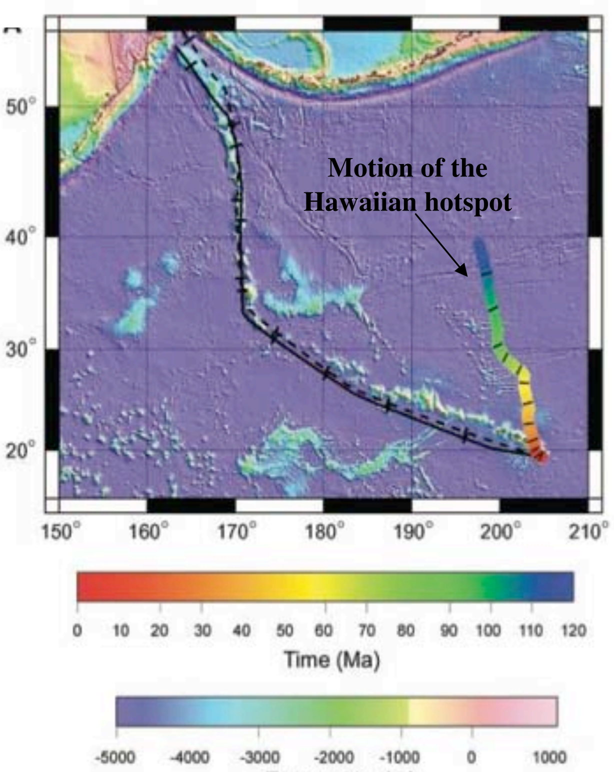
Dynamic models of plume behaviour. Unfortunately, plume details (e.g. stems) are difficult to image seismically

How fixed are hotspots?

If hotspots are fixed in the deep mantle, then each seamount in the Hawaiian-Emperor chain should have formed at the same latitude as Hawaii.

We can test this using paleomagnetic data. This is because the Earth's magnetic field approximates a dipole and there is a relationship between the inclination of the remanent magnetisation, I, in a rock and the latitude, λ, where it formed. $\tan I = 2\tan\lambda$ (see GG, p51-53).

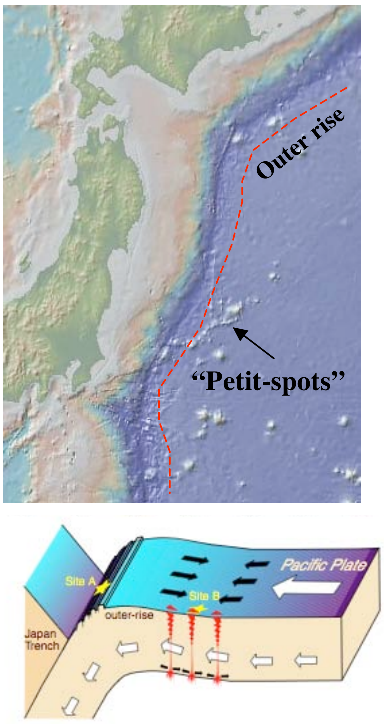
Results suggest that the Hawaiian hotspot has been fixed for the past ~40 Ma, but prior to this it migrated south by as much as ~50 mm/yr.



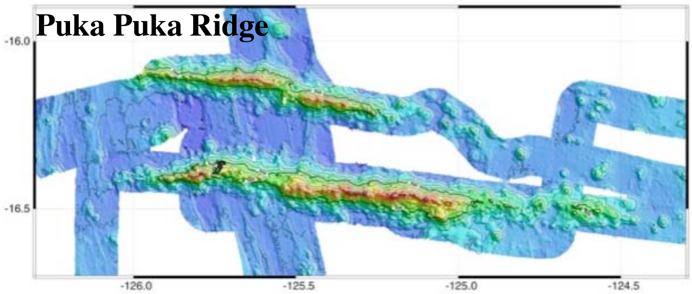
Tarduno et al (2003)

What about the numerous other seamounts?

The crack hypothesis



Hirano et al. (2008)



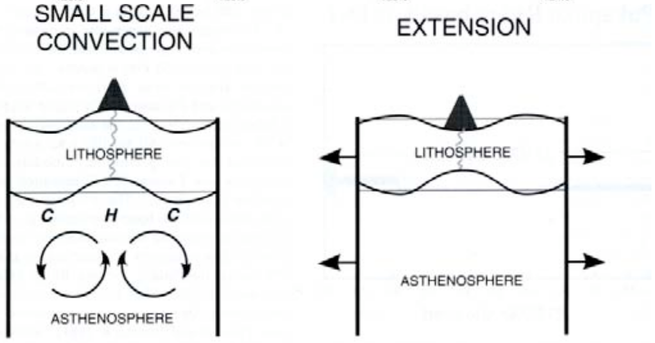


Plate boundary forces (e.g. slab pull) and mantle convection cause the rigid plates to bend and break allowing magma in the mantle to find a pathway to the sea-floor

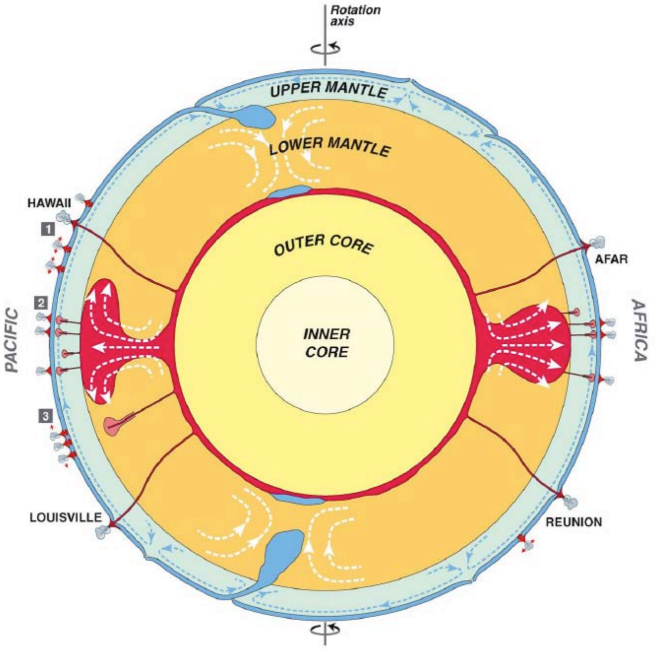
Multiple classes of seamounts

1. Hotspots

2. "Superplume" - lots of small hotspots

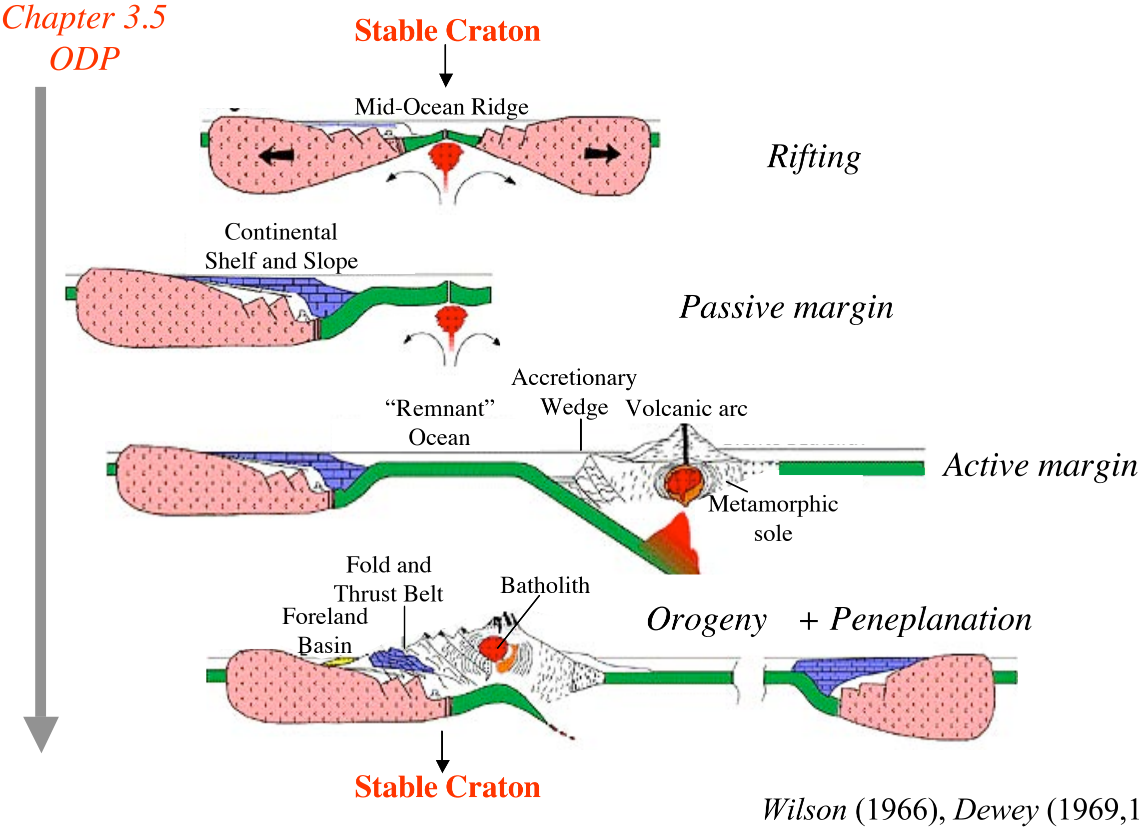
3. "Petit-spots" - plate cracks, magma pathways and fertile mantle

Courtillot (2003)



The Wilson cycle, Supercontinents and the Future World

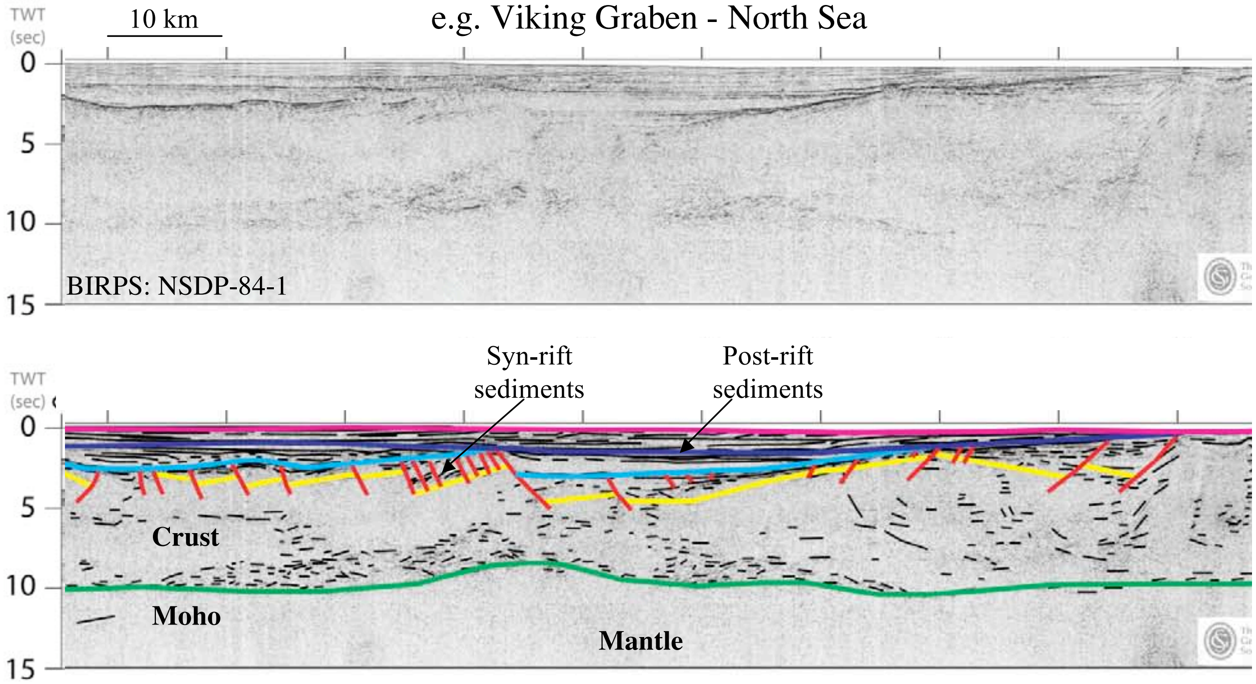
Chapter 3.5
ODP



Wilson (1966), *Dewey* (1969,1988)

Rifting

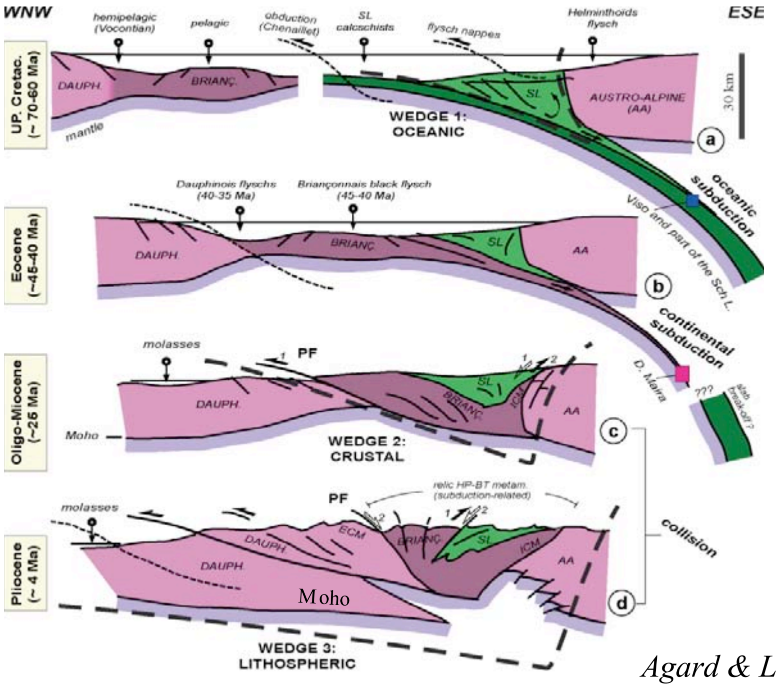
e.g. Viking Graben - North Sea



Rifting begins with the development of normal faulting and rapid subsidence in narrow half-grabens (syn-rift) in the brittle upper part of the crust and ductile flow in the lower part of the crust. It ends with a slow, broader, subsidence (post-rift).

Orogeny:

Western Alps - The schist lustrés

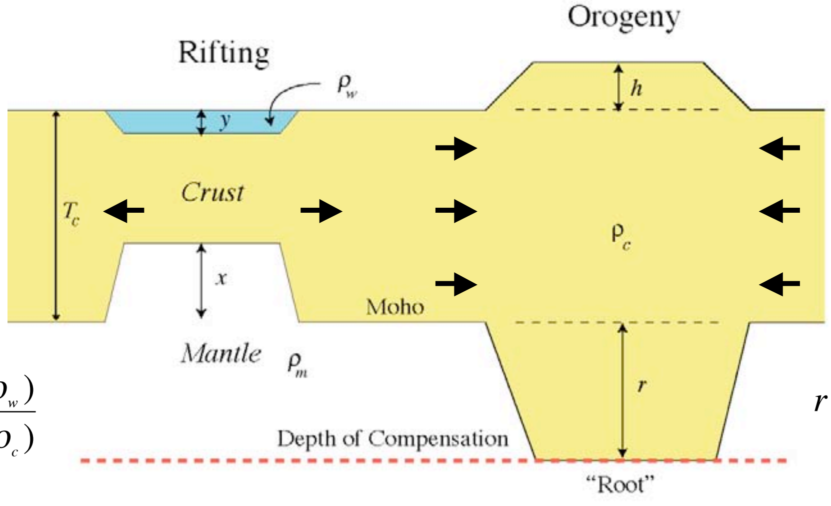


Agard & Lemoine (2005)

Orogeny begins with the development of a subduction zone and a sedimentary oceanic accretionary wedge and ends with crustal thickening, outward thrusting and the development of nappe structures

Isostasy

We can assume isostatic equilibrium and calculate the crustal thickness that results from rifting and orogeny using the subsidence, *y*, and uplift, *h*.



$$x = y\frac{(\rho_c - \rho_w)}{(\rho_m - \rho_c)}$$

$$r = h\frac{\rho_c}{(\rho_m - \rho_c)}$$

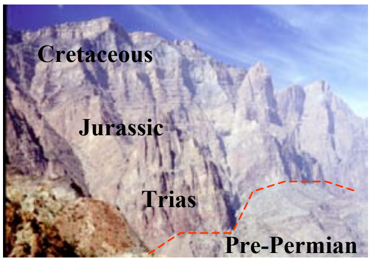
$$\text{Rifting} = T_c - x - y = T_c - y\frac{(\rho_m - \rho_w)}{(\rho_m - \rho_c)}$$

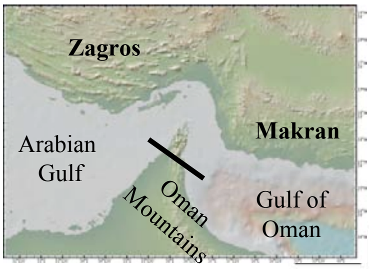
$$\text{Orogeny} = r + h + T_c = T_c + h\frac{\rho_m}{(\rho_m - \rho_c)}$$

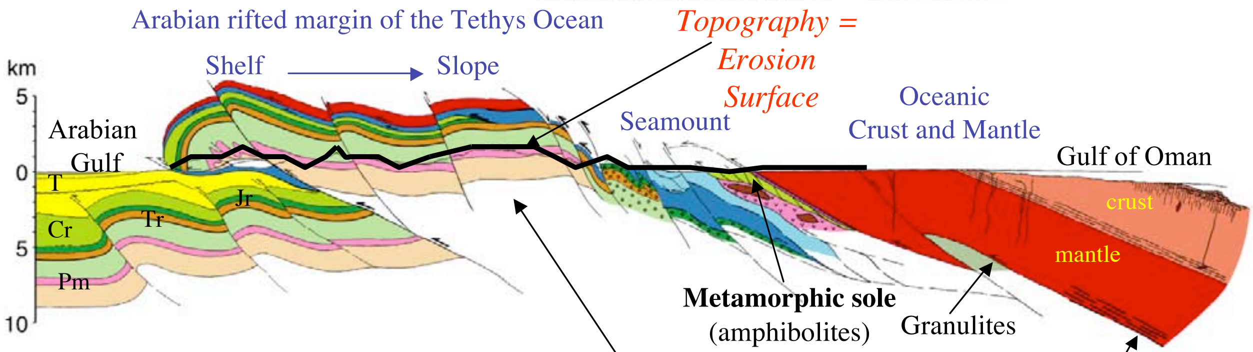
T_c = 30 km. ρ_w = 1030 kg/m^3, ρ_c = 2800 kg/m^3, ρ_m = 3330 kg/m^3

Rifted crust = 19.1 km (y = 2.5 km), Orogenic crust = 61.4 km (h = 5 km)

The Oman Mountains: The transition of a rifted margin to an orogenic belt







0 5 10 km

Vertical = Horizontal Scale

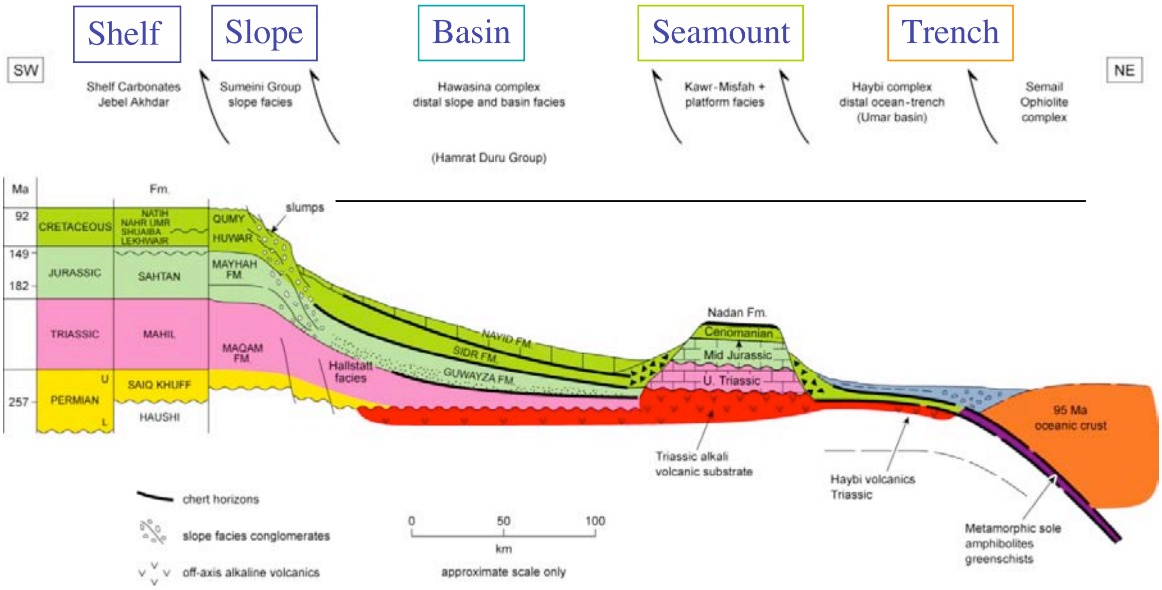
Searle (2007)

Metamorphic sole
(amphibolites)

Musandam culmination
Late Oligocene to
Miocene folding and
thrusting

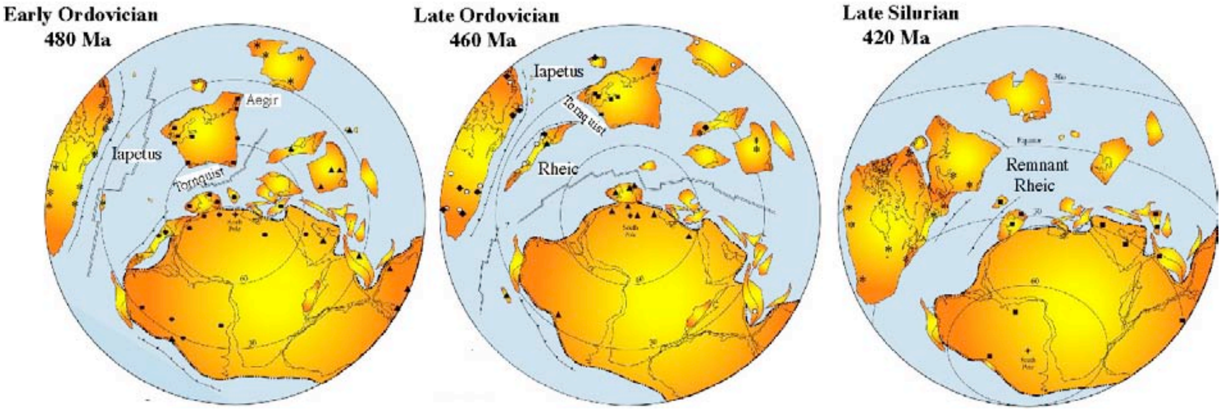
Semail ophiolite
Thrust up onto the Arabian
margin during Late
Cretaceous (95-70 Ma)

Late Cretaceous reconstruction



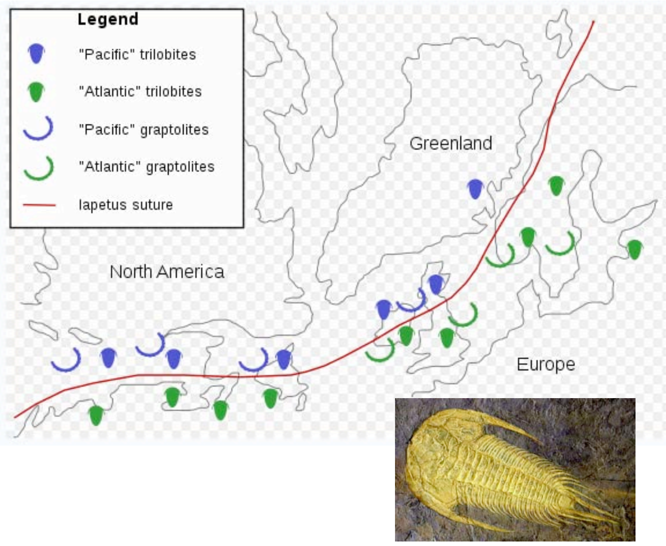
Examples of oceans that have closed

- **Iapetus** (Caledonian - Late Sil./Early Dev.)
- **Rheic** (Variscan - Late Carb./Early Perm.)
- Paleo-Tethys (Cimmerian - Late Jur./Early Cret.)
- Tethys (Alpine-Himalaya - Early/Mid-Tertiary)



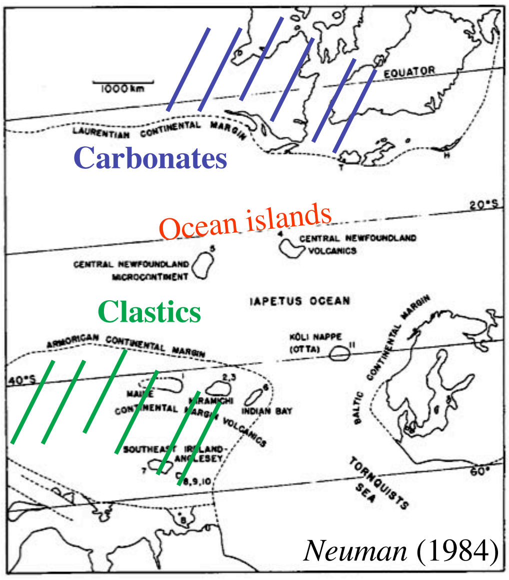
The evidence for an Iapetus Ocean…

Paleontology



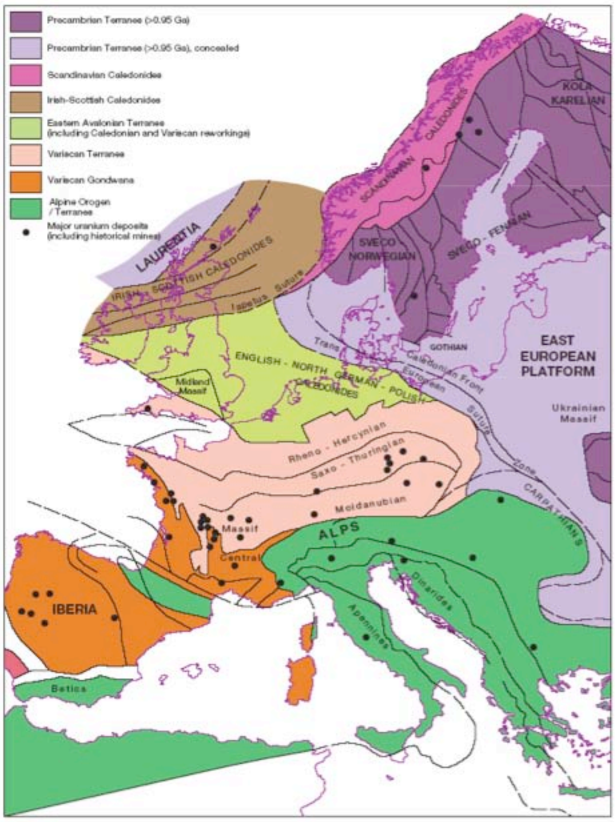
Differences of faunal assemblages and lithological associations either side of a central dividing line

Sedimentology and Stratigraphy



Neuman (1984)

Amalgamation, Terranes and Sutures

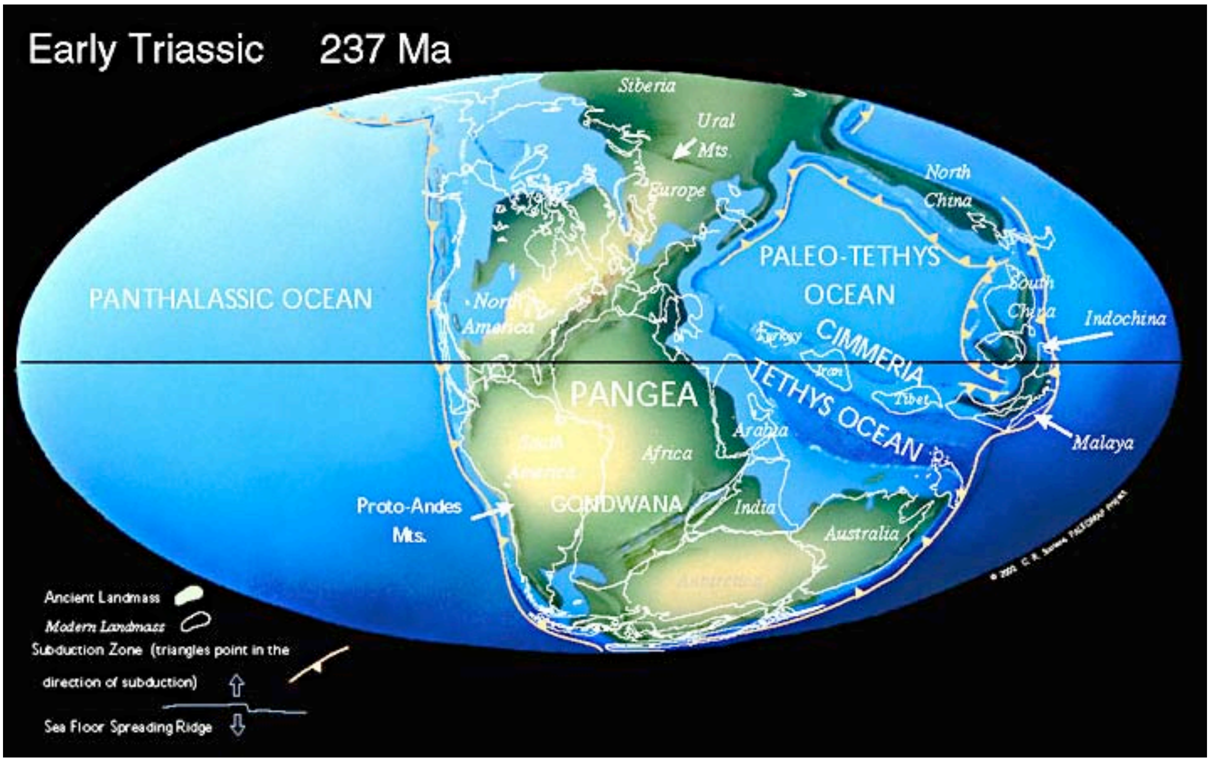


A terrane is an area possessing unique tectonic assemblages which differs from adjacent terranes and is bounded by faults.

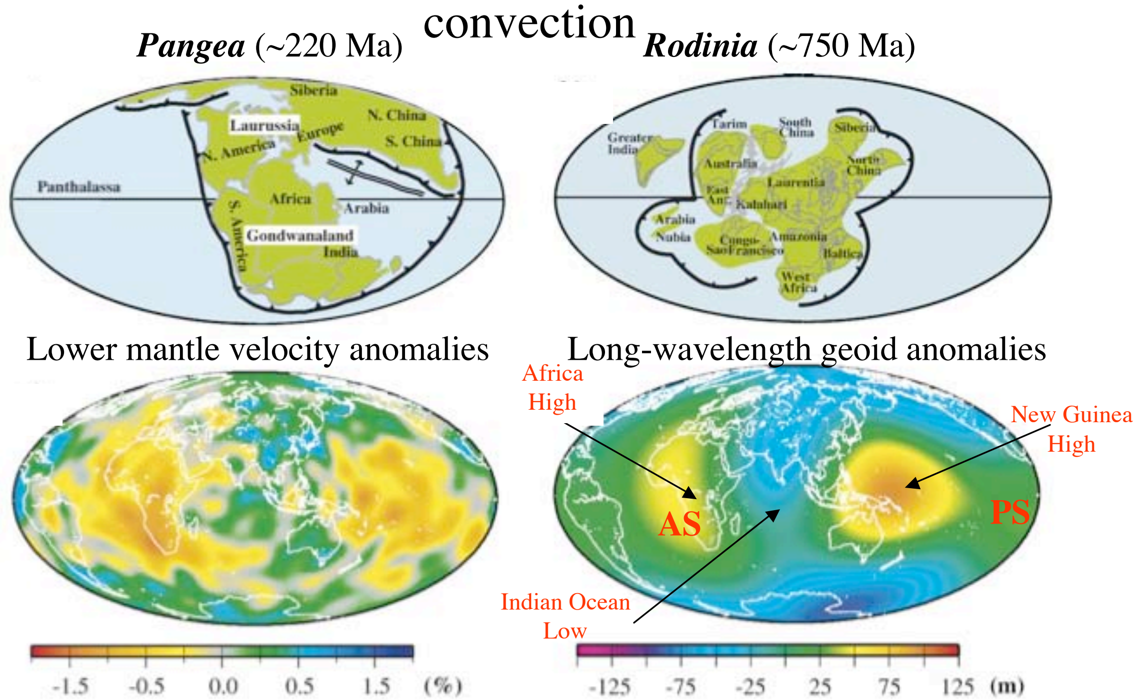
In North-West Europe Caledonian, Variscan (Hercynian) and Alpine terranes are juxtaposed as a result of successive ocean closures.

The actual join is a suture and deformation may extend for some hundreds of km either side of a suture.

Supercontinents



Continental assembly, fragmentation and large-scale mantle convection



Zhong et al. (2007)

Continents assemble over downwellings in the mantle and fragment over upwellings. The Pacific Superplume is the main upwelling system that led to the assembly of Pangea while the Africa Superplume may have caused it to fragment.

Future World

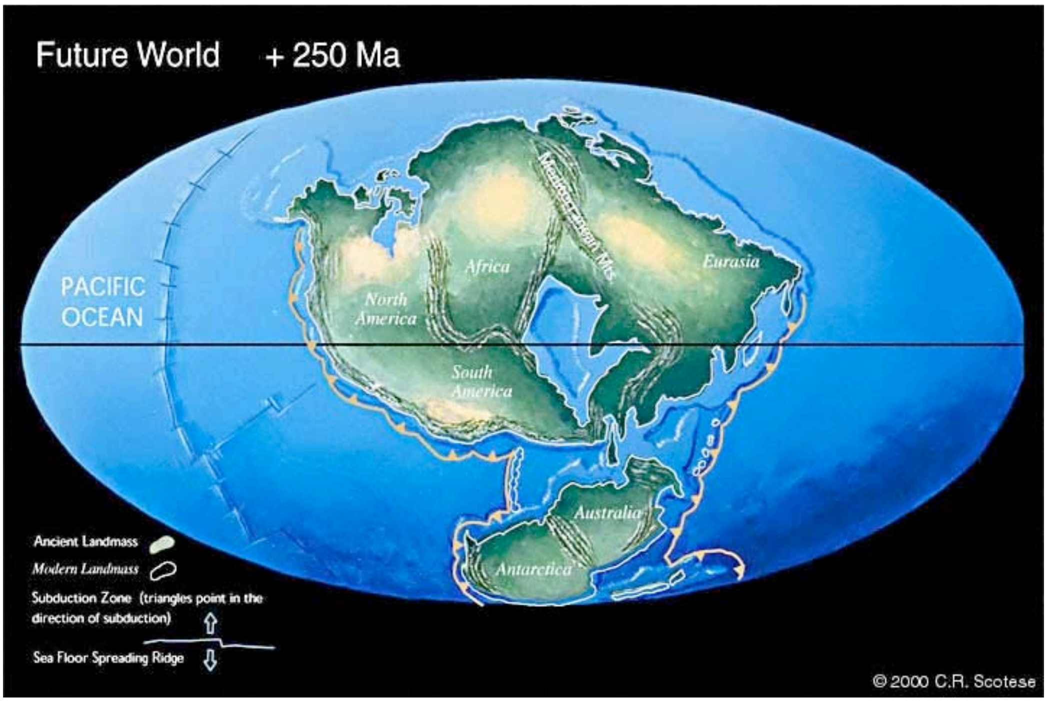


Plate Tectonics and Climate Change (See Chapter 3.5.2 - ODP)

Planet Earth

Plate Tectonics

Problem Set

Tuesday 3-4 pm, Weeks 7 and 8

Part I: Model

Figure 1 shows a hypothetical system comprising Plates A, B and C. Plates A and B are separated by a mid-ocean ridge that is spreading at a rate of 20 mm/yr. The southern end of the ridge is offset by a transform fault. Plates A and C are separated by a right-lateral strike-slip fault slipping at a rate of 30 mm/yr. The three plates intersect at a point known as a "triple junction".

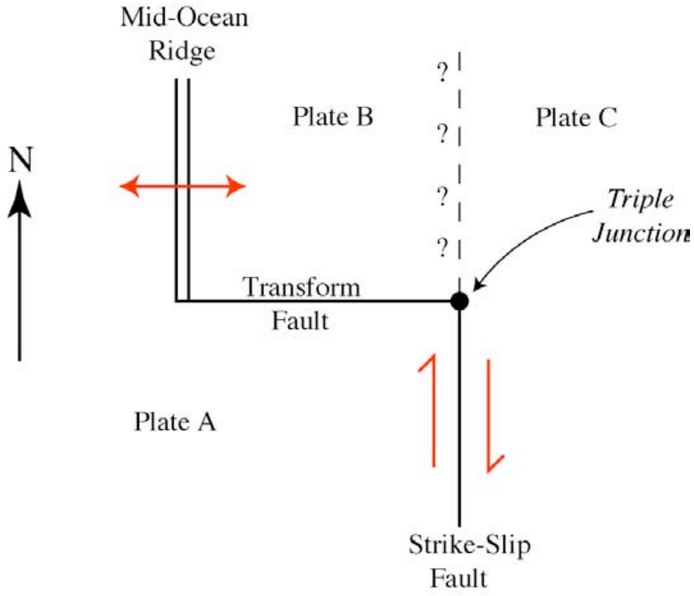


Figure 1

1. Mark on the figure the slip direction along the transform fault.
2. What is the slip rate along the transform fault?
3. Using the given motions of Plate B with respect to Plate A and Plate A with respect to Plate C calculate the motion of Plate B with respect to Plate C.
4. What is the direction (i.e. azimuth) of this motion?
5. What does the motion of Plate B with respect to Plate C indicate to you about the nature of the plate boundary that separates the two plates and the geological processes that are occurring there?
6. What is the nature of the triple junction and comment whether you think the configuration of Plates A, B and C in Figure 1 is a stable or unstable one.

Part II: Observations

Figures 2, 3 and 4 show the bathymetry/topography, oceanic crustal age and free-air gravity anomaly of the western USA region. Each map shows the historically active volcanoes (red filled triangles) and a selection of earthquakes (white filled circles) where the magnitude, depth and focal mechanism are known.

1. Use the information in the figures, together with Table 1, to determine the plate boundaries in the region.
2. Using the bathymetry map (or the tracing paper provided) plot the plate boundaries. Label the plates and indicate the relative motions between them.
3. Trace the earthquakes and size the symbol you use according to magnitude. Use different colours to delineate shallow (<35 km), intermediate (35-100 km) and deep (>100 km) earthquakes.
4. Where do the deepest earthquakes occur?
5. Discuss the pattern of historical volcanoes and the size and sense of motion of earthquakes and whether you think they are consistent with your choice of plate boundaries.
6. Calculate the average spreading rate over the past 15 Ma to the north of Cape Mendocino (CM in the figures) and then at 4 equally spaced points to the south.
7. What is the relationship between spreading rates and latitude? Explain.
8. What are the prominent E-W trending features that cross the oceanic part of the map area? How do they form?
9. The region of the seafloor marked X in the figures is shallower than the region to the north and south. Why is this? The free-air gravity anomaly, however, is about the same. Why?

Part III: Synthesis

1. Using your results, comment on how well the model predictions in Part I fit the observations in Part II.
2. Speculate on the evolution of plate boundaries in the western USA region, from the Eocene (~55 Ma) to the present day.

References

Atwater, T. (1970), Implications of plate tectonics for the Cenozoic evolution of western North America, Bull. Geol. Soc. Am., 81, 3513-3536. PDF.

Fowler, C. R. M. *The Solid Earth.* An introduction to Global Geophysics, 2nd edition, (2004), Cambridge University Press, p11-14 (Modeling three-plate systems) and p77-87 (Tectonic evolution of the Western USA/Eastern Pacific region) in particular.

Lectures 1-6, (2009), Hand-outs.

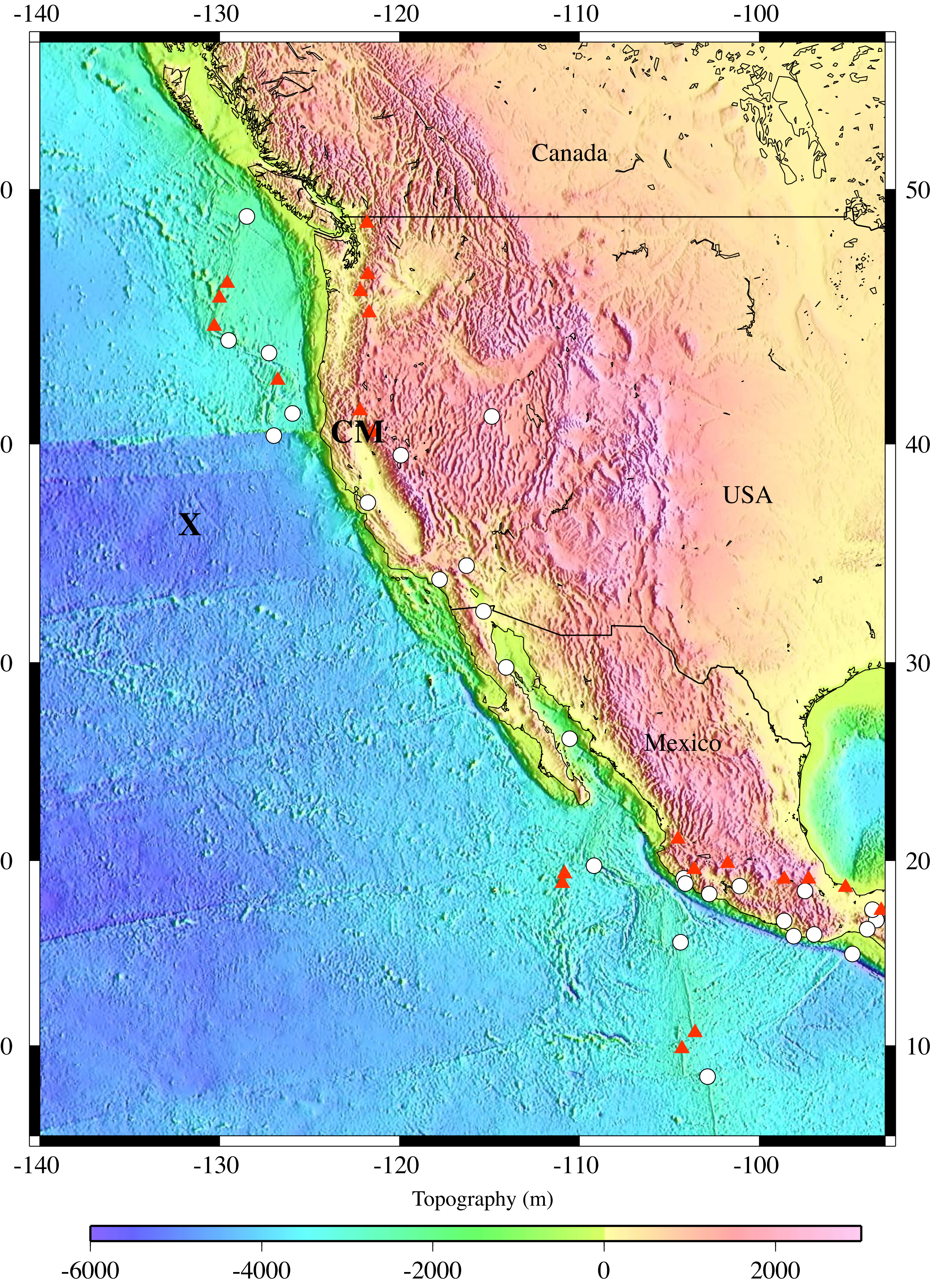
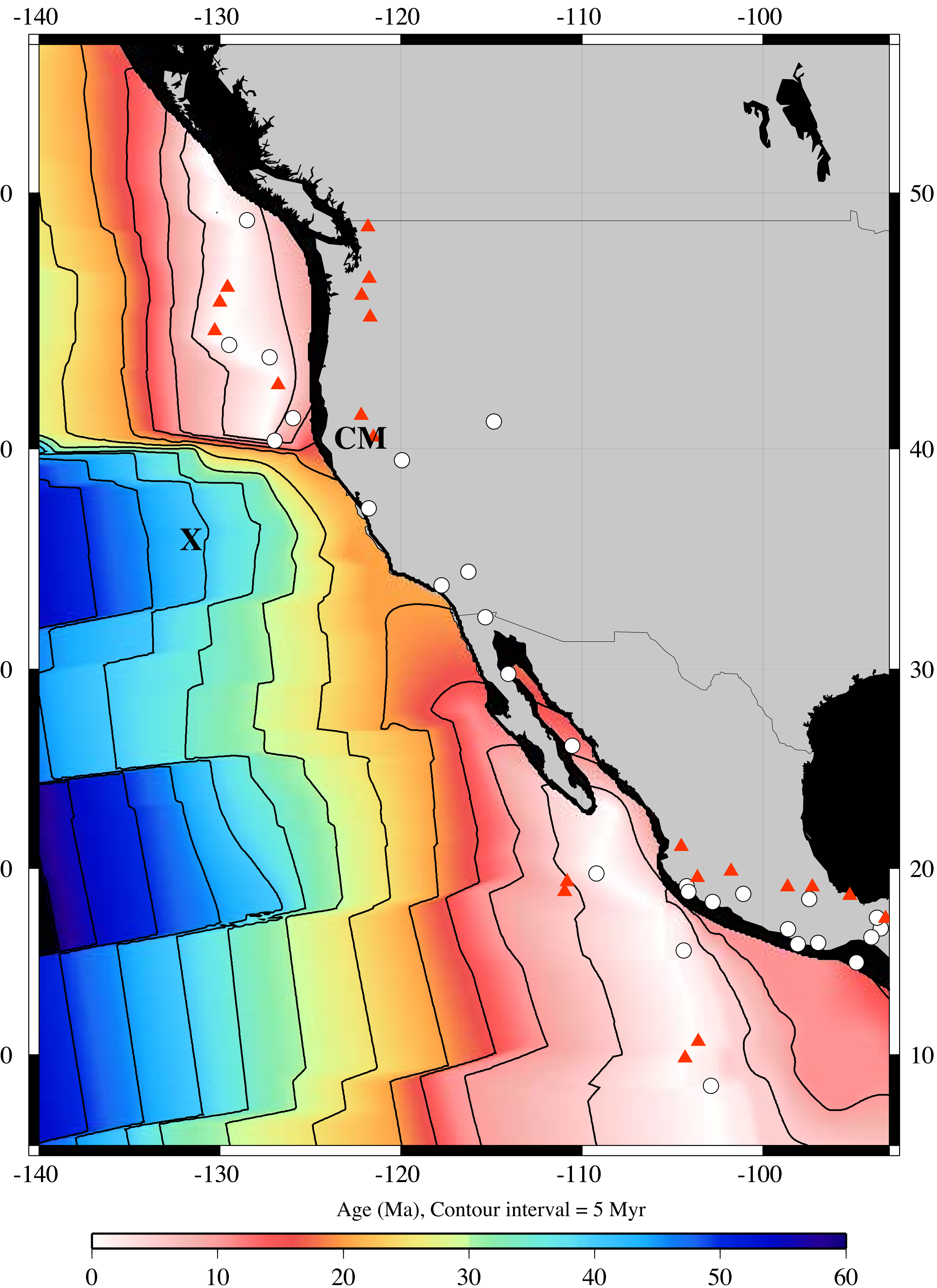
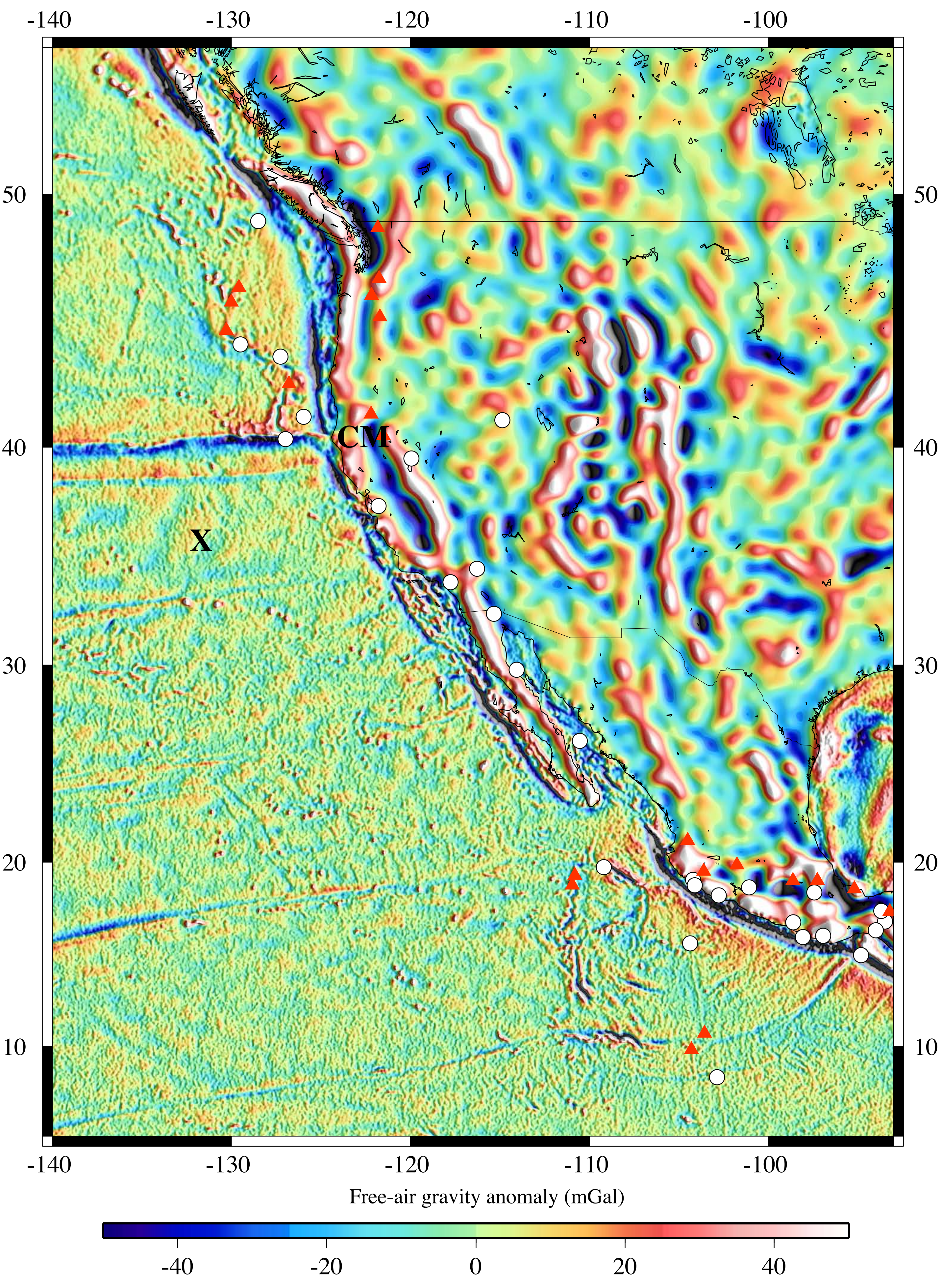

-140
-130
-120
-110
-100
50
40
30
20
10
Canada
USA
Mexico
CM
X
Topography (m)
-6000
-4000
-2000
0
2000

Figure 2



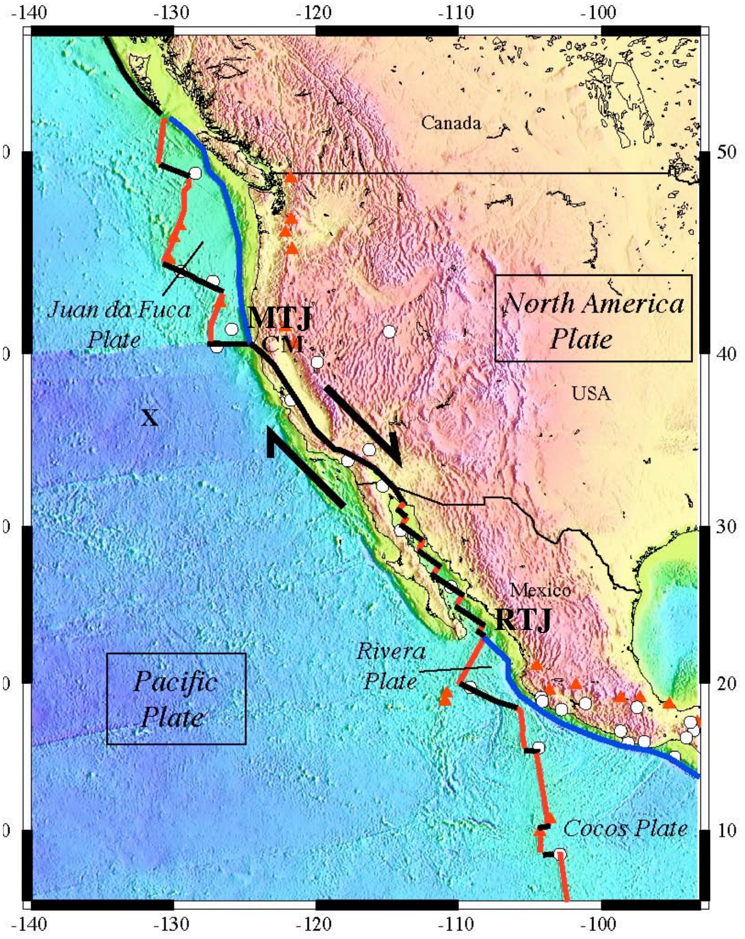
-140
-130
-120
-110
-100
50
40
30
20
10
CM
X
Age (Ma), Contour interval = 5 Myr
0
10
20
30
40
50
60

Figure 3



-140
-130
-120
-110
-100
50
40
30
20
10
CM
X
Free-air gravity anomaly (mGal)
-40
-20
0
20
40

Figure 4



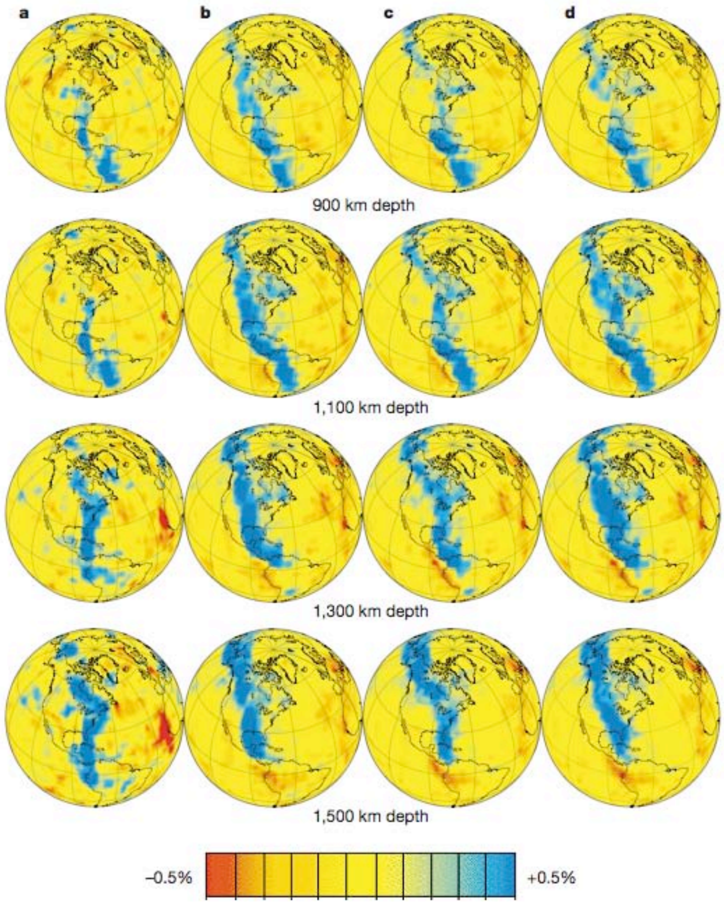
Answer Sheet: Western USA and NE Pacific - Plate Boundaries

Tectonic Evolution Movies

http://emvc.geol.ucsb.edu/animations/quicktime/sm02Pac-NoAmflat.mov

http://emvc.geol.ucsb.edu/animations/quicktime/sm03socalcities.mov

MTJ = Mendocino Triple Junction
RTJ = Rivera Triple Junction



The Fate of the Farallon Plate

Seismic tomographic data showing the present-day position of the Farallon plate beneath central and eastern USA

Bunge & Grand (2000)

Planet Earth: *Plate Tectonics*

Resources

Selected Books

Primary:

Fowler, C. R. M. *The Solid Earth*. An introduction to Global Geophysics, 2nd edition, (2004), Cambridge University Press, 685 pp. Chapters 2, 3, 9 and 10 in particular.

Rogers, N. (Editor), *An introduction to our Dynamic Planet*, (2008), Cambridge University Press, 390 pp. Chapters 3-6 in particular.

Secondary:

Le Pichon, X., J. Francheteau, and J. Bonnin (1973), *Plate Tectonics*, Elsevier, 300 pp. Long out of print, but arguably the definitive book on Plate Tectonics.

Menard, W. (1964), *Marine Geology of the Pacific*, McGraw-Hill, 269 pp. Classic text on the geology of the Pacific seafloor.

Schubert, G. (Editor) (2008), *Treatise of Geophysics*, Elsevier. Volume 6 – Crust and lithosphere dynamics. A selection of recent papers on the physical properties, structure and evolution of Earth's lithosphere. Includes a useful review chapter by P. Wessel on Plate Tectonics.

Web

Plate motion calculator: http://ofgs.ori.u-tokyo.ac.jp/~okino/platecalc_new.html
Plate reconstructions: http://www.ig.utexas.edu/research/projects/plates/

References

The following is a list (by lecture) of the references referred to on the PowerPoint slides. It is not intended as a reading list, but as an information source in case you wish to pursue particular topics in more depth.

* = copies of these references are in a reading box in the library (see Jenny for details)

Lecture 1: Plate mechanics and kinematics

Barrell, J. (1914), The strength of the Earth's crust. VI. Relations of isostatic movements to a sphere of weakness - the asthenosphere, J. of Geology, 22, 655-683.

*Burbank, D. and R. Anderson, (2001), *Tectonic geomorphology*, Chapter 5, p96 onwards in particular.

*Stein, S. and M. Wysession, (2003), *Introduction to Seismology*, *Earthquakes and Earth*, p251-253

Lecture 2: Mid-ocean ridges and extension

*Grassle, J. F. (1985), Hydrothermal vent animals: Distribution and biology, Science, 229, 713-717.

*Langmuir, C. H., and D. W. Forsyth (2007), Mantle melting beneath mid-ocean ridges, Oceanography, 20, 78-89.

Parsons, B. E., and J. G. Sclater (1977), An analysis of the variation of ocean floor bathymetry and heat flow with age, J. Geophys. Res., 82, 803-827.

*Vera, E. E., J. C. Mutter, P. Buhl, J. A. Orcutt, A. J. Harding, M. E. Kappus, R. S. Detrick, and T. M. Brocher (1990), The structure of 0- to 0.2-m.y.-old oceanic crust at 9°N on the East Pacific Rise from expanded spread profiles, J. Geophys. Res., 95, 15,529-515,556.

*Toomey, D. R., D. Jousselin, R. A. Dunn, W. S. D. Wilcock, and R. S. Detrick (2007), Skew of mantle upwelling beneath the East Pacific Rise governs segmentation, Nature, 446, 409-414, doi:410.1038/nature05679.

Lecture 3: Transform faults, fracture zones and strike-slip faults

Detrick, R. S., R. S. White, and G. M. Purdy (1993), Crustal Structure of North Atlantic Fracture Zones, Reviews of Geophysics, 31, 439-458.

*Petrunin, A., and S. V. Sobolev (2006), What controls thickness of sediments and lithospheric deformation at a pull-apart basin?, Geology, 34, 389-392; doi:310.1130/G22158.22151.

*Pockalny, R. A. (1997), Evidence of transpression along the Clipperton Transform: Implications for processes of plate boundary reorganisation, Earth and Planet. Sci. Lett., 146, 449-464.

*Sandwell, D. T. (1984), Thermomechanical evolution of oceanic fracture zones, J. Geophys. Res., 89, 11,401-411,413.

Lecture 4: Deep-sea trenches and compression

Bangs, N. L. B., G. F. Moore, S. P. S. Gulick, E. M. Pangborn, H. J. Tobin, S. Kuramoto, and A. Taira (2009), Broad, weak regions of the Nankai megathrust and implications for shallow coseismic slip, Earth and Planet. Sci. Lett., 284, 44-49.

*Calvert, A. J., S. L. Klemperer, N. Takahashi, and B. C. Kerr (2008), Three-dimensional crustal structure of the Mariana island arc from seismic tomography, J Geophys. Res., 113, doi:1029/2007JB004939.

*Hacker, B. R., S. M. Peacock, G. A. Abers, and S. D. Holloway (2003), Subduction factory 2. Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration reactions?, J Geophys. Res., 108, doi:10.1029/2001JB001129.

*Ranero, C. R., J. Phipps_Morgan, K. McIntosh, and C.Reichert (2003), Bending related faulting and mantle serpentinisation at the Middle America trench, Nature, 425, 367-373.

*Taylor, B., and F. Martinez (2003), Back-arc basin basalt systematics, Earth and Planet. Sci. Lett., 210, 481-497.

Zhao, D., Y. Xu, D. A. Wiens, L. Dorman, and S. Webb (1997), Depth Extent of the Lau Back-Arc Spreading centre and its relation to Subduction Processes, Science, 278, 254-257.

Lecture 5: Oceanic islands, seamounts, mid-plate swells and mantle plumes

*Courtillot, V., A. Davaille, J. Besse, and J. Stock (2003), Three distinct types of hotspots in the Earth's mantle, Earth Planet. Sci. Letts., 205, 295-308.

*Funck, T., and H. U. Schmincke (1998), Growth and destruction of Gran Canaria deduced from seismic reflection and bathymetric data, J. Geophys. Res., 103, 15,393-315,407.

*Hirano, N., A. A. P. Koppers, A. Takahashi, T. Fujiwara, and M. Nakanishi (2008), Seamounts, knolls and petit-spot monogenetic volcanoes on the subducting Pacific plate, Basin Research, doi:10.1111/j.1365-2008.00363.x, 1-11.

*Tarduno, J. A., R. A. Duncan, D. W. Scholl, R. D. Cottrell, B. Steinberger, T. Thordarson, B. C. Kerr, C. R. Neal, F. A. Frey, M. Torli, and C. Carvallo (2003), The Emperor Seamounts: Southward motion of the Hawaiian hotspot plume in Earth's mantle, Science, 301, 1064-1069.

Lecture 6: Wilson cycle, supercontinents and the future world

Agard, P., and M. Lemoine (2005), Faces of the Alps: Structure and geodynamic evolution, Commission for the geological map of the world (CCGM), 48pp.

*Dewey, J. F. (1969), Continental margins: A model for conversion of Atlantic type to Andean type, Earth and Planet. Sci. Lett., 6, 189-197.

*Dewey, J. F. (1988), Extensional collapse of orogens, Tectonics, 7, 1123-1139.
Searle, M.P. 2007. Structural geometry, style and timing of deformation in the Hawasina Window, Al Jabal al Akhdar and Saih Hatat culminations, Oman Mountains. GeoArabia, 12, 99-130.

*Wilson, J. T. (1966), Did the Atlantic close and then re-open?, Nature, 211, 676-681.

*Zhong, S., N. Zhang, L. Zheng-Xiang, and J. H. Roberts (2007), Supercontinent cycles, true polar wander, and very long-wavelength mantle convection, Earth Planet. Sci. Letts., 261, 551-564.