MID-OCEAN AREAS – SHALLOW FOCUS

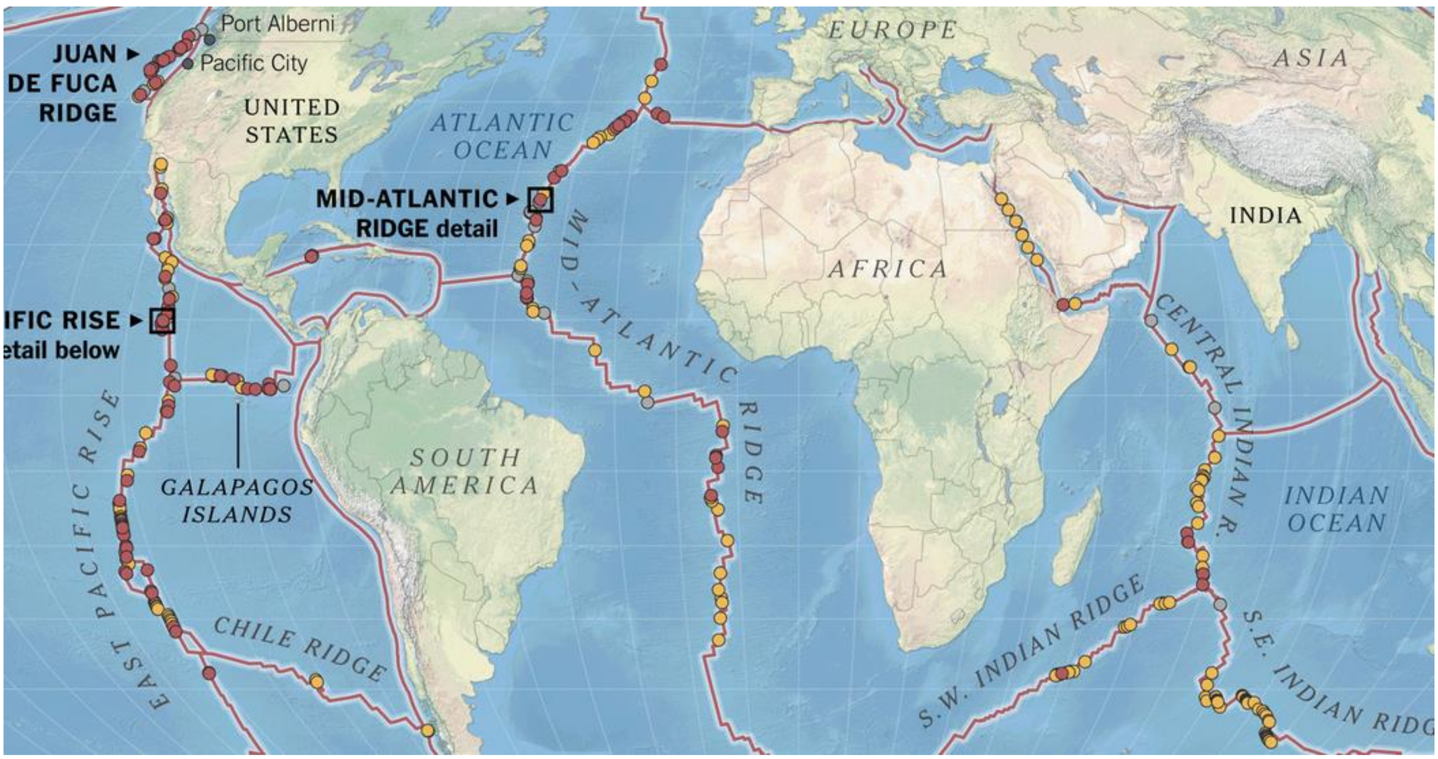
In these cases, **earthquakes are confined to the lithosphere**, the **brittle part** of the crust/upper mantle. As these are **shallow focus earthquakes**, the **lithosphere** must be **thin under the MOR**. Underlying, less rigid **asthenosphere (plastic)** moves steadily beneath without sudden displacements and therefore **does not produce any earthquakes**. Most earthquakes are **low magnitude** (2 or less) and occur almost **every day.**

1. MAGMA AT MOR– SHALLOW FOCUS

Magma rises up at **an MOR and sub aqueous eruptions of basaltic** lava form **pillow lavas** or **flood (plateau) basalts**. The **high heat flow** indicates this.
When magma moves up , it **vibrates to produce harmonic waves** (similar to the wave patterns of instruments that use fundamental modes of vibration).

These **shallow focus earthquakes** are small and can be **detected. It** is the same phenomenon that makes old pipes rattle and bang as water flows through them.

The **rising magma** along the normal faults of an early forming axial rift system can also result in **harmonic vibrations**.

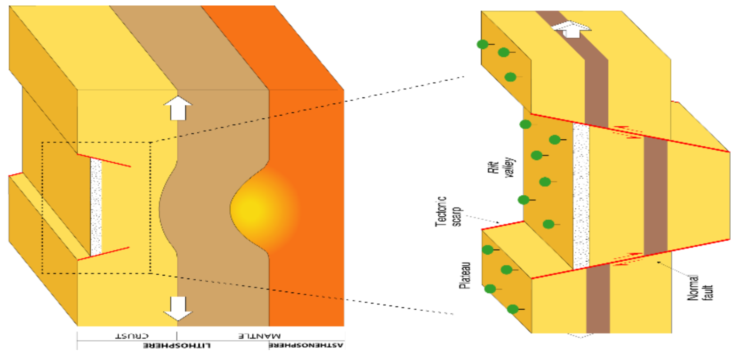


South America separated from Africa 180 million years ago. The divergent margin was in the center of the **supercontinent Gondwanaland**. This split along a **major rift system**. Widespread extrusions of **basalt plateaus** accompanied the split. This **rift valley widened** and **subsided below sea level**, allowing the **ocean to flood** in. As the **separation continued**, the **continental crust separated** and became **thinner,** leaving wide **continental slopes** on the edge of each plate. The **thinned continental** crust finally split **and was filled with basalt**, forming the beginning s of the **ocean crust**. Sea floor spreading began as new crust is generated at the MOR (**constructive boundary** is the other name for this boundary).

*All divergent margins create crust.

2. AXIAL RIFT SYSTEM– *SHALLOW FOCUS*

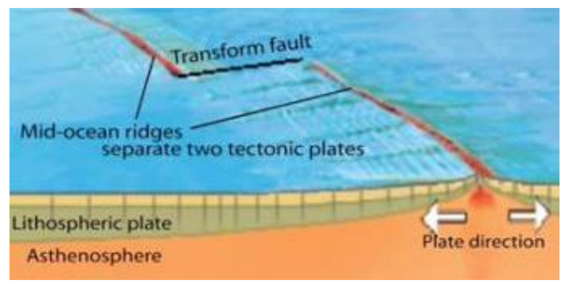
Magma rising up at an **MOR** forming on a continental plate induces **tensional forces** as the **crust arches upwards**. **Normal faults develop** facing inwards and the ground between **subsides**. **Movement along the normal faults** (usually **subsidence**) causes **shallow focus earthquakes**.



3. TRANSFORM FAULT – *SHALLOW FOCUS*

The **oceanic crust spreads** away from the MOR in sections since there are **different rates of movement** within the plate. **Transform faults** develop to allow for the rigid plates to have different rates of movement.

They are common **at 90° to a MOR** and **horizontal movement along** them causes **shallow focus** earthquakes.



<u>Examples of Divergent Margins</u>

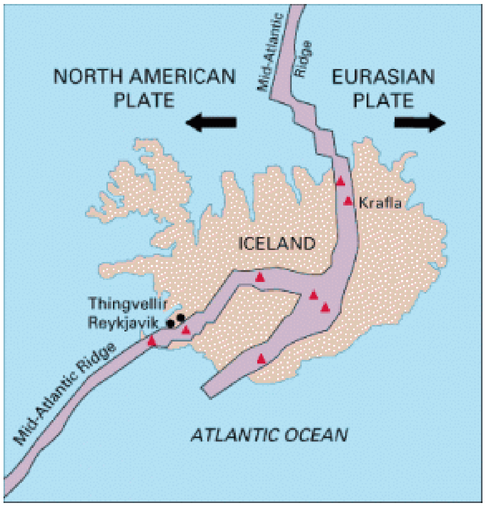
Divergent plate margins are locations where plates are moving away from one another. **Rising convection currents** in the mantle **push up** and move along the bottom of the lithosphere, **flowing sideways beneath** it. This **lateral flow** causes the lithosphere plate above to be dragged along in the direction of flow.

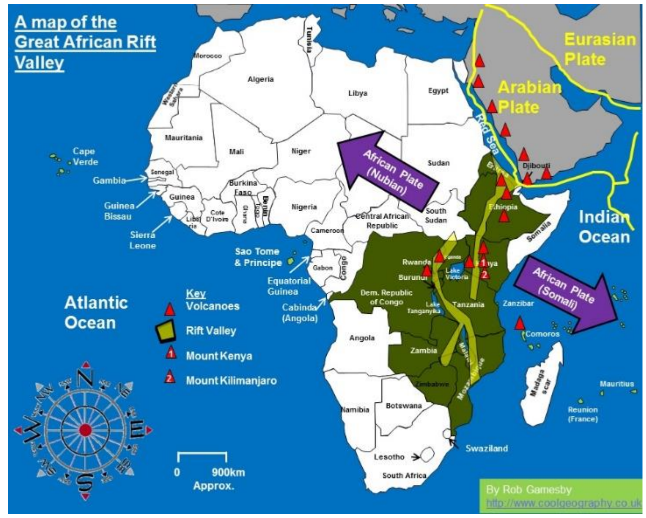
In this area where the convection current is moving up, the **overlying plate is being stretched thin, breaks and pulls apart**, forming a **Mid-Ocean-Ridge (MOR).** Extensional forces stretch the lithosphere and produce a **deep axial rift.**

When plates start to move apart **pressure is reduced**. This means that **peridotite of the mantle** can **partially melt** and some moves up by **diapiric action.** The **magma accumulates** below the **ridg**e or finds its way up through **feeder dykes** (typically along normal faults) until it reaches the **surface or sea floor and** becomes a **fissure lava flow**.

The Mid-Atlantic ridge is a good example of a divergent margin. For **most** of its **7000km length** it is below sea level, but, Iceland is **above sea level** due to the location coinciding with a **hot spot.**

The **East African Rift Valley** may become a **new ocean in time**. The **northern part** of this rift system, **in the Red Sea between North Africa and Arabia**, is now a **divergent plate margin** where **new basaltic ocean crust** is being formed.
The split **started in the Eocene** (about 40 Ma) and **accelerated during the Oligocene** about 23 Ma). The **sea is still widening** and it is likely **it will become an ocean** in perhaps another 50 Ma.



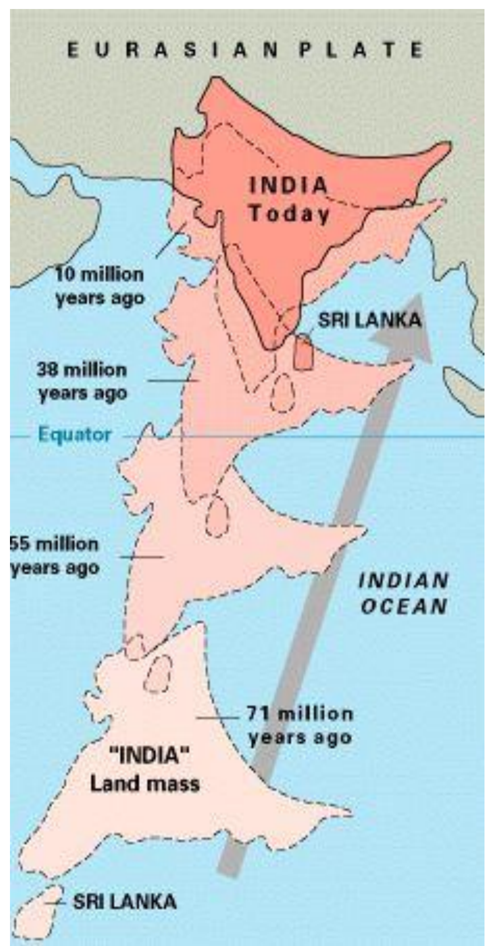


CONVERGENT MARGINS – VARYING FOCUS

1. CONTIENNTAL-CONTINANTAL COLLISION BOUNDARY– *SHALLOW TO INTERMEDIATE FOCUS*

Where two **continents collide** (neither can sub duct below the other), such as **India (Indian plate**) and **Asia (Eurasian Plate**).

Compressional forces act to deform the crust and form an **orogenic belt** with a **chain of fold mountains** (**Himalayas and Tibetan Plateau**). The Indian Plate is still being pushed to **the North** from the **Indian Ocean MOR.** There will be **shallow to medium focus** earthquakes occurring **along deep faults.** The **Collision** between **the Indian plate** and the **Eurasian plate** began around 60 million years ago and continues today.



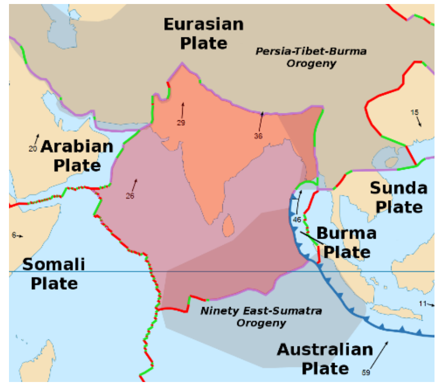
In the past (~60 Ma to 10 Ma) there was an Ocean floor subducting beneath the Eurasian plate – **The Tethys Ocean** was between Indian and Asia.

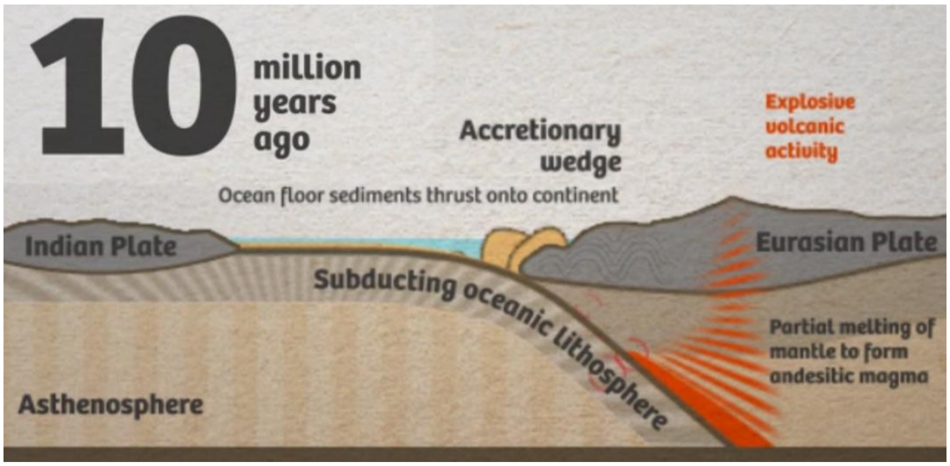
As the Tethys Ocean floor had completely sub ducted below the Eurasian plate, the collision between the continental part of the Indian plate and the continental Eurasian plate began (**Tethys Ocean** closed).

Continental crust was thickened due to **folding and faulting** by **compressional forces** pushing up the **Himalayas** and the **Tibetan Plateau**. The thickening of the continental crust marked the end of volcanic activity in the region as any magma moving upwards (**diapiric action**) would **solidify before** it could reach the **surface.**

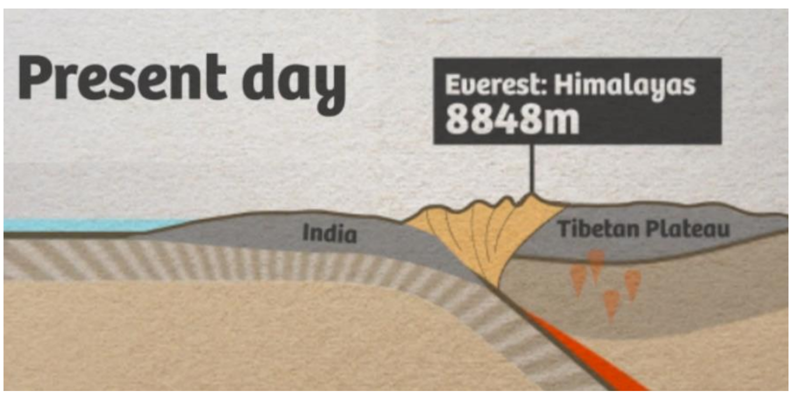
The continental crust here is twice the average thickness at around **75 km.**

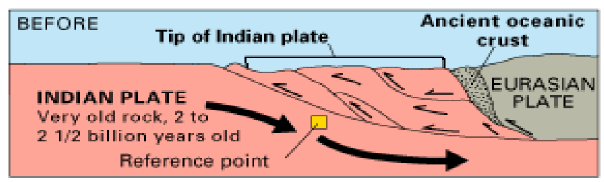
Most of the **thick sediments** on the **Indian margin** of the **ocean were scraped off** and **accreted** onto the **Eurasian continent** in what is known as an **accretionary wedge.**

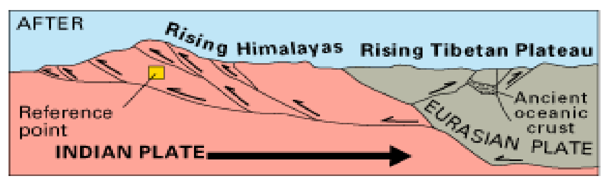




Accretionary wedge = a **zone of deformed sediment** made up of **thrust slices scraped off** a **subducting oceanic** plate and added **onto** the over-riding plate. (these form majority of Himalayas).







Convergent continental-continental continued

Two continental plates of similar composition and density meet under the Himalayas. The Indian plate has spent the **past 100 million years as an island**, drifting **northwards away from Africa and Antarctica (when it was part of Gondwanaland 180 Ma**). Movement was **initially slow** but has **increased in past 60 Ma**. Maximum rate of 19cm per year until it **collided with Asia (Eurasian** plate).

Subduction soon stopped as densities were so similar and the **ocean sediments occupied** the decreasing space between the advancing plates. These were **crumpled and intensely metamorphosed**. These ocean sediments from an **accretionary wedge** of thrust slices scrapped form the ocean crust. Uplift has meant they now form the **Himalayas**. The rest of the **ancient ocean subducted below** without the chance to form magma to feed volcanoes. Intense levels of heat and pressure have resulted in some **partial melting** of continental crust but the rising magma (silicic) can't reach the surface due to depth.

No magma feeds volcanoes here. The **base of the continent began to melt** to form **viscous magma (silicic)** and lower **temperature (650-800 C)**. This slowly rise through continental crust to form **granite batholiths as it cools gradually**.

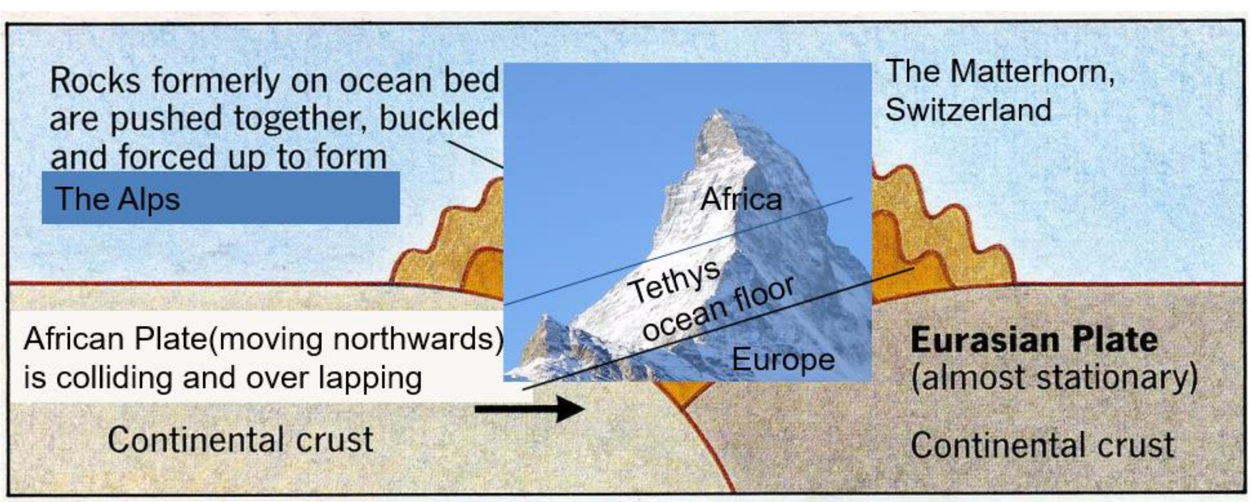
Summary Table					
Magma Type	Solidified Rock	Chemical Composition	Temperature	Viscosity	Gas Content
Basaltic	Basalt	45-55 SiO_2 %, high in Fe, Mg, Ca, low in K, Na	1000 - 1200 °C	Low	Low
Andesitic	Andesite	55-65 SiO_2 %, intermediate in Fe, Mg, Ca, Na, K	800 - 1000 °C	Intermediate	Intermediate
Rhyolitic	Rhyolite	65-75 SiO_2 %, low in Fe, Mg, Ca, high in K, Na.	650 - 800 °C	High	High

The **Indian plate** (**subducted ocean part 2.9 g/cm3**) is less dense than the **surrounding mantle** into which it was forced (**3.3 g/cm3**). The **added buoyancy** of this plate means the Himalayas are **elevated even more.**

Fossilized sea creatures such as ammonites can be found at the top of the Himalayas.

Another case study is The Alps:

This is slightly Westward, where the **African plate is colliding with the Eurasian plate**. Once again the **Tethys ocean floor** has been **subducted beneath the Eurasian** plate and is slightly **more buoyant** than the mantle so has caused u**plift**. Moreover, the continen**tal part of the African plate has now collided**, as the Tethys ocean has shortened/subducted, **with the Eurasian plate**. The **scraping off of the ocean floor sediments** has formed a buildup of **thrust slices called an accretionary wedge**. This forms the Alps too (**many nappes**). Further c**ompression** of the two continental plates has **uplifted ophiolites into the orogeny too**. The Alps are a highly complex regime comprising both **ophiolites and nappes, as well as high grade metamorphism, faulting and folding**.

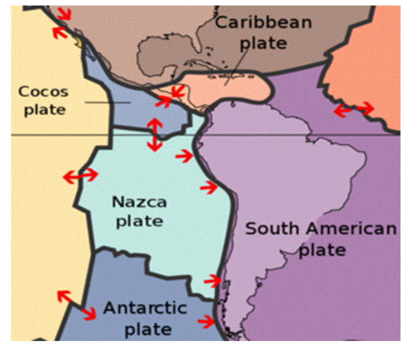


2. SUBDUCTION ZONES– *SHALLOW/MEDIUM/DEEP FOCI (CONVERGENT OCEANIC-CONTINENTAL)*

Where an oceanic plate meets a continental plate, the **denser ocean plate sub ducts below**. Earthquakes have a **shallow focus** under the **deep-ocean trench** and along the o**ceanic sides of the fold mountains** (e.g. **Nazca plate** colliding with the **South American** plate to from the orogenic belt – Andes mountain range along Pacific Coast). The earthquakes occur due to friction between the plates.

The **Benioff zone** is the sloping plane along which an oceanic plate sub ducts below a continental plate causing earthquakes of **increasing depth of foci**. Further inland, the depth of focus increases. The Benioff zone typically **slopes at 45°** and is marked by the start of the oceanic trench.

The **Benioff Zone (active zone) is present** beneath the full **length of mountain ranges (**Peru and Chile experience some of the **most devastating earthquakes**). The Benioff zone is also present under island arcs. Rising magma under island arc causes shallow focus earthquakes.



The inclined boundary between the plates, starting at the trench and ending where the subducting plate melts, is an active zone of stress and displacement.

Largest earthquake was in 1960, magnitude **9.5** in Chile, near Valdivia

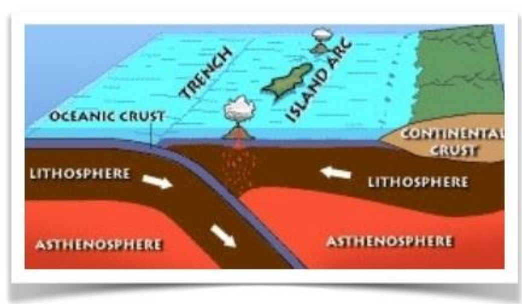
EVIDENCE FOR CONVERGENT MARGINS

- ✓ **Ocean-continental**: Collision of the Nazca plate and South American to form Andes.
- ✓ **Oceanic-oceanic**: the collision of the Pacific plate with the Eurasian plate in Japan (Japanese Alps) .
- ✓ **Continental-continental**: Collision of Indian plate with Eurasian plate (Himalayas/Tibetan Plateau).

Ocean always descends as it is made of denser basalt (2.9 g/cm3 compared to 2.7 g/cm3) and continent I lighter granite. Ocean crust is older and colder too.

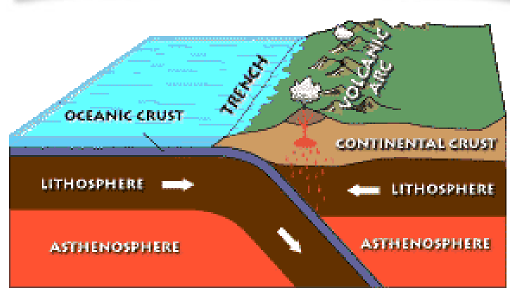
1. Heat flow anomalies

Heat flow of both **oceanic-oceanic** (OC-OC) and **oceanic-continental** (OC-CC) show the same pattern. There is a **negative anomaly at the trench** where the **cold lithosphere is subducting** and a **positive anomaly** at the **island arc or volcanic belt** where **magma** is being intruded.



2. Volcanic activity

As the **subducting plate heats up** there is **partial melting** along the top surface of the descending **ocean crust**, producing **basaltic magma**. This is **less dense** than the surrounding material and so **rises (as diapirs)** to form **volcanoes in an island arc or chain in a continent**. However, basaltic magma is at a temperature of 1200°C and as this rises through



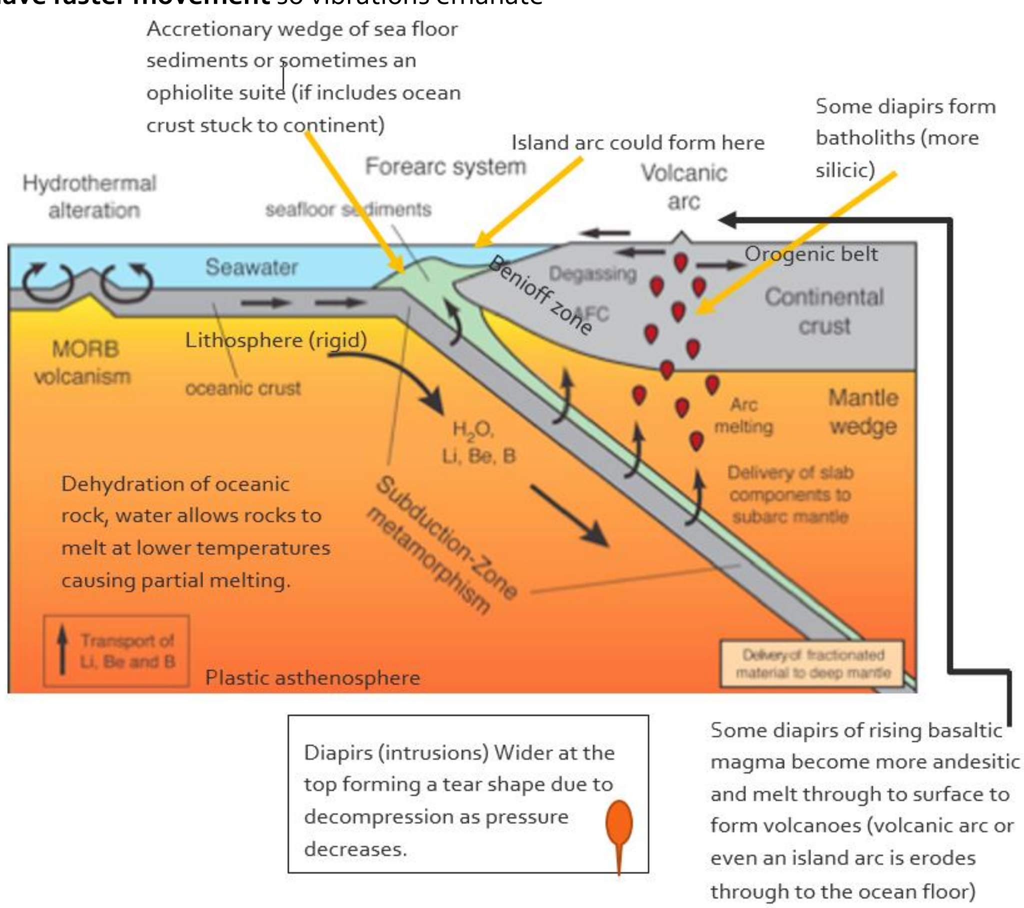
silicic continental crust, it causes partial melting and some mixing of magma may occur (magma assimilation) to give the intermediate rock andesite.

3. <u>Batholiths</u>
Where the **continental curst is melted** by uprising magma from the oceanic plate, the **different magmas** have **different viscosities** so often **remain separate**. The **melted silicic material** will go to form **large batholiths** deep below fold mountains (as it melts a lower **temperate** and **cools before diapirs can reach the surface**).

4. <u>Trenches</u>
Trenches are **arranged parallel to the edge** of a subduction **margin**. They are **linear, long narrow features** running along the zone where a **oceanic plate is sub ducted** (paralleled to the edge of the plate) and form some of the **deepest parts** of the Earth's surface (**<11km**).

5. <u>Fold mountains/orogenic belts</u>
Fold mountains form on the **edge of continents paralleled to the subduction** zone. They are **compressional features** made of **folded or faulted** sediments that have been **scrapped off the descending plate** onto the **non- subducting plate (accretionary wedge**). **High pressures** and **temperatures** at convergent plate margins mean rocks are **regionally metamorphosed**.

6. <u>Benioff zone</u> As the oceanic plate **subducts** the plane along which it does this is the **Benioff zone, a 45°** slope along which earthquakes of **increasing depth of foci occur.** AT higher levels in the crust where subduction zones being the shallow focus to intermediate focus earthquakes are caused by **friction along the boundary between the plates**. **Deeper down/further inland** the earthquakes are caused by the **interior parts** of the subducting plate remaining **rigid and cold** but the outer **parts partially melting so moving easier**. The edges **have faster movement** so vibrations emanate



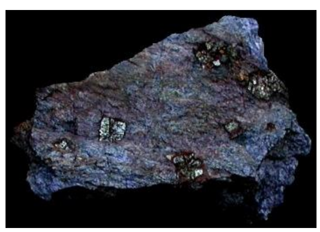
All the processes occurring at an oceanic-oceanic is the same as at oceanic-continental only the silicic material changes magma:

1. Magma rising from the subducting oceanic plate is at **high enough temperature (1200C basalt/mafic**) to cause **partial melting of some of the continental crust** that it **assimilates and passes through**. As the **mafic minerals react** with magma the composition **changes down the reaction series in steps** and **silicic magma will rise to the surface** to from **explosive rhyolitic volcanoes** or **even batholiths** if it cools before reaching the top**.**

Some **intermediate volcanoes** (**strato volcanoes of andesite**) may form if there are larger volumes of **mafic magma rising up.** Andes = andesitic strato volcanoes.

2. **Large batholiths** are intruded deep in the core of fold mountains. R**emember silicic magma is viscous and cooler (600C to 800C).**
3. **Compression of the continental crust**, **scrapped of sediments** from the ocean plate form an **accretionary wedge** that compresses ("and also the buoyancy of the oceanic plate compared to the mantle" – this is more so and continent-continent) will all result in **formation of fold mountains**.
4. The **orogenic belt of mountains** involves **folds, faults major thrusts, nappes and overfolds**.
5. The **continental crust shortens laterally** and therefore **extends vertically** as high mountains with **deep roots**, adding to **any uplift caused by the oceanic plate** forcing its way under the continental plate.
6. Many of the **rocks in the deeper part of the chain** will be **regionally metamorphosed** by heat and pressure. Migamatite, Gneiss in the core while grade gets lower outwards from (green) schist to slate.

   NOTE:
   Green schist is lower grade regional (low heat + pressure, e.g. chlorite schist is a type).
   Blue schist forms from a basaltic rock (containing glaucophane) under higher pressures but lower temperatures (burial metamorphisms at ocean trench).



7. Sections of former oceanic crust may be broken off at the top of the subduction zone, trapping an ophiolite suite within the fold mountains.

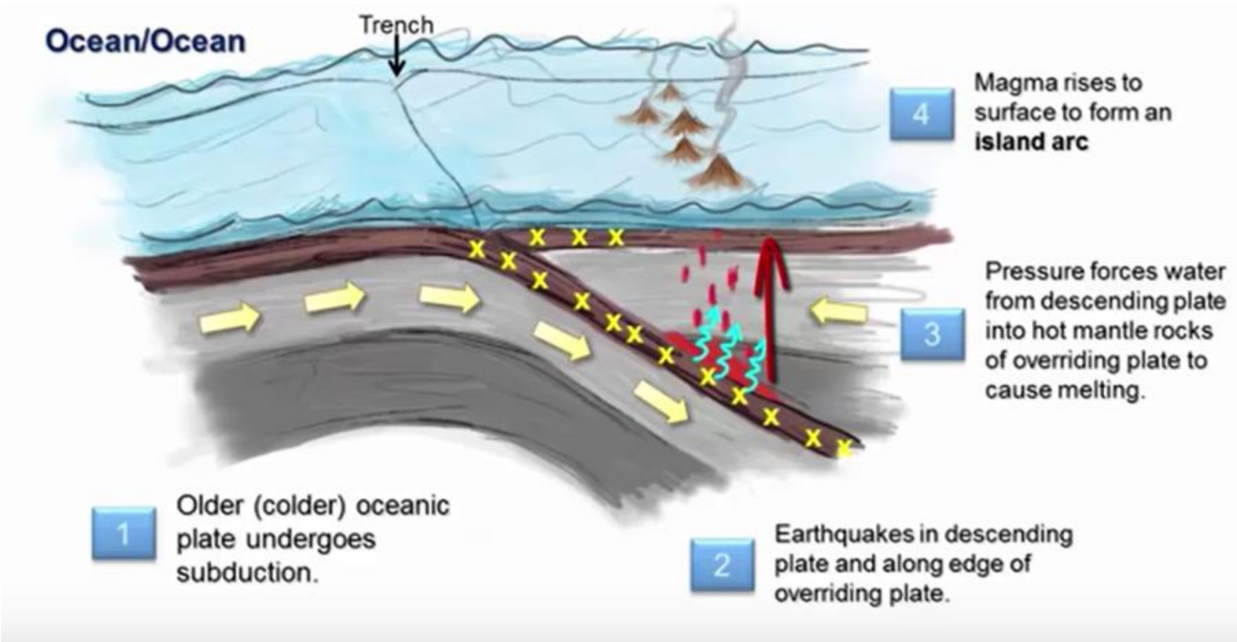
The **Andes fold mountains are over 5000m high** and **7000km long**. There are some of the world's largest **volcanoes** too. Area is prone to **earthquakes,** epicenters close to **Chile-**

3. COLLISION ZONES– SHALLOW/MEDIUM/DEEP FOCI (CONVERGENT OCEANIC-OCEANIC)

Case Study- Japan **(Pacific plate subducting below the Philippines plate)**

1. Along the length of the coast of Japan there is a **deep ocean trench**.
2. There are **shallow to deep focus** earthquakes.
3. There is an arc of **island volcanoes**. The islands are made of **volcanic, not continental** material.

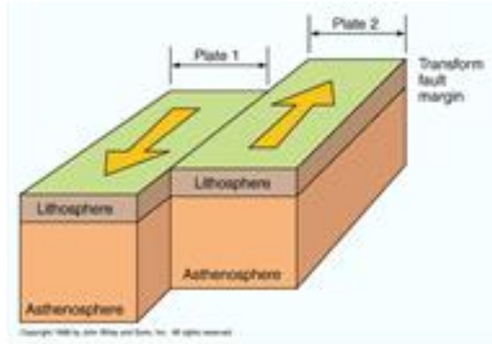
The older, denser and colder ocean crust (Pacific) will subducts below the younger oceanic crust. AN Island arc forms parallel on the younger crust above the subduction zone.

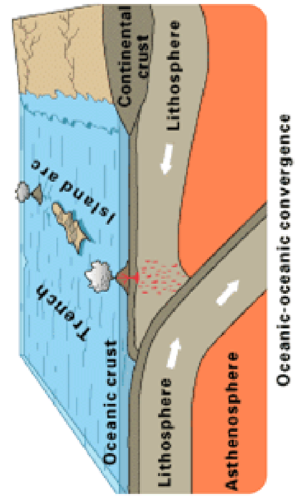


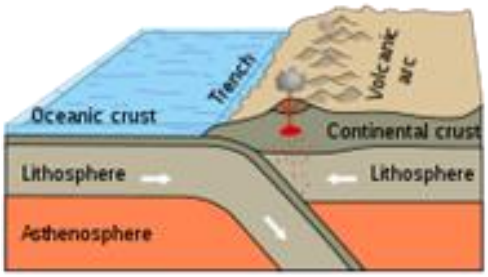
The geothermal gradient increases as the oceanic plate is subducted so temperature increases.

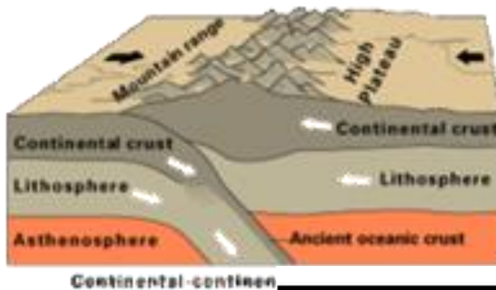
1. **Partial melting of basaltic plate begins** as the **lower temperature minerals** begin to **melt**.
2. The **melted minerals separate** and are **hot so less dense** than the ocean plate, they therefore **rise u**p and become **intermediate in composition**.
3. Magma erupts at the surface with an **intermediate composition (andesite**) or as **mafic lava (basaltic**).
4. Volcanoes create an **island arc**, reflecting the **curving shape of the convergent boundary beneath.**
5. The **rocks on the island are metamorphosed** by the **increase in temperature and pressure**. Some of these rocks are **metamorphosed sediment scrapped off the descending plate** (**accretionary wedge**).

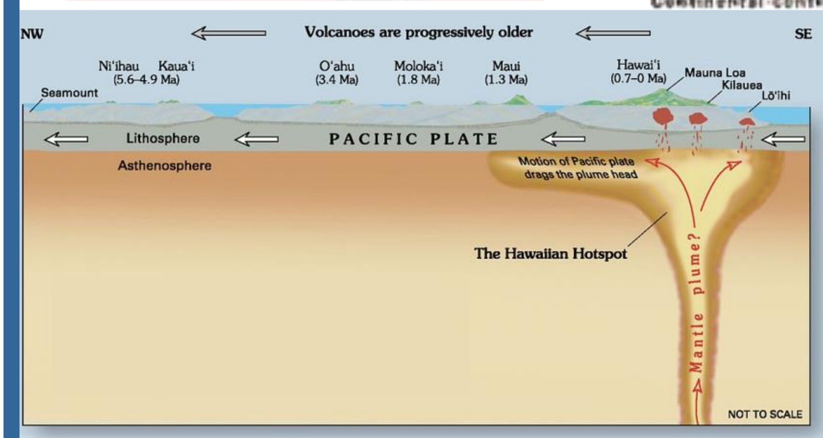
Summary of where margins, mountains and volcanoes are found:

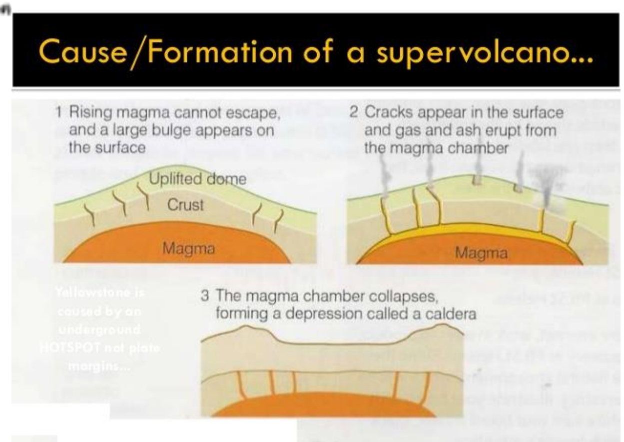


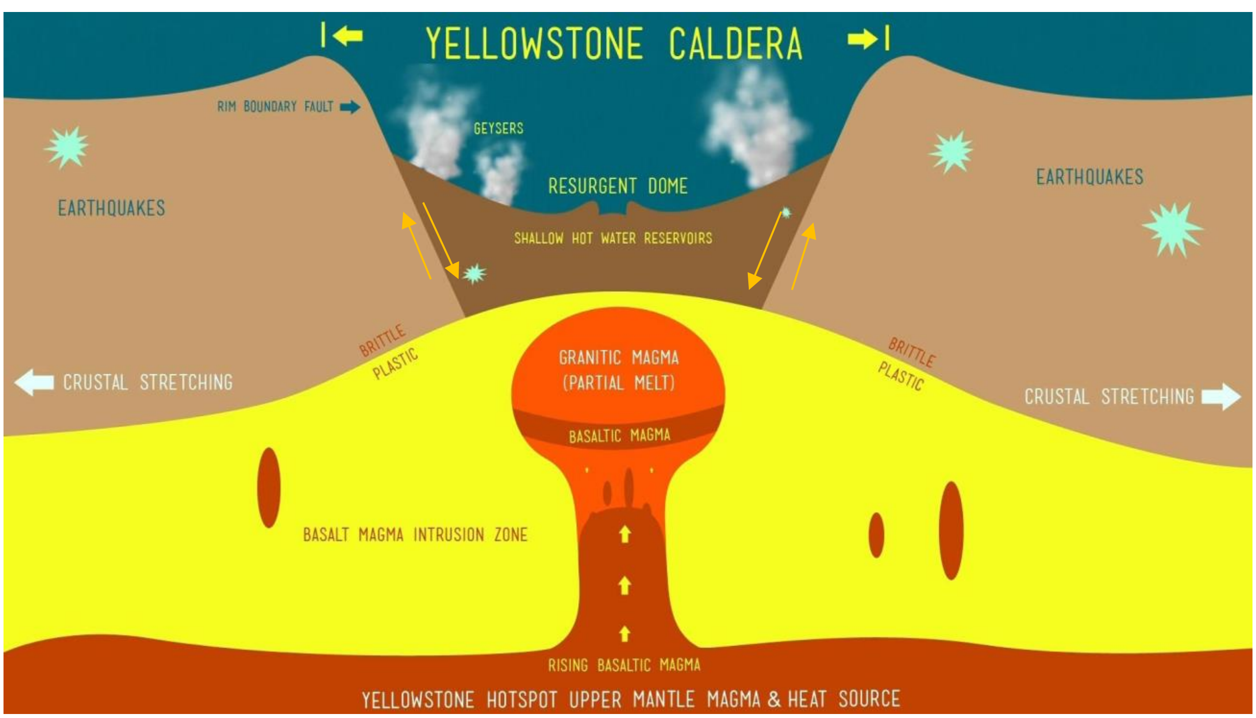












Conservative margins - Shallow foci

= When plates move laterally past each other, there is neither destruction nor construction of the plates.

The only earthquakes that can occur will be shallow-focus since no subduction is involved. There are no volcanoes or other features to mark the plate boundary. The most well-known case study is the San Andreas Fault – although it has many other associated faults).

The movement of the plate alongside the other is unremitting (continuous without slackening) , so California will continue to suffer from severe earthquakes well into the future.

The difficultly when trying to predict movement is that parts of the fault are creeping, making small movements, while other sections become stuck. In these 'quiet' sections, there are seismic gaps where no earthquakes have occurred to release the stress for some time. A large amount of potential energy is stored and when the friction is overcome as stress builds up, the rocks suddenly move to produce a major release of strain energy causing an earthquake. (refer to elastic rebound theory).

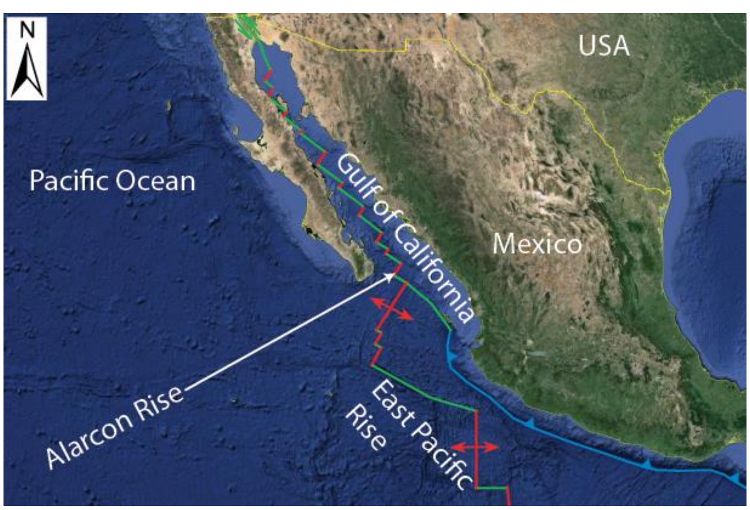
#Creep is a regime of permanent deformation dictated by the influence of mechanical stresses.

SAN ANDREAS FAULT

The fault is a **1300km long,** vertical strike slip (**transform**) fault (San Andreas Fault) where North American and Pacific plates slide past each other. Both move North westerly but P**acific Plate moves faster**. Therefore the `relative movement' of the North American plate is to the south east.

It extends at least 25km depth. Since both move in the same direction but at different speeds this is a **transform fault** like the associated strike slip faults at the MOR.

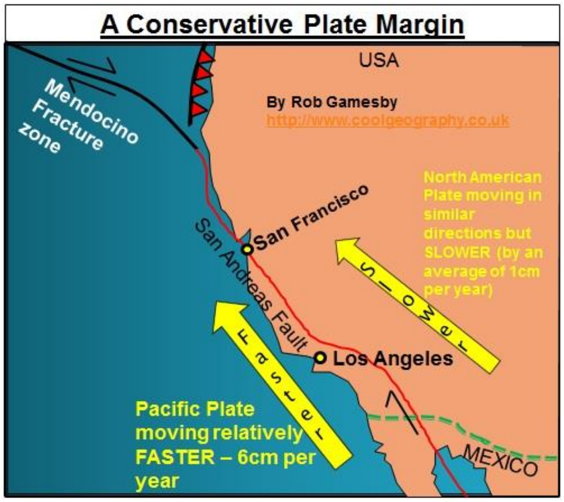
This is a **sliding boundary** between the Pacific Plate and the North American plate. The Pacific Plate is being pushed northwest due to the sea floor spreading from the **East Pacific Rise (divergent margin) in the gulf of California.**
The North American Plate is being pushed **west-northwest due to the sea floor spreading from the Mid Atlantic Ridge** (divergent margin).



- **Landscape and manmade features** (e.g. rivers, fences and roads) are **displaced** across the fault as movement occurs.
- **Shallows focus earthquakes** have been recorded historically **(notably in 1989 and 1906).**

The San Andreas fault **connects two volcanically inactive oceanic rift systems** in the **Gulf of California to the South** and in the **Pacific just north of San Francisco**.

San Francisco is **actually on the Pacific Plate not the North American Plate.**



LEARN THESE KEY POINTS

- **Pacific Plate**: 6cm north west annual
- **North American Plate**: 1cm north west annual
- **Relative movement is ~ 5cm per year with Pacific Plate moving fastest**
- **Length: > 1300km**
- **East Pacific Plate** is moving **northwest** but **North American Plate** is moving **west-northwest** at a slower rate.
- In the **last 140 million** years, the displacement of the **Jurassic rocks** has been **560 km**

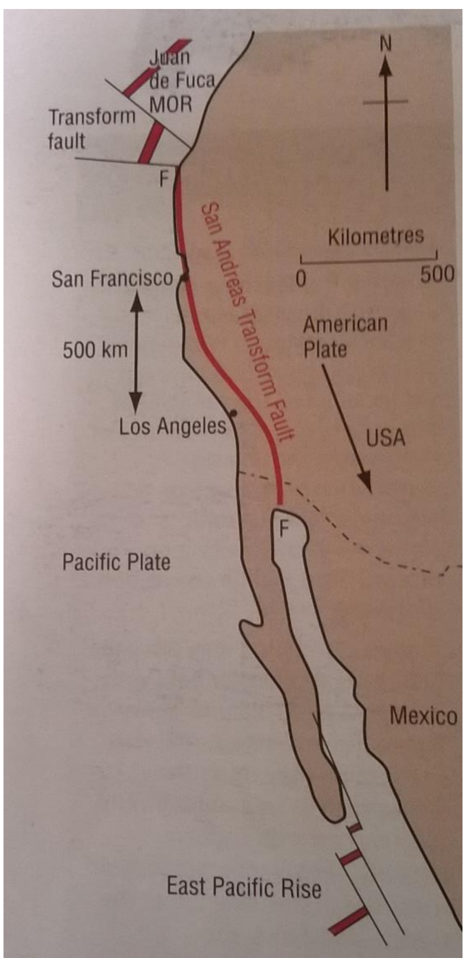
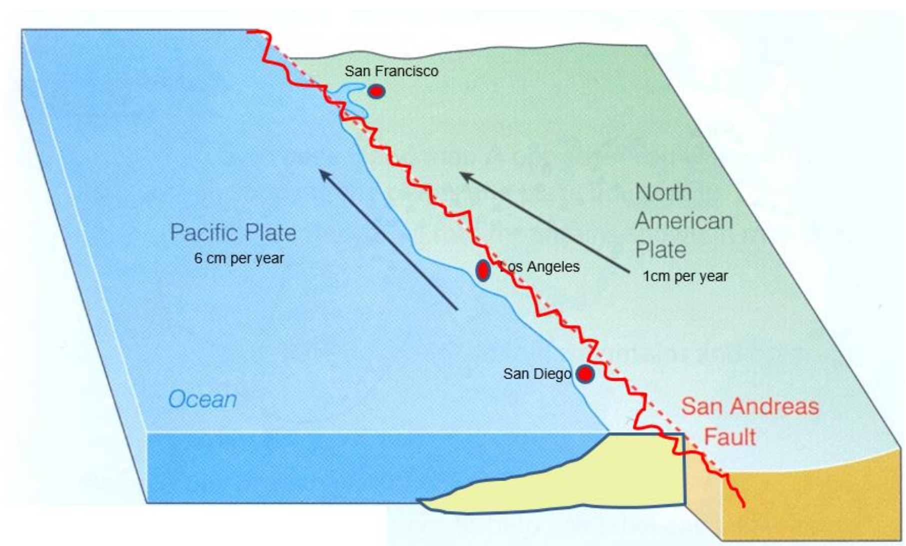


Figure 4 The San Andreas Fault map



WHAT MAKES TECTONICS HAPPEN?

When Wegener proposed the idea of continental drift at the beginning of the 20th Century but his idea was hard to prove **without a mechanism.**

- Limited knowledge of the interior of the Earth
- Other more convincing theories at the time (sinking landmasses)
- Difficult to see how continents could move over the top of the ocean crust (mechanism) .

CONVECTION CELLS

The heat of the interior of the Earth is partly due to the left over thermal energy from the formation of the Earth (4500 Ma), but more evidently, the ongoing decay of radioactive heat-producing elements. If more heat is generated in some areas than others, convection currents are set up, as suggested by the English Geologist, Arthur Holmes in 1928. Slow moving convection currents within the asthenosphere, or possibly within the whole mantle (excluding lithosphere), move the overlying lithospheric plates with them.

Hot lower density material (namely peridotite), rises upwards to form convection cells. This then flows sideways and starts to cool down, becoming denser and sinking back down.

Where a convection current rises to the surface, a hot spot or a divergent margin forms with:

***Increased heat flow** ***Rising magma** ***Eruption of lava**

Near the surface of the Earth, the current stops rising and s**preads out laterally on either side of the MOR**s, resulting in the **sea floor spreading**. It is this part of the **convection cell** that carries the rigid lithospheric plates across the Earth's surface like a **conveyor belt**.

Beneath he lithosphere, **partial melting in the asthenosphere (1 to 5%)** creates a **lubricated surface, reducing friction,** for the movement of the lithosphere.

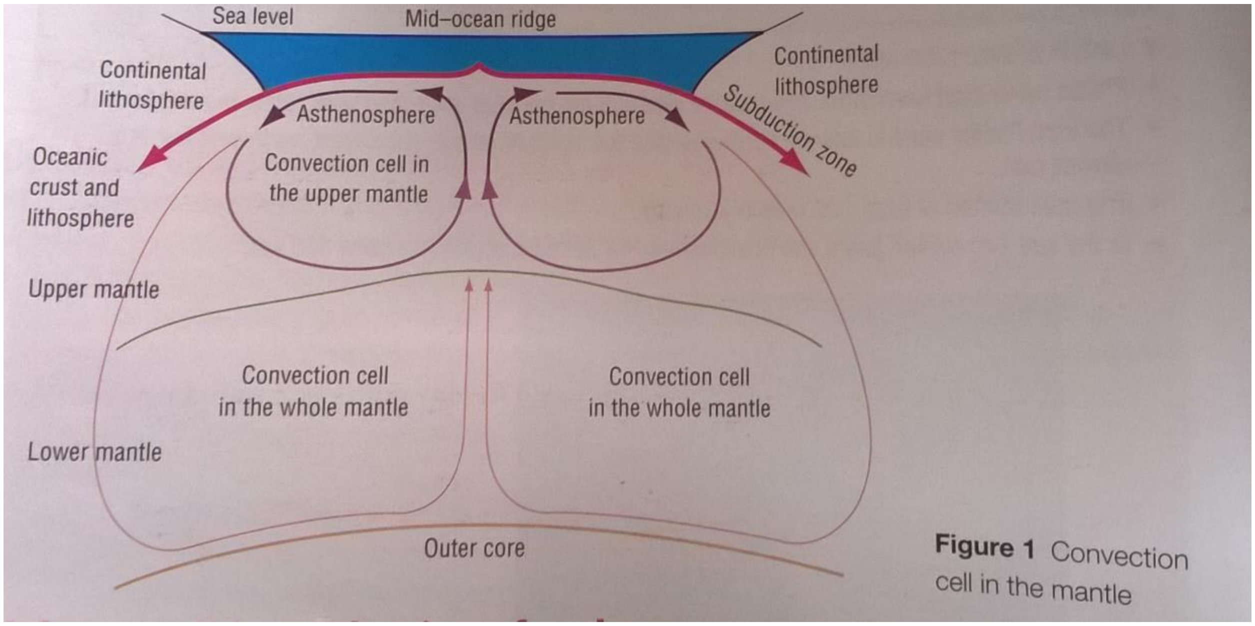
Where two lateral currents meet at subduction zones, either one or both start to sink, as they are now much cooler and therefore denser. There is:

***A deep ocean trench (up to 11km)** ***Lower heat flow** ***Evidence of compression**

The subduction zones are convergent margins. This **descending** flow of material eventually **replaces the mantle material, which rises under the MOR.**

A diapir is another name for a rising plume/volume of hot less dense material in the mantle.

Diapiric action = low density buoyant material (mantle plumes) rising upwards through the Earth's mantle. These may intrude into the crust or melt through to the surface causing an eruption.



OTHER POSSIBLE MECHANISMS FOR PLATE MOVEMENT

a. Ridge push at MORs

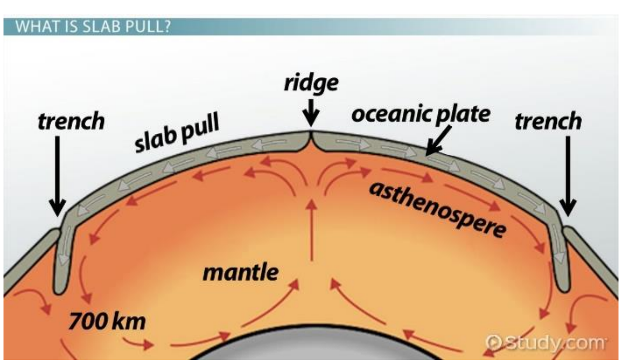
In this model, rising **magma is injected** along the MORs at divergent plate **margins forcibly**, **pushing the lithospheric plates apart**. The **sheeted dykes** (igneous intrusions) found **either side** of the ridge axis are evidence for this.

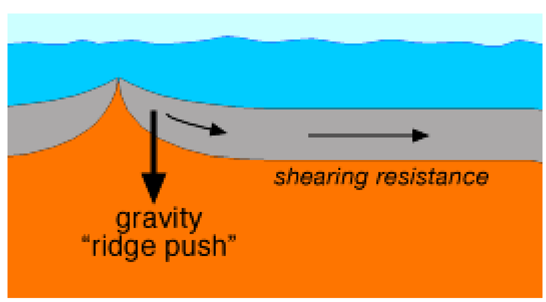
Some geologists argue though that it **is flawed since tensional forces are dominant** along ridges and it would be **more accurate to describ**e this process **as gravitational sliding of the raised ridges**.

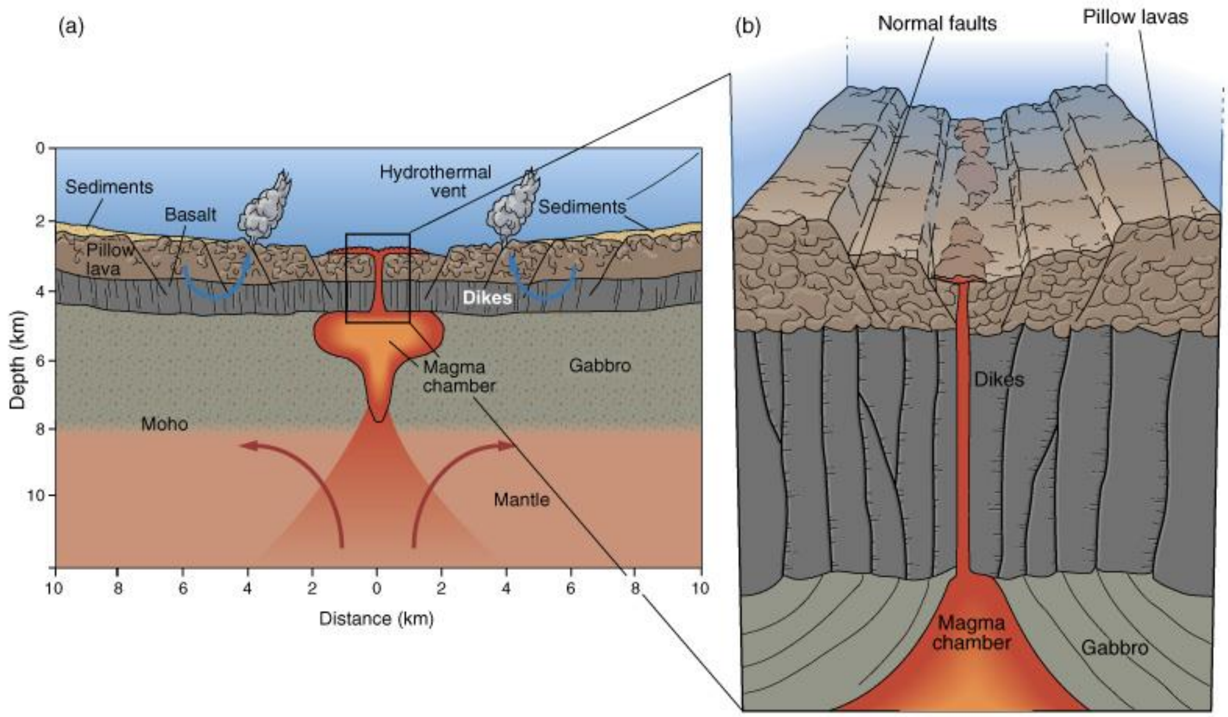
Note: the raised ridges can be 2-3km above the abyssal plain (which is 3-5km deep).

b. Slab Pull at subduction zones

Recently, attention has focused on the idea **that gravity pulls the subducted oceanic lithosphere** down into the mantle at **convergent boundaries**. This **may be the main driving force** of the lithospheric plate movement. The **weight of the cold dense lithosphere sinking** downwards at ocean trenches **pulls** the rest of the oceanic lithosphere.







Ideas of mantle convection

Plate tectonics tends to be an process that releases strain sporadically while the tectonic stress and motion of the lithosphere across the asthenosphere is unremitting. Computer simulations fail to include all features of the Earth's structure that may affect plate movement: **pressure (with depth), temperature, volume of the mantle, the uneven distribution of radioactive elements.**

Convection cell model –ascent and descent of convection cells

1) **Mantle convecti**on may carry the plates like a **conveyor belt**. **Divergent margins** above mantle plumes/**where convection cells rise**. **Convection cells cause the lithosphere to split** at the MOR, and then **carry the lithosphere laterally** towards the **subduction zone** at the **descending end** of the cell (at the **ocean trench**). Here the lithosphere is **dragged down into the mantle**.

Another model, The slab pull at subduction zones

2) The lithosphere is the cold upper layer of the Earth but is considered as the **cold upper layer of the convection cells**. The **ocean crust gets thicker** (sedimentation from planktonic organisms - radiolaria and foraminifera (siliceous oozes)), **colder, denser** and older with distance from the MOR. Because of **the lithosphere's greater density**, it **tends to sink**. Subduction occurs not because of the plate is being pulled down by the descending mantle but **instead because the plate is the dense sinking limb of the cell, driven by slab-pull.**

Another model, convection cells in both the mantle, asthenosphere and at base of lithospheric plates.

3) The **whole mantle may convect as a single layer** driven by heat from the outer core. There could be **jet like plumes of low-density material** that rise form the core-mantle boundary (5100km) to from mantle **hot spots** . The mantle may form two **separate convecting layers**. The upper mantle consists of the asthenosphere and lithosphere that **subducts to depths of 700km**, before being **undetectable by seismic activity**. Below 7000km, the mantle **may form separate cells** which **convect** at a **very slow rate independently of the upper mantle.**

Recycling the Earth

- **Maximum age** of the **ocean crust is 200 Ma** (near ocean trench); because geologically speaking, **oceans are temporary features** that **open and close** due to the shi**fting balance between formation at MORs and destruction at subduction zones.**
- The **complete cycle** of the opening and closing of an ocean is **called a Wilson Cycle**.
- Wilson cycle is named after geologist J Tuzo Wilson, who suggested the idea in 1967.

The Earth **never runs out of basaltic material** as the ocean floor is like a continuous belt and the basalt **forming new crust at the MOR (divergent)** will by cycl**ed back into the mantle when it subducts** at a convergent margin.
Melted material sinks down through the mantle and is carried back as a return current, gaining heat form the underlying core over which it passes, back to the `start' of the convection cell where it rises once again under the MOR.

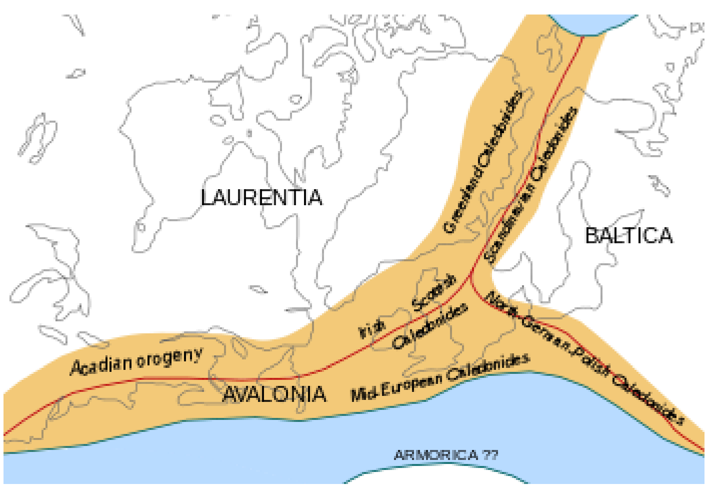
Slab pull probably limits the maximum size of an ocean and **one complete cycle takes ~ 500 Ma.**

PLATE MOVEMENT CASE STUDY

Scotland was part of North America and **England & Wales were part of Europe**, separated by the **large proto-Atlantic Ocean** or **Iapetus.**

In Britain, the **400 Ma Caledonian mountain belt** marks the **ancient convergent margin**. It was formed when the **Iapetus ocean subducted/closed and the plates of Laurentia and Baltica** a collided to form **Euramerica (or Laurussia** NOT to be confused with Laurasia). This event formed the **Caledonian Mountain belt** and joined **Scotland And North America to England/wales and Europe**. This event occurred around 400 Ma in the **Devonian period**. In Greek mythology, Iapetus was the father of Atlantis.

The **southward continuation** of the convergence meant **shortly after,** the continent of **Avalonia collided** to (forming the **Acadian orogeny**).



Further south was a continent called **Gondwana.** In the Late Mississippian (**early Carboniferous 340MA)**, **Laurussia** collided with **Gondwana** and the Variscan orogeny began to form (what is now central Europe).

Collison between Gondwana and Laurussia **continued form some time**, forming orogenic belts across Europe and north America.

By **270 Ma (Permian** period) **Pangea** had formed (the most recent largest supercontinent).

This began to **split up 200Ma** (**Early Jurassic**) eventually forming the **Atlantic and Indian oceans**. Pangea split **into Laurasia** and **Gondwanaland.**

Gondwanaland started to **break up 167 Ma** to form **South America**, **Africa**, India, Antarctica and Australia. This is important as there is evidence that South America and Africa were once joined –see evidence of continental drift. While **Laurasia** had **split into North America, Europe, Siberia and China** (**Roughly 152 Ma** or Late Jurassic).

Although the Atlantic began to open (167Ma) and ultimately caused **Pangea/Gondwanaland to split and Laurasia to drift north**, the spreading ridge to form the Atlantic occurred **at different rates**. **The part that formed what would become the North Atlantic rifted around 100 M**a.

And by **66Ma the South Atlantic had opened** up and **India was well on its way northward towards Asia**. The **Tethys Ocean was closing** to form the Mediterranean**. India closed Eastern part** of the **Tethys Ocean** when it collided with Asia (**50Ma)** to form the **Himalayas**.

- Green = case study of formation of Caledonian belt (forming Lake district and Scottish highlands).
- Pink = information to have a background knowledge on for other parts of this course.
- Orange brown = extra information to help build the picture.

The evidence for an ancient plate margin includes:

1. **Extensive intermediate volcanic lavas** and **pyro clasts in N. Wales**, the **Lake District** and **southern Scotland.**
2. **Folded and faulted rocks** in an ancient fold mountain belt (**Caledonian mountain belt**).
3. **Regionally metamorphosed** rocks
4. **Granite batholiths**
5. Fossils of **different genera of trilobites** that must have been **two separate faunas** on either side of the Iapetus ocean.

After the **closure of the Iapetus Ocean 400Ma,** for the next 300 Ma (i.e. up until 100 Ma), Europe and North America were joined. **Around 100 Ma**, the **present day North Atlantic Ocean started to open** as a result of **rifting in a direction different to that of the Iapetus ocean**.

This split Laurasia into North America and Europe (~ 100Ma).

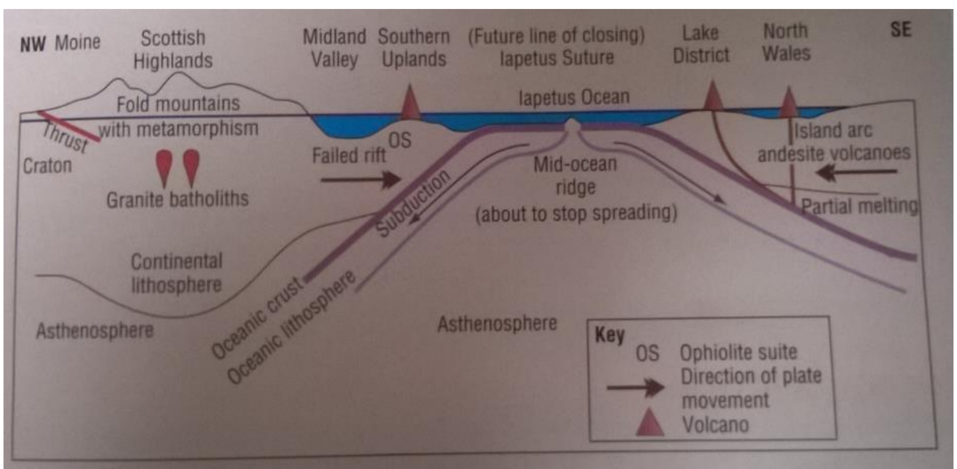
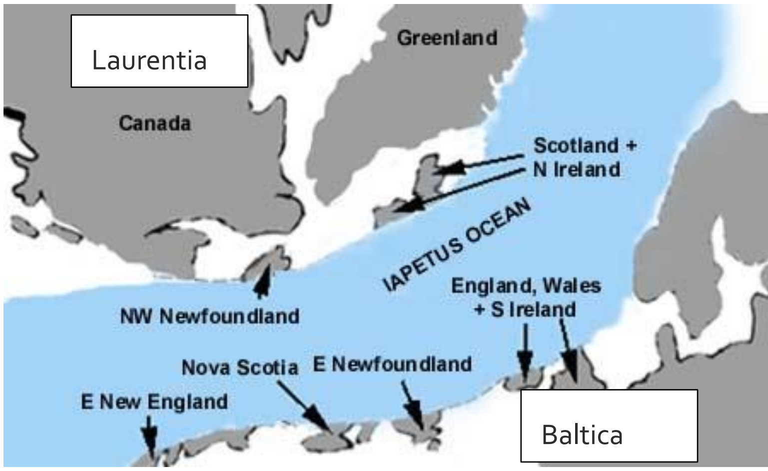
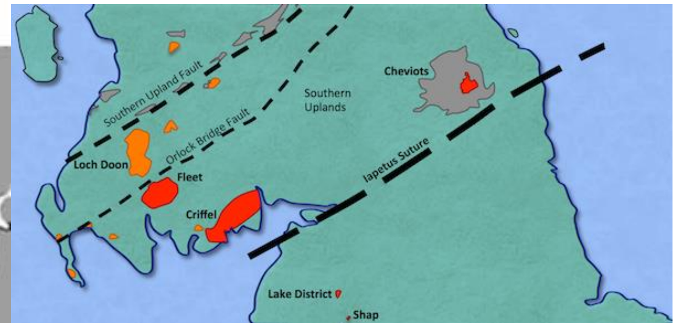
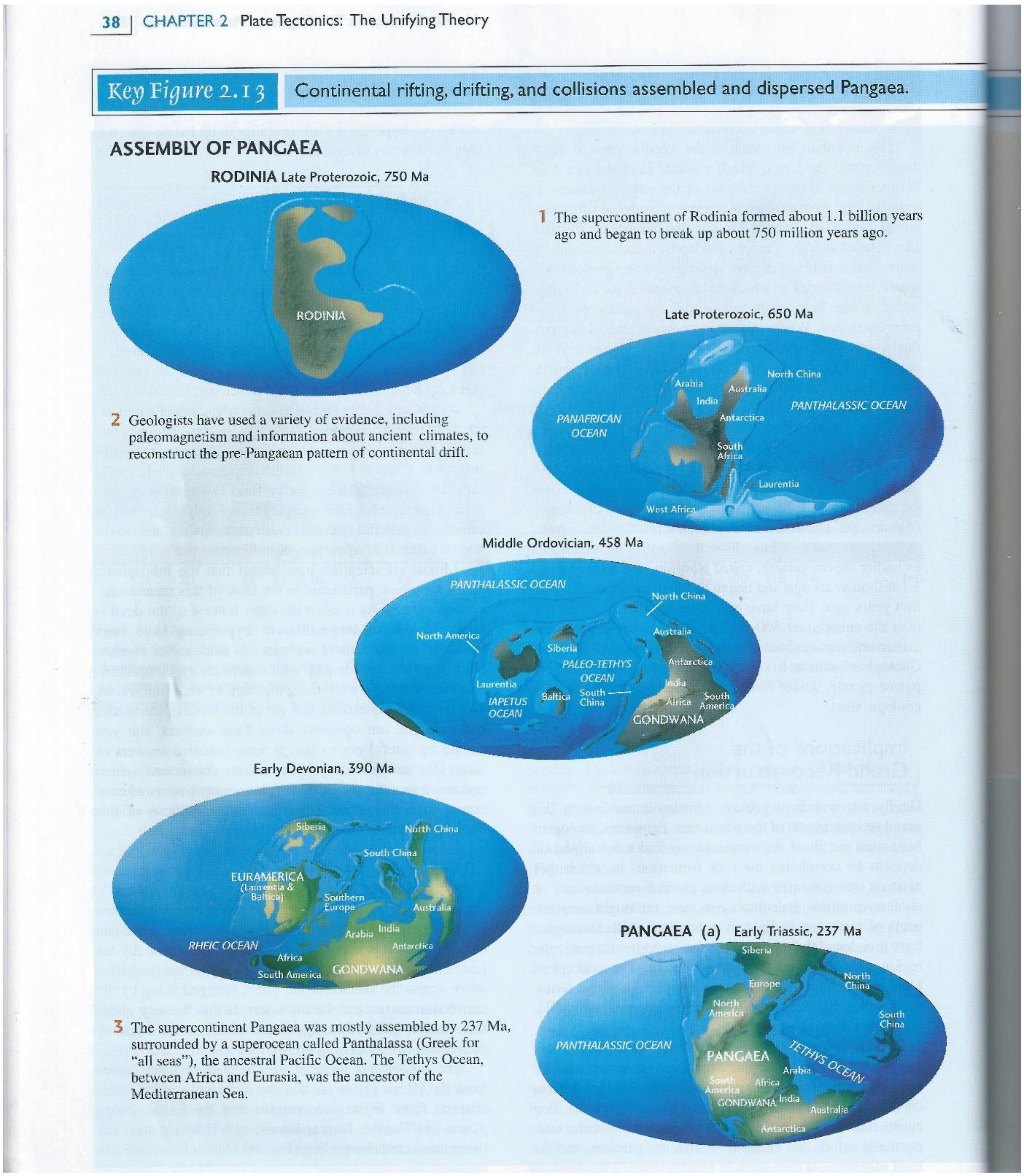


Figure 2 Plate movement 400 Ma







Key Figure 2.13 Continental rifting, drifting, and collisions assembled and dispersed Pangaea.

ASSEMBLY OF PANGAEA

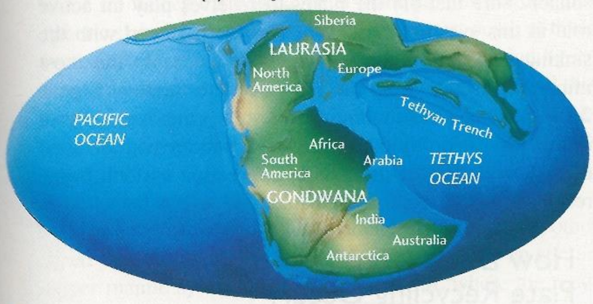
1 The supercontinent of Rodinia formed about 1.1 billion years ago and began to break up about 750 million years ago.

2 Geologists have used a variety of evidence, including paleomagnetism and information about ancient climates, to reconstruct the pre-Pangaean pattern of continental drift.

3 The supercontinent Pangaea was mostly assembled by 237 Ma, surrounded by a superocean called Panthalassa (Greek for "all seas"), the ancestral Pacific Ocean. The Tethys Ocean, between Africa and Eurasia, was the ancestor of the Mediterranean Sea.

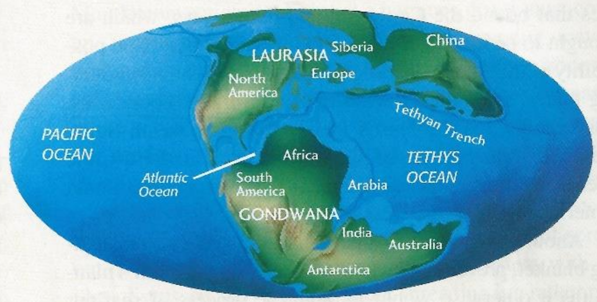
BREAKUP OF PANGAEA

(b) Early Jurassic, 195 Ma



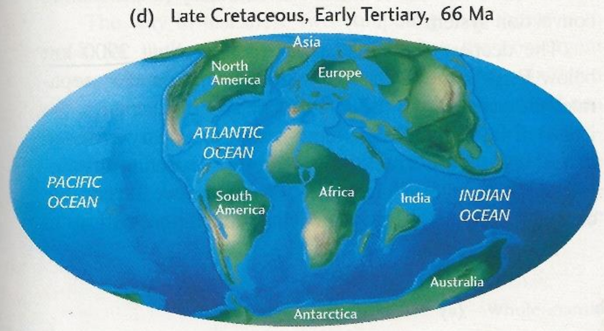
4 The breakup of Pangaea was signaled by the opening of rifts from which lava poured. Rock assemblages that are relics of this great event can be found today in 200-million-year-old volcanic rocks from Nova Scotia to North Carolina.

(c) Late Jurassic, 152 Ma



5 By about 150 million years ago, Pangaea was in the early stages of breakup. The Atlantic Ocean had partially opened, the Tethys Ocean had contracted, and the northern continents (Laurasia) had all but split away from the southern continents (Gondwana). India, Antarctica, and Australia began to split away from Africa.

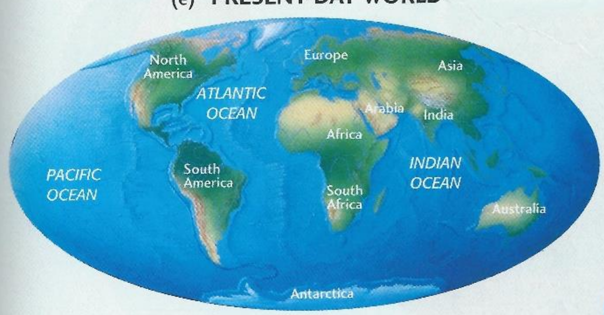
(d) Late Cretaceous, Early Tertiary, 66 Ma



6 By 66 million years ago, the South Atlantic had opened and widened. India was well on its way northward toward Asia, and the Tethys Ocean was closing to form the Mediterranean.

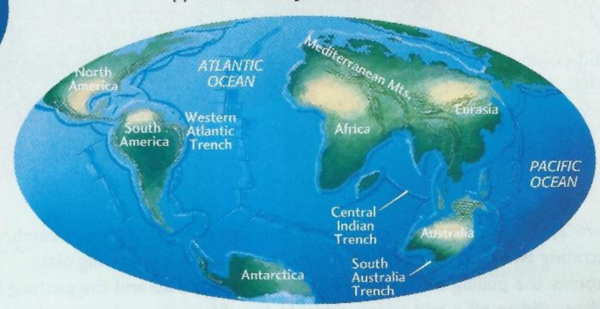
THE PRESENT-DAY AND FUTURE WORLD

(e) PRESENT-DAY WORLD



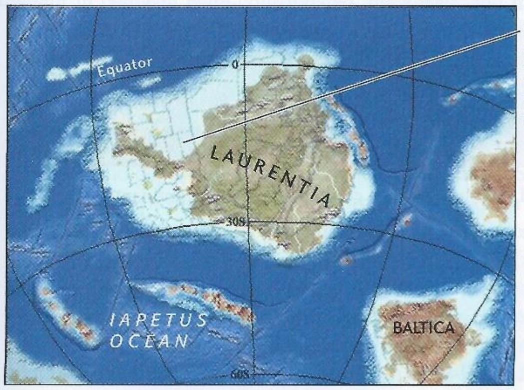
7 The modern world has been produced over the past 65 million years. India collided with Asia, ending its trip across the ocean, and is still pushing northward into Asia. Australia has separated from Antarctica.

(f) 50 million years in the future

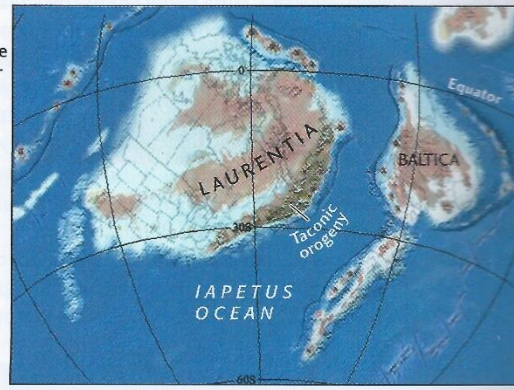


[Paleogeographic maps by Christopher R. Scotese, 2003 PALEOMAP Project (www.scotese.com).]

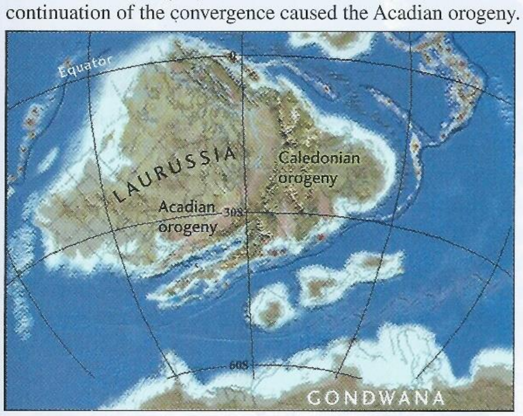
Middle Cambrian (510 Ma)
After the breakup of Rodinia, the continent of Laurentia straddled the equator, and its southern side was a passive continental margin, bounded on the south by the Iapetus Ocean.



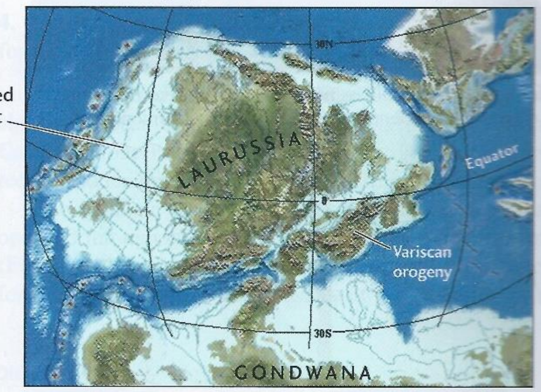
Late Ordovician (450 Ma)
The island arc built up by the southward-directed subduction of Iapetus lithosphere collided with Laurentia in the middle to late Ordovician, causing the Taconic orogeny.



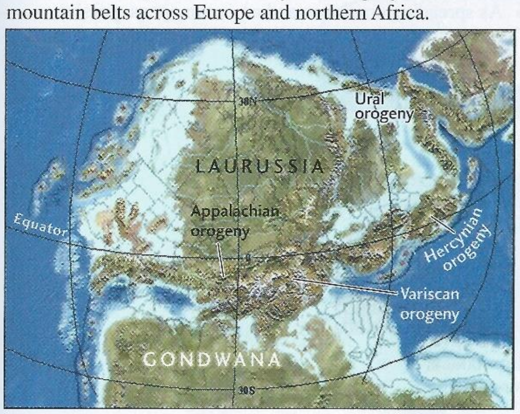
Early Devonian (400 Ma)
The collision of Laurentia with the continent of Baltica caused the Caledonian orogeny and formed Laurussia. The southward continuation of the convergence caused the Acadian orogeny.



Late Mississippian (340 Ma)
The collision of Gondwana with Laurussia began with the Variscan orogeny in what is now central Europe…



Upper Pennsylvanian (300 Ma)
… and continued along the margin of the North American craton with the Appalachian orogeny. During this terminal cataclysm, Siberia converged with Laurussia in the Ural orogeny to form Laurasia, while the Hercynian orogeny created new mountain belts across Europe and northern Africa.



Early Permian (270 Ma)
The end product of these episodes of continental convergence was the supercontinent of Pangaea.

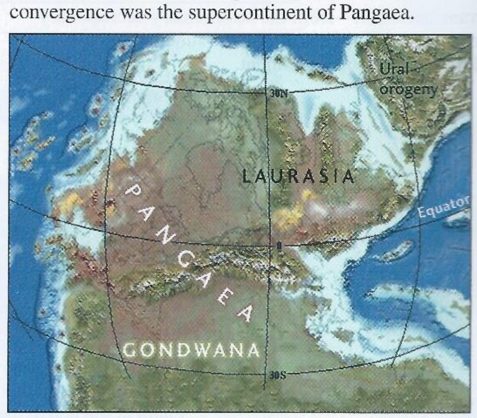


Figure 10.17 Paleogeographic reconstructions of the North Atlantic region, showing the sequence of orogenic events that resulted from the assembly of Pangaea. [Ronald C. Blakey, Northern Arizona University, Flagstaff.]

Hot Spots and Mantle plumes

#A hot spot is a volcano within a plate, which is a surface expression of a mantle plume.
#**A Mantle plume** is a stationary area of high heat flow in the mantle, which rises from great depths and produces magma that feeds hot spot volcanoes.
#A diapir is low density, bouyant material rising upwards in the same way as a lava lamp .

There are a number of volcanoes which can form away from active plate margins – within plates. The most noticeable being the island chain of Hawaii in the middle of the large Pacific plate.

The `Big island' of Hawaii is built up of 5 different volcanoes. 3 of which are still active today.

- Mauna Loa (**4100m**) is the highest
- Kilauea is the most active volcano on Earth.
- The true height from sea floor to summit of Hawaiian volcanoes exceeds the height of Everest.

This suggests there must have been an enormous volume of lava.
Remember, the volcanoes have formed in the **middle of an oceanic crust** (roughly 5km thick, average 7km). Hawaii is nearly 3200 Km form the nearest plate margin.

The hot spot may represent the top of a mantle plume which originated deep down at the **outer core - lower mantle** boundary.

The **rising mantle plume** is a **long-lived area of high heat flow** within the **mantle.** The buoyant material rises up by **diapiric action** and forms a **long, thin , conduit and bulbous head** that **spreads out as pressure decreases** nearer the base of the lithosphere.

As the plume head **reaches the lithosphere**, the **reduction in pressure** results in **widespread partial melting** of **ultramafic mantle**, producing huge volumes of mafic magma.

The **mantle plume hot spot stays stationary** beneath the oceanic lithosphere.

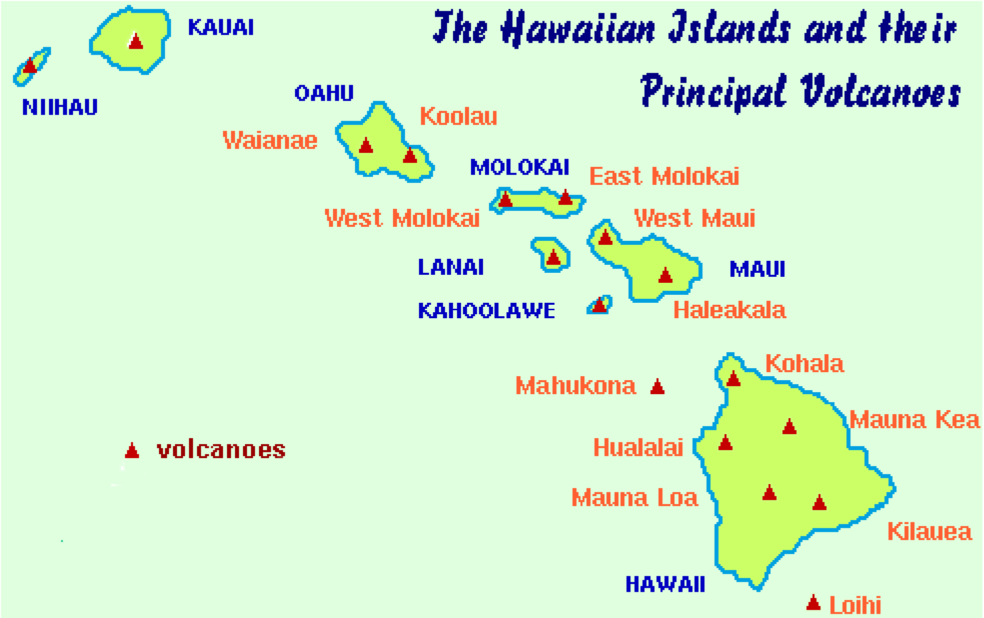
Mafic **magma accumulates** below the lithosphere until it manages to **melt through** to form a **shield volcano** (the surface expression). A volcano forms when a **vent or a series of vents** are created through the lithosphere.

The **Pacific Plate** is being pushed northwest (6cm year) due to the sea floor spreading from the **East Pacific Rise (divergent margin**) in the **gulf of California**.

As **the oceanic lithosphere shifts ,** a **different region of oceanic lithosphere is positioned over the hot spot**, so a new vent and volcano form over the stationary plume.
As oceanic lithosphere moves to **carry the volcano off the mantle plume**, it becomes e**xtinct** and it **cools**, becomes **denser,** and **slowly subsides.**

Eventually a **chain of volcanoes form, each one younger than the one before.**

Youngest (active) ***Hawaii > Maui > Molokai > Oahu > Kauai*** ***Oldest (extinct).***



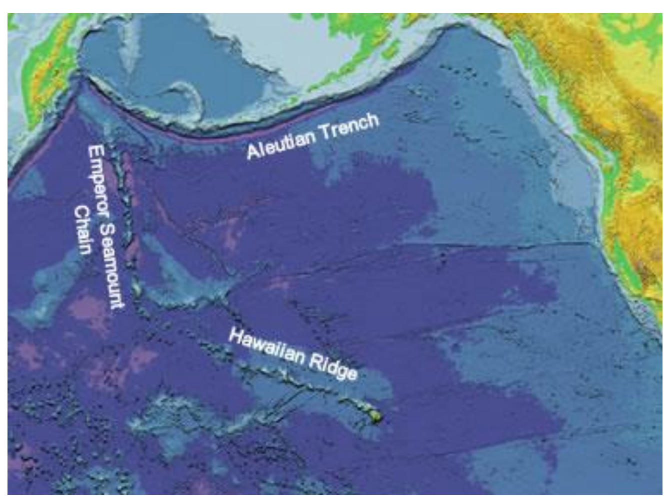
*<u>Exam tip</u>: Hot spot and mantle plume are often used interchangeably. However, technically, **the plume refers to the rising material in the mantle** which results in **high heat flow values**, which can be recorded as `**hot spots'** on a **map.***

- All the islands of the **Hawaiian-Emperor chain** are made of **basaltic shield volcanoes**.
- Apart from the volcanoes on `Big Island', Hawaii, (Mauna Loa, Kilauea, Hualālai), all of the other volcanoes **are extinct.**
- **Towards the northwest** they get **progressively older** and **more eroded**, continuing as a **600km line of submarine guyots and seamounts**, which **extend to the Aleutian islands.**

<u>#Seamount</u> = a basalt volcano rising at least 1000m above the ocean floor without reaching sea level (volcanic islands that may have subsided or never reached the surface). Sea mounts can occur singly or in groups or in chains. Some seamounts are topped by a coral atoll.
<u>#A guyot</u> = a seamount (submarine basaltic volcano rising >1000m) with an eroded flat top.

The **position and ages of the seamounts** show the **direction and rate** of plate movement. In the case of Hawaii, the age of the **volcanic islands and sea mounts** show the **hot spot is 80 Ma**. A new **submarine volcano, Loihi**, is **growing 30km south of Kilauea**, showing the mantle plume is **still active** today.

At the **Hawaiian-Emperor bend**, the **chain of seamounts turns northwards** towards the **Aleutian Trench,** indicating there was a **change in direction of plate movement 42 Ma**.



It is very unlikely (and we know that) that the plume has (NOT) moved towards the south east so this theory is dismissed.

Evidence for mantle plumes and their origin

A geophysicist, W Jason Morgan, proposed the theory of mantle plumes in 1971. He suggested that, along with **mantle convection cycles**, **mantle plumes** are another way which the Earth loses heat energy. The Earth's core is considerably hotter than the mantle. There is **little evidence that any material moves across the Guttenberg Boundary** (**5100km**), so heat must be **transferred by conduction across the boundary.** The material in the **lower part of the mantle** becomes **less dense**, **hotter and more buoyant**.

Overhead portions of the mantle will **start to rise as low density diapirs** that **become mantle plumes.** Therefore it is possible mantel **plumes originate from as deep as the core-mantle boundary**.

Evidence of mantle plumes

#Seismic tomography = a computer imaging technique based on **seismic wave velocities**.

There are several lines of evidence that have been suggested to explain hot spot volcanoes within plates to support the theory.

1. **Seismic tomography and heat flow**: Using a **network of seismometers**. Geologists can interpret **seismic wave velocities** to **construct three-dimensional computer generated** images of **heat flow within the Earth**. **Seismic waves slow down** when they travel through **less dense, less rigid, hotter** material that is partially **melted**. There are **32 regions** in the Mantle where **P waves travel slower than average**. These have been interpreted as large mantle plumes. **Changes in S-waves velocities** indicate that **plumes extend to the core-mantle boundary.**

2. **Geochemistr**y: **Chemical** and **isotopic analyses** of **basalts erupted at hot spots** show them to be di**fferent** from basalts erupted at **mid-ocean ridges (MORs**) **or island arcs (oceanic-oceanic collision)**. This suggests that the magma originates form a **different source area** in the mantle. It seems that **subducted oceanic crust** that has sunk down as far **as the core-mantle boundary** forms a **major component of the plume material**.

When any volcanic island is **above sea level it is rare**. Seamounts tend to be submarine. When a volcano does exceed sea level height then it **suggests** it is situated in the **presence of a hot spot and mantle plume**. E.g. The Mid-Atlantic Ridge at Iceland is both a spreading ridge and a hot spot area.

The Icelandic magmas are said to have evolved, implying there has been **plenty of time** for them to **develop (differentiate**) as they rise through the mantle, producing **silicic and intermediate** lavas as well as **mafic** basalts (**magmatic differentiation**).

Hawaiian eruptions give lava that is **effusive, basaltic with low viscosity.**

There are numerous examples of oceanic hot spots from around the world – **Hawaii**, the **Canary islands**, the Azores, **the Galapagos islands**, St Helena and Ascension.

Due to the thickness of continental crust, mantle plumes do not manifest themselves in continents. They do exist – like **Yellowstone super-volcano in North America.**

<u>Sea floor spreading rate from hot spots</u>

If the age of a volcanic island is known from **radiometric dating** and its distance from the active hot spot is measured, then it is possible to calculate the rate of plate movement and **hence sea floor spreading**.

Speed = distance/ time   this can be measured in Km per Million Years or mm per Year.

For a spreading ridge we must multiply the answer by two as two sides spread at the same rate.

Remember when a convection current occurs at a divergent boundary or hot spot there is:

1. High heat anomaly
2. Rising magma
3. Eruption of lava
4. Positive gravity anomaly

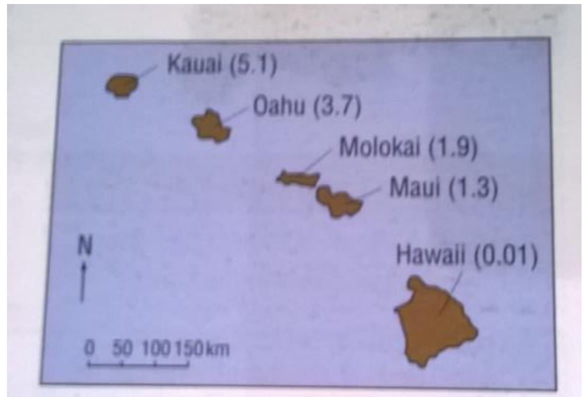


Figure 2 Map showing part of the Hawaiian island chain

Distance between Hawaii and Maui = 15 mm on map. Using the scale 15 mm = 225 km.
Age difference between Hawaii and Maui = 1.3 – 0.01 = 1.29 million years.

$$\text{Speed} = \frac{\text{distance}}{\text{time}} = \frac{225\text{ km}}{1.29\text{ million years}} = \frac{225 \times 1000 \times 100\text{ cm}}{1\,290\,000\text{ years}} = \frac{22\,500\,000}{1\,290\,000} = 17.4\text{ cm/year}$$

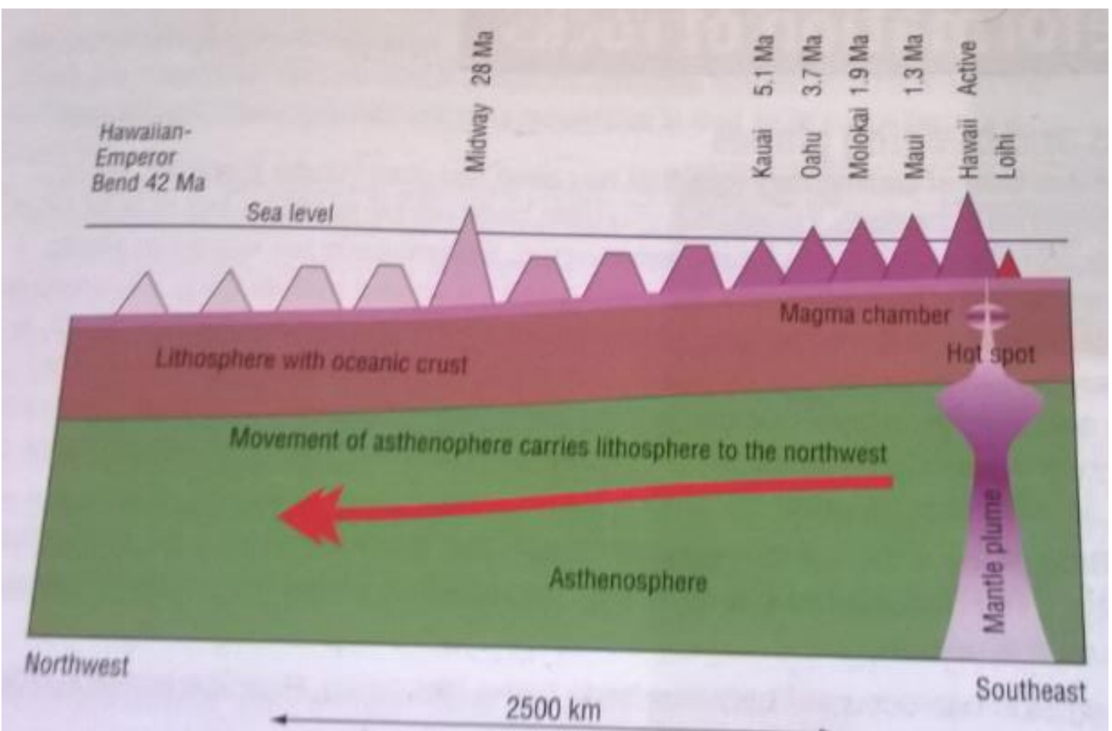


Figure 1 Cross-section through the Hawaiian-Emperor chain