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GEOLOGICAL SLANT ON PLATES

Alfred Wegener, a German meteorologist born in 1880, is not a name that most people would think of if they had to name a scientific pioneer. People are more likely to say Darwin, Newton, Da Vinci or Galileo, but like these famous names he had a brilliant idea which seemed so far-fetched and revolutionary as to be considered ludicrous by his fellow scientists. His idea of **continental drift** suggested that continents moved around the Earth like giant rafts. He is now considered the father of the theory of what we call **plate tectonics**, the key to modern geological science. Although part of his theory of continental drift, that the continents ploughed through the ocean floor, has now been discounted, there is certain evidence for the break-up and movement of continents over the surface of the Earth.

The evidence for continental movement

- Evidence of an Upper Carboniferous glaciation (300 million years ago (Ma)) is found in the Southern Hemisphere continents from when they were part of a supercontinent called **Gondwanaland** near the South Pole at the time.
- The continental shelf outlines of the world's continents, if pieced together, fit near perfectly with very little overlap to form a supercontinent called **Pangaea,** which we now know was in existence 200 Ma. For instance, a glance at any world atlas will show that the eastern coastline of South America mirrors that of Western Africa.
- Fossil remains of a small freshwater reptile called **Mesosaurus** have been found in both South America and Africa. It seems very unlikely either that they could have crossed thousands of miles of ocean or evolved identically on separate continents.
- Fossils of **Glossopteris,** a seed fern, from 270Ma are found across the southern continents.
- Coal is found in Antarctica; coal is unlikely to have formed at its current latitude, as it requires tropical climates and dense vegetation to form.
- Basalt lava flows are located where continents tear apart. When Africa and South America rifted apart large volumes of flood basalt were erupted. This occurred over the Walvis Hot Spot which today is marked by the island of Tristan de Cunha.

Evolution of plate tectonic theory

Continental drift theory evolved into plate tectonic theory in the 1960s when extensive maps were made of the ocean floor. A mid-Atlantic ridge of mountains 1000 miles wide and 2500m high was discovered, as were deep ocean trenches at the edges of some continents, the deepest being the 11km-deep Marianas Trench off the Philippines. Echo sounders were used to probe the crust, and the ocean floors were found to be thinner than the continents. The layer below the crust was termed the mantle.
Oceanographers towed magnetometers (instruments which measure the strength of the Earth's magnetic field) behind survey ships and a stripy pattern of **magnetic anomalies** related to the reversal of the Earth's poles was found. In 1963 it was eventually deduced by a Cambridge geologist, Fred Vine, that lavas erupting at mid-ocean ridges recorded the Earth's polarity at the time of their formation (Figure 1).

But if new ocean floor was being created, why was the planet not getting bigger? Ocean trenches held the answer. Hugo Benioff, a seismologist, observed that there was a zone of earthquakes and an arc of volcanoes close to these trenches. The depth of the earthquakes got progressively greater away from the trenches and disappeared at about 700km. Benioff suggested that this was due to oceanic crust sinking underneath the overlying plate, and named this area the **Benioff zone**. Figure 2 shows the main plates and their key characteristics.

The Structure of the Earth

The structure of the Earth can be likened to three concentric spheres of increasing diameter encasing one another. The centre of the Earth, the core, is divided into inner and outer sections. The **outer core** (at 2900 km depth) is liquid and composed mostly of iron with a temperature of 4000–6000ºC. We know it is liquid, as seismic waves cannot pass through it. The **inner core** is under intense pressure and, although very hot, is solid and made of iron with possibly around 20% nickel content. The **mantle** is 2300km thick and consists of silicate minerals, it surrounds the core and makes up 68% of the bulk of the Earth and can also be divided into two divisions. The lower mantle, also known as the **asthenosphere**, is largely solid with a temperature of 1000–1200ºC. Although solid, it is able to flow very slowly, like plastic, due to convection currents caused by heating from the core. The upper mantle is more brittle and is welded to the overlying crust. Together they form a layer called the **lithosphere** which is around 50km thick. Although the upper and lower mantle are effectively welded together, there is nevertheless a sharp division between the two called the **Moho** (**Mohorovicic discontinuity**), defined by differences in seismic wave speed.

The **crust** of the Earth is divided into two types, **continental crust** and **oceanic crust**. **Oceanic crust** covers 65% of the Earth's surface and is on average 6km thick; throughout its thickness it has the same basic composition, similar to basalt lava flows on its surface. **Continental crust** forms the Earth's continents and can be up to 70km thick. It is less dense then oceanic crust due to its high silica content (60%).

Plate tectonic theory

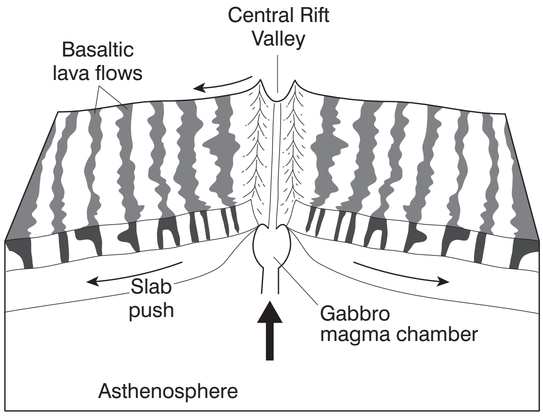
If we plot a world map of volcanic and earthquake activity, elongated bands can be picked out. These are the boundaries of the tectonic plates along which most activity occurs. Each plate consists of a section of lithosphere comprising of upper mantle, continental and oceanic or sometimes just oceanic crust. The plates move very slowly (5–20cm/year) over the lower mantle due to convection currents which originate from the intense heat given out by the core. Along these plate boundaries most of the world's earthquake and volcanic activity occur Crust is created,

Figure 1: Plate tectonic boundaries and intra-plate volcanism

Constructive: Where oceanic crust is created
Mid-ocean spreading ridges.

Examples:
Mid-Atlantic Ridge

Oceanic crust is created along **mid-ocean ridges** with chains of submarine volcanoes. The oceans grow wider through sea floor spreading as more lava is erupted. As they widen a magnetic record is held within the iron rich minerals such as magnetite, which records changes in the Earth's magnetic field. This gives a stripy magnetic anomaly pattern. As the plates pull apart magma is produced by decompression of the underlying zone (70–110km down) to produce a mafic magma. The magma is added to the edges of the plates as an igneous rock called gabbro, which has crystallised in a magma chamber. If magma erupts on to surface of the sea floor it is then termed a basaltic lava flow.



Ocean coastal cross-section

Basalt lava	Oceanic crust
Dolorite dykes	
Gabbro magma chamber	
Peridofite	Mantle

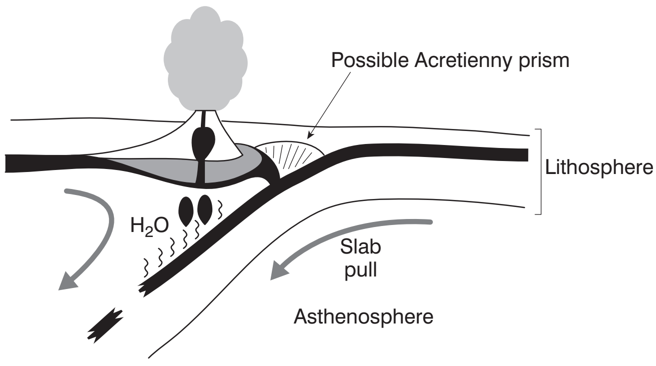
Magnetic anomalies of polar reversal are recorded in the magnetic minerals as 'stripes' Ridge is uplifted doe to buoyancy of crust before cooling and upswelling of magma, eg Mid-Atlantic Ridge

East Pacific Rise

Destructive: Where oceanic crust is destroyed and returned to the Earth's interior.
(including collision in some classifications)
(a) Oceanic crust subducts under oceanic crust.
(b) Oceanic crust subducts under continental crust

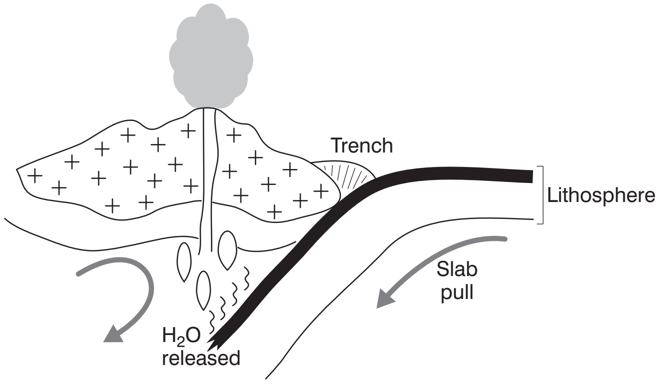
Old, cold and dense oceanic crust sinks or is subducted beneath a neighbouring plate and forms a deep ocean trench at a destructive boundary or **subduction zone**. The path of the subducting plate is indicated by a zone of dipping earthquakes called a Benioff zone. Above the subducting plate a **volcanic arc or chain** forms caused by melting. As the plate subducts temperature and pressure changes cause it to change to a rock type called eclogite which contains the minerals garnet and pyroxene. The type of volcanism produced is called intermediate or calc-alkaline. A variety of volcanic rocks can be produced from basalt to rhyolite. Volcanism is explosive due to the high silica content which increases the **viscosity** of the magma and volatile content (water). The crust above the subduction zone is uplifted due to the volumes of rising magma. Oceanic sediments are scraped from the descending oceanic plate to form an **accretionary prism.**

a) Ocean ⟶ Ocean subduction



Eg, Antilles Arc Caribbean: N. American plate subducting beneath Caribbean

b) Ocean ⟶ Continent subduction



Eg, Andean volcanic arc S. American plate subducting beneath S. America
Age temperature and rate of subduction will affect the angle of the subducting plate

(a) Antilles Island Arc: Caribbean
(b) Cascade Range: USA Pacific North West

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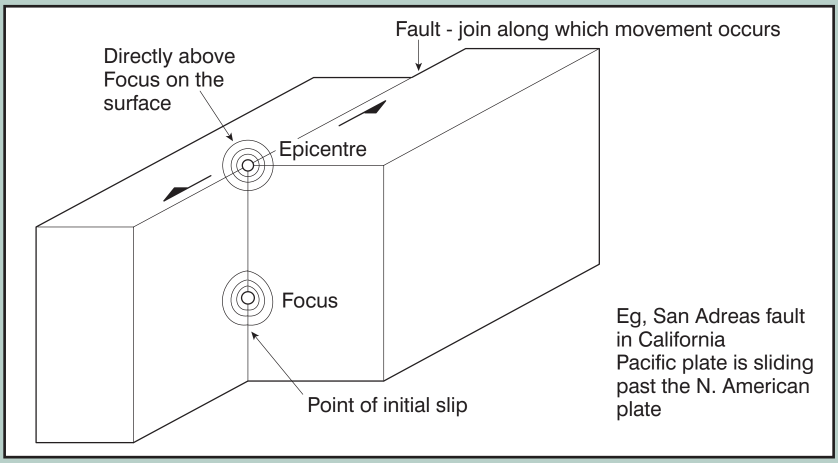
Figure 1 continued

Conservative: Where crust is neither created nor destroyed
Strike slip
Transform

At conservative margins there are no volcanoes but strong earthquakes occur. Here two plates or parts of plate slide past each other. Also known as a strike slip boundary, the most famous land example is the San Andreas Fault in California but the ocean ridges are split by many such faults caused by different rates of spreading at the ocean ridge. Friction causes the plates to become locked, when the fault breaks because a critical level has been reached seismic waves travel through the surrounding crust as an earthquake.

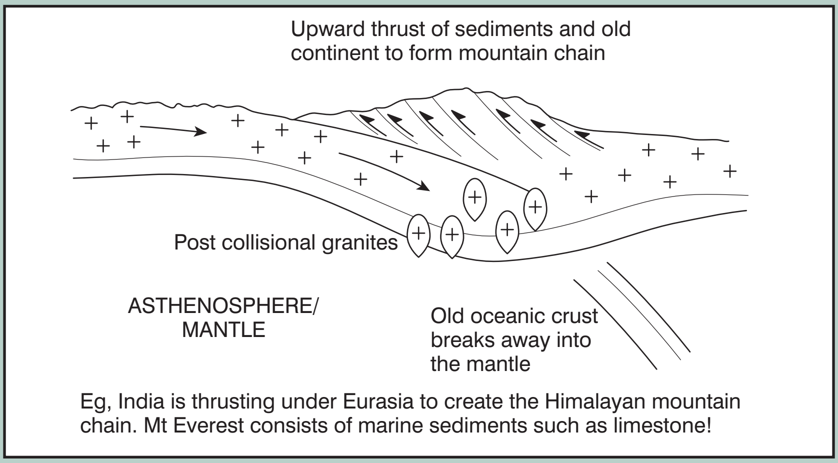


E.g. San Andreas Fault: California: USA

Collision: Where two continents collide – orogenic belt

E.g. India colliding with Asia to form the Himalayas

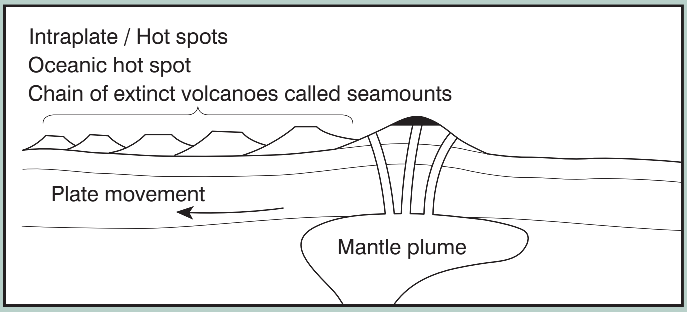
Where continents are pulled towards each other across a shrinking ocean by **slab pull** eventually collision will take place and large fold mountain ranges such as the Himalayas are formed. The "pulled" continent cannot be subducted like oceanic crust as it is too buoyant due to its low density. The continent is **thrust** under the leading edge of the other plate uplifting fold mountains made of oceanic sediments. Occasionally a segment of oceanic crust called an **ophiolite** is scraped off giving an insight into the geology of the ocean floors. Post collision al **granites** are intruded into the base of the mountain chain. Crustal shortening and thickening (70km) takes place.



Africa moving towards Europe to form the Alps

Intra-plate volcanism
Volcanic activity away from plate boundaries

"Jets" of hot mantle or **mantle plumes** called hot spots can pierce the crust away from the plate boundaries and cause intra-plate volcanoes such as those at Hawaii. They also occur in **continental rift zones** and aid the splitting of continents, erupting large volumes of basalt lava in the process. As the plate moves over the stationary hotspot a line of extinct volcanoes is created. Basaltic lava flows are indicative of this type of volcanic plate setting and form extensive flood basalts or **shield volcanoes**.



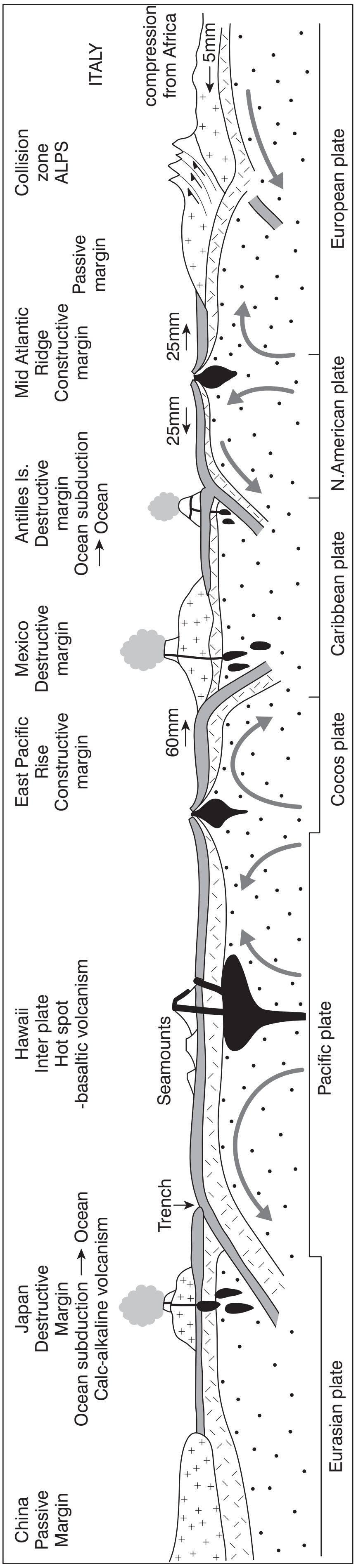
E.g. Hawaii Hot Spot
Yellowstone National Park

destroyed, torn apart and thrust up into fold mountain ranges. Plate movements can be said to be constructive, destructive or conservative.

Constructive, destructive and collisional plate margin relationships

The estimated age of the oldest piece of oceanic crust on the Earth is 200Ma; all older crust has been subducted back into the mantle. For an ocean to form, a continental mass must split or rift. This is thought to be due to increased heat flow from the mantle on the base of the continental crust such as a

Figure 2: Global cross-section of interrelationships between plates and margins

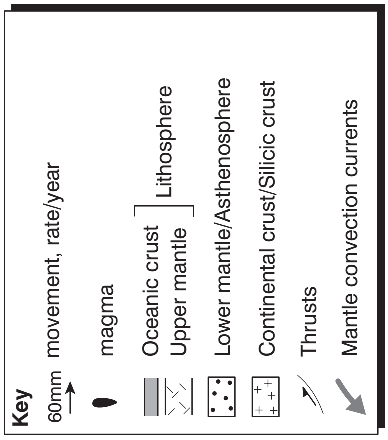


mantle plume. The crust thins as it stretches and extension takes place forming a rift valley. This is thought to be happening in the East African Rift Valley. Volcanism will occur as the crust is stretched. Eventually the continent will rift into two and a new ocean basin and constructive margin will form. As the ocean grows the continental margins will become passive and will move away from the constructive margin. Geologists think that after 200Ma the oceanic crust next to the passive margin will become cold and dense enough to be subducted and the margin will transform into a destructive margin. Once the process of subduction has started it is impossible to stop and the weight and momentum of the descending slab will start to close the ocean if the rate of subduction is faster than the rate of spreading at the constructive margin. Eventually the constructive margin itself will be subducted, as is happening along Pacific North West coast as the last remaining segments of the Juan De Fuca plate are subducted. The two continents will travel towards each other and eventually collide to form a new continent. The complete cycle of ocean opening and closing probably takes around 400Ma.

India was originally attached to Madagascar 65Ma. Rifting and extension caused enormous volumes of continental flood basalts called the Deccan traps to erupt. The rifting was triggered by the Reunion Island hot spot to the east of Madagascar. At one time attached to Madagascar, India has since moved rapidly northwards and collided with Asia to form the Himalayas.

Conclusion

In comparison to the life span of a human being, plate tectonic processes happen impossibly slowly. However, if we consider that the Earth is probably 4.5 billion years old, in that context continents are positively “whizzing” around the planet, splitting apart, forming oceans and then colliding with other continents to form mountain ranges. In Britain we have a while to wait until the North Atlantic starts to subduct underneath Ireland and creates a new chain of volcanoes.



Focus Questions

1 (a) What is the evidence for plate tectonic theory?
(b) In what ways does modern plate tectonic theory differ from Wegener’s theory of continental drift?

2 (a) With the aid of a diagram describe and explain the processes involved at each plate tectonic boundary.
(b). Explain the role of hot spots in continental break-up and intra-plate volcanism.

3. Summarise the way in which plate tectonics accounts for the opening and closing of oceans.

4. Research an example of each of the main types of plate boundary. How do the processes happening affect people? Produce your own plate map and add detailed labels of these examples.

5. Using this article and a geographical/geological dictionary create a glossary of the key terminology highlighted in bold.

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