

Tectonic Setting

By Dr. Shareef Al-Hamed

Introduction

The Earth is composed of layers of different composition and physical properties, principally the solid central or inner core, the fluid outer core, the viscous mantle, and the solid lithosphere. The lithosphere comprises the upper mantle and the crust. There are two types of lithospheres, according to the crust resting on the solid mantle: **(1) Oceanic lithosphere:** has a 5 to 8 km thick oceanic crust (with a basaltic composition). **(2) Continental lithosphere:** has a 30 km to 40 km thick granitic-dioritic crust.

The lithosphere is fragmented into pieces of variable shape and size, called plates. The edges of the plates are known plate boundaries. The Earth has 7 major plates (Africa, Antarctica, Australia, Eurasia, North America, South America, and Pacifica) and several minor ones (Adria, Arabia, Caribbean, Nazca, Philippines, and others). Most of the plates are composed of continental and oceanic lithosphere.

The lithosphere is fragmented into pieces of variable shape and size, called plates. The edges of the plates are known plate boundaries. The Earth has 7 major plates (Africa, Antarctica, Australia, Eurasia, North America, South America, and Pacifica) and several minor ones (Adria, Arabia, Caribbean, Nazca, Philippines, and others). Most of the plates are composed of continental and oceanic lithosphere.

The plates move relative to each other at speeds ranging between 1 and 18 cm/year. This relative movement is expressed as the plates either diverge and then spread, converge and then collide along the boundaries, or slip sideways. According to these movements, igneous rocks are classified based on their tectonic setting or emplacement, as will be discussed later.

Lithospheric plates, commonly called tectonic plates, fit together on the Earth's surface like a jigsaw puzzle. Scientists believe that the plates float on a hot, semi-solid region of partially molten rock that lies within the Earth's upper mantle, known as the **asthenosphere**.

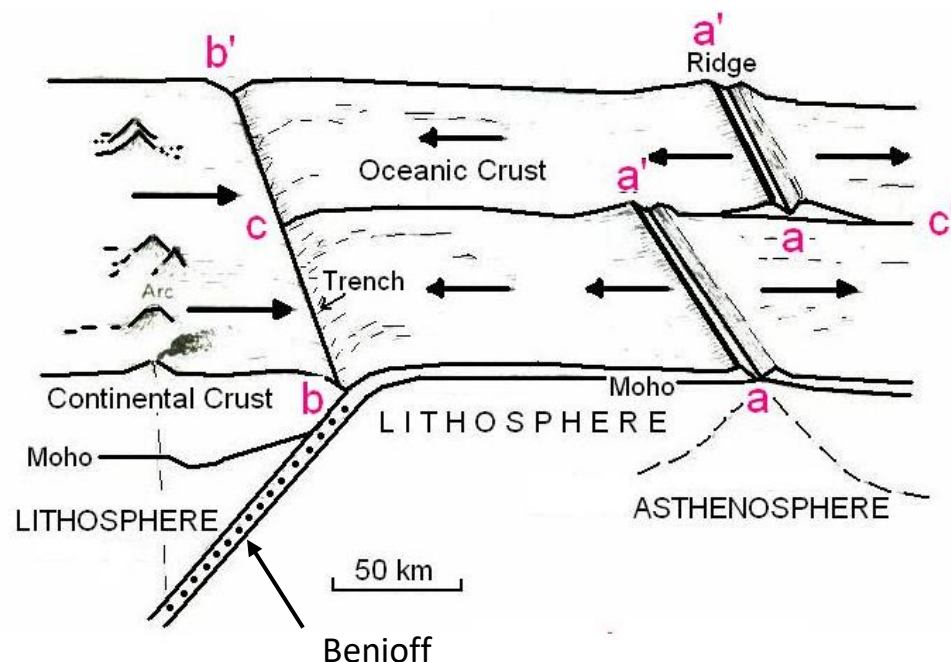
Movement of the lithospheric plates is most easily observed at the plate boundaries, where the plates converge, diverge, or slip sideways. Most earthquakes and volcanism occur along or near lithospheric plate boundaries.

Plate Boundaries

Scientists now have a fairly good understanding of how the plates move and how such movements relate to earthquakes and volcanic activities. Most movement occurs along narrow zones between plates, where the results of plate-tectonic forces are most evident.

There are three types of plate boundaries:

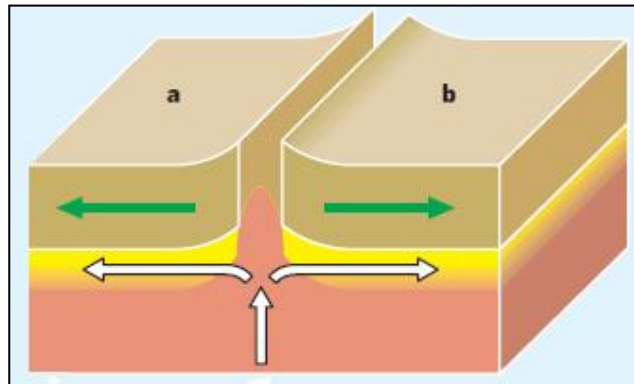
1. Divergent Boundary (Constructive boundary or spreading): where new crust is generated as the plates pull away from each other. It is indicated by the oceanic ridge and expressed by (a-a') in the schematic diagram below.
2. Convergent Boundary (Destructive or Collision): where crust is destroyed as one plate dives under another. It is indicated by the oceanic trench and expressed by (b-b') in the schematic diagram below.
3. Transform Boundary (Conservative boundary): where crust is neither produced nor destroyed as the plates slide horizontally past each other. It is marked by a transverse fault (c-c').



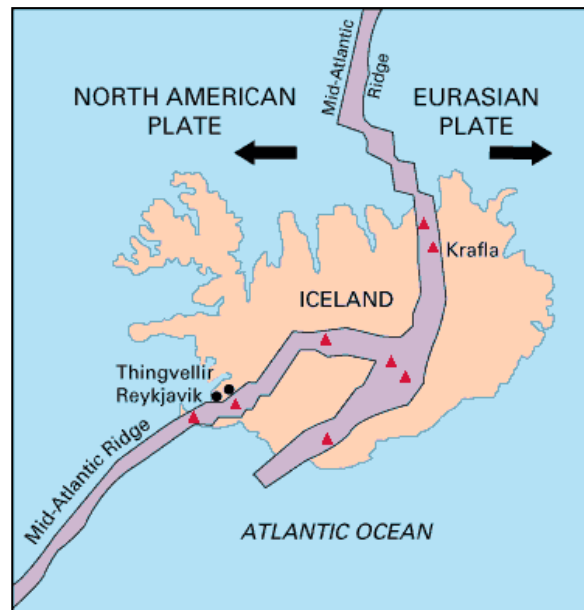
Schematic diagram shows three types of plate boundaries (Barker, 1985).

1. Divergent Boundaries

Divergent plate boundaries occur where two plates are pulling away from each other, and new crust is created by magma pushing up from the mantle. As plates move apart (slowly moving), magma wells up from beneath the surface to fill the spaces left by the diverging plates. The magma rises and cools in a continuous process, forming chains of volcanic mountains and rift valleys called the Mid-Oceanic Ridge (MOR). This process formed the Mid-Atlantic Ridge.



As magma cools and forms a new crust, it pushes the plates apart in a process called oceanic spreading. For example, oceanic spreading pushed North America away from Eurasia.



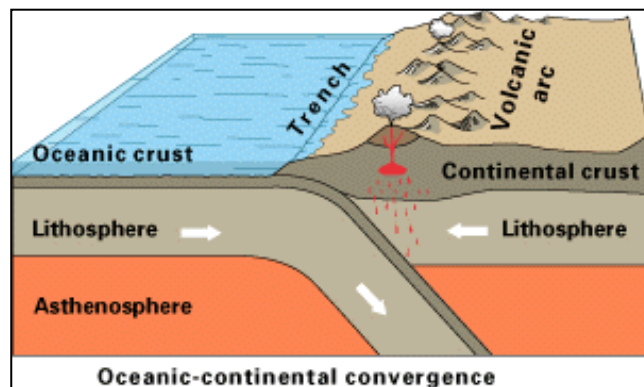
Map showing the Mid-Atlantic Ridge splitting Iceland and separating the North American and Eurasian Plates. The map also shows Reykjavik, the capital of Iceland and the locations of some of Iceland's active volcanoes (red triangles).

2. Convergent Boundaries

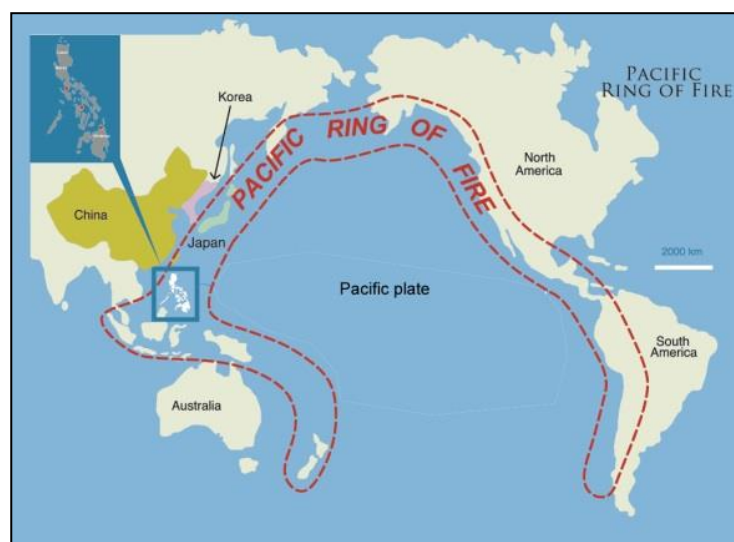
The plates are moving toward each other. The type of convergence, called by some a very slow "collision" that takes place between plates, depends on the kind of lithosphere involved. Convergence can occur between an oceanic and continental plate, or between two oceanic plates, or between two continental plates.

(a) Oceanic-Continental Convergence

When the oceanic lithosphere and continental lithosphere collide, the dense oceanic lithosphere subducts beneath the less dense continental lithosphere. The location where the sinking of a plate occurs is called a subduction zone. Subduction zones are associated with strong earthquakes and spectacular volcanic landscapes.

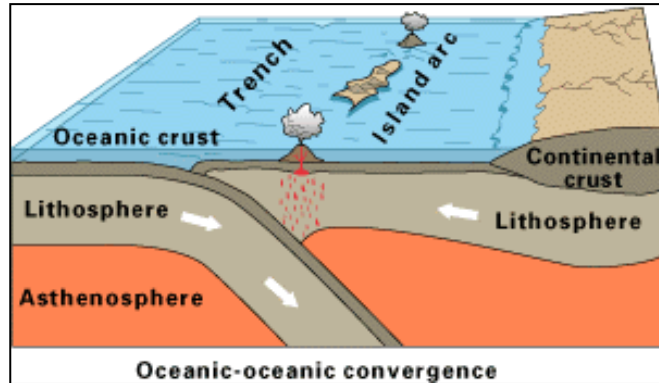


The Ring of Fire around the margins of the Pacific Ocean is a direct result of plate convergence and subduction.

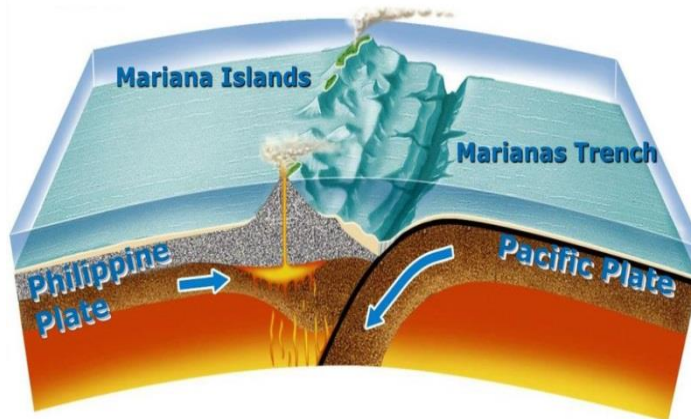


(b) Oceanic-Oceanic Convergence

When collisions occur between two oceanic plates, the cooler, denser oceanic lithosphere sinks beneath the warmer, less dense oceanic lithosphere.



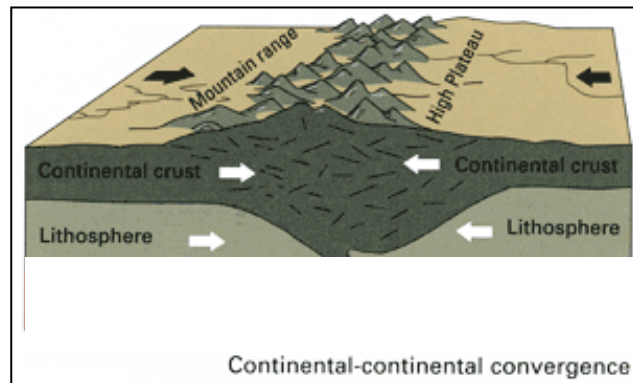
The Marianas Trench (paralleling the Mariana Islands), for example, marks where the fast-moving Pacific Plate converges against the slower-moving Philippine Plate.



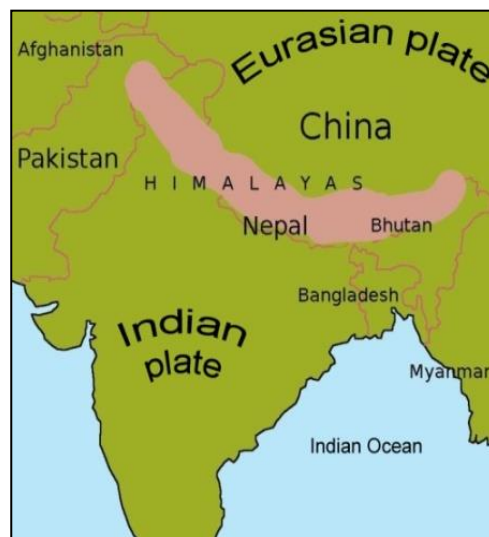
Subduction processes in oceanic-oceanic plate convergence also result in the formation of volcanoes. Over millions of years, the erupted lava and volcanic debris pile up on the ocean floor until a submarine volcano rises above sea level to form an island volcano. Such volcanoes are typically strung out in chains called island arcs. Magmas that form island arcs are produced by the partial melting of the descending plate and/or the overlying oceanic lithosphere. The descending plate also provides a source of stress as the two plates interact, leading to frequent moderate to strong earthquakes.

(c) Continental-Continental Convergence

Sometimes continental plates of similar density collide and neither is heavy enough to create a subduction zone. When this happens, the brittle crust folds up and splinters as the plates collide.



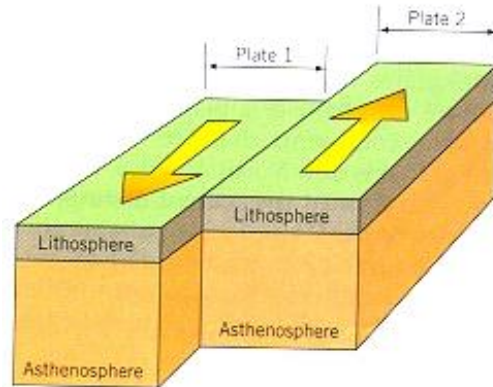
This process created the Himalayan Mountains.



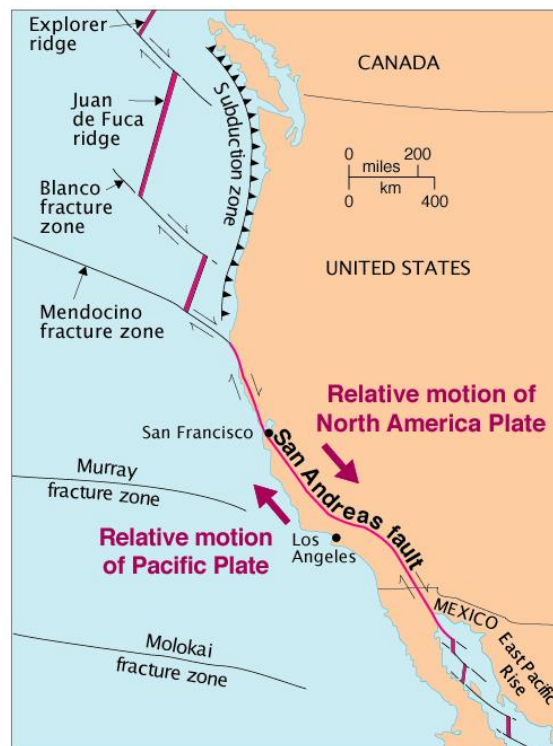
This figure shows that the collision between the Indian and Eurasian plates has created the Himalayas.

3. Transform Boundaries

The zone between two plates sliding horizontally past one another is called a transform-fault boundary, or simply a transform boundary.



Most of these faults are hidden in the deep ocean, but the San Andreas fault zone in California is one of the few transform faults exposed on land. This transform fault connects the East Pacific Rise (divergent boundary) with the Juan de Fuca, Explorer Ridge, and another divergent boundary. The San Andreas fault zone, which is about 1,300 km long and in places tens of kilometres wide, slices through two-thirds of the length of California.



Tectonic Environments of Igneous Rocks

We can summarize the tectonic environments of igneous rocks as follows:

(A) At divergent boundaries

- (1) Mid-Ocean Ridges (MOR)
- (2) Back-arc basins
- (3) Continental rifts

(B) Along convergent boundaries

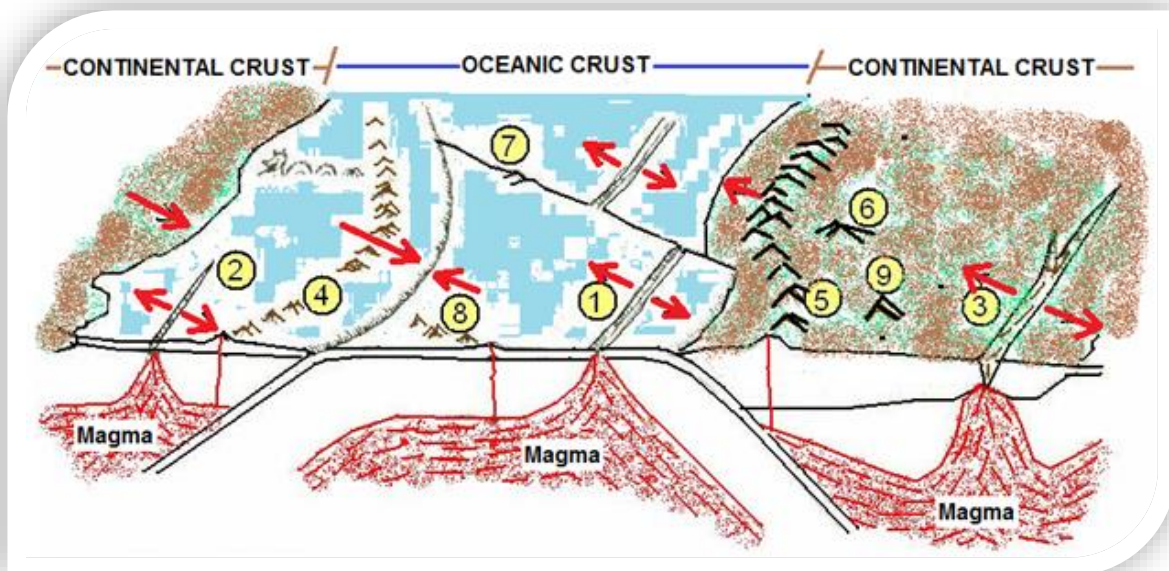
- (4) Oceanic-oceanic collision → Island arcs (oceanic arcs)
- (5) Oceanic-continental collision → Volcanic arcs
- (6) Continental-continental collision → Mountains

(C) At transform boundaries

- (7) Volcanoes in the faults area

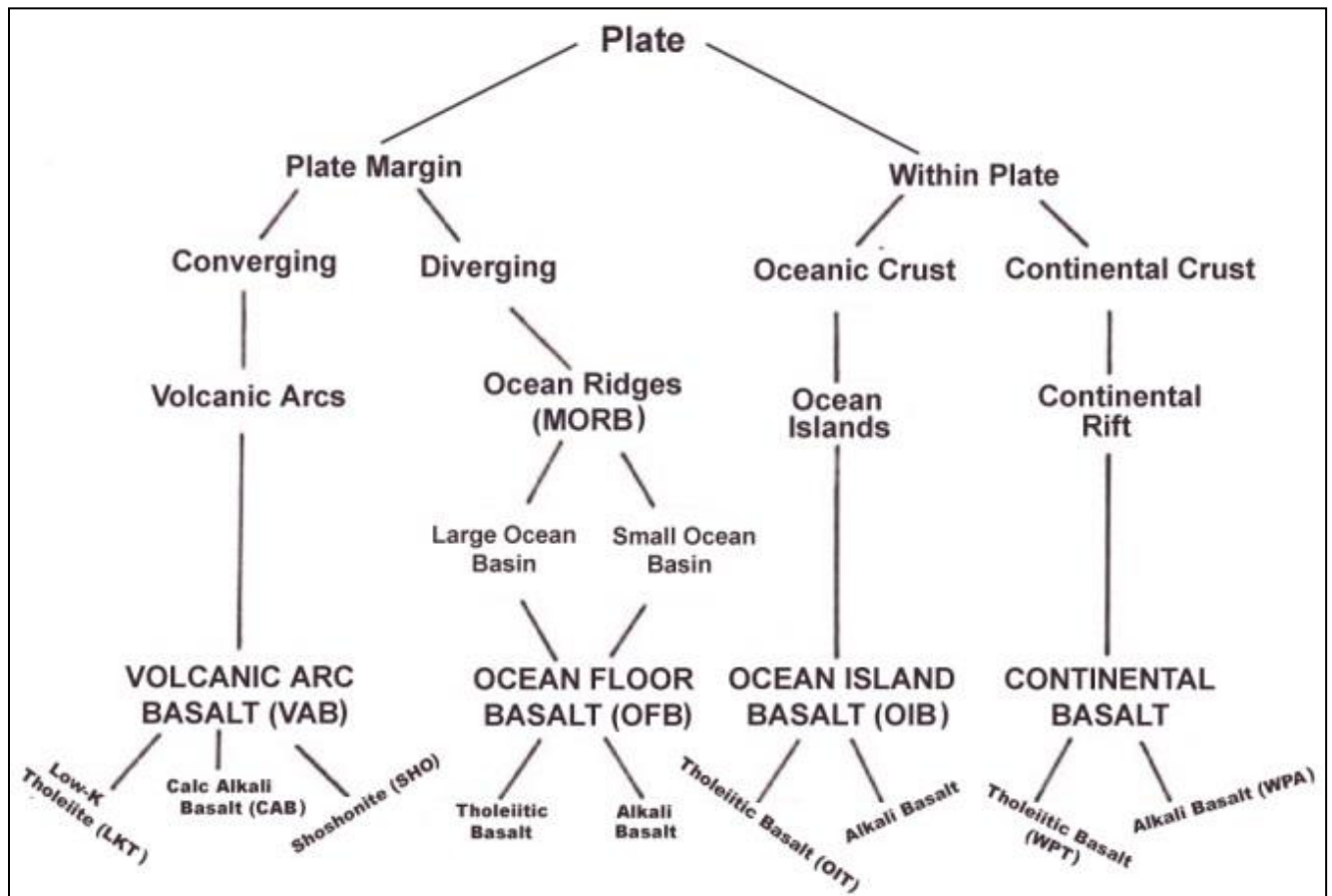
(D) Intraplate magmatism

- (8) Oceanic Islands and islands chains.
- (9) Intracratonic magmatism



Schematic diagram showing the nine tectonic environments of igneous rocks (Barker, 1983).

Tectonic Classification of Basalts



Oceanic Igneous Rocks

The ocean basins cover the largest area of the Earth's surface because of plate tectonics; however, most oceanic lithosphere eventually is subducted. Most of the oceanic magmatism is difficult to access, where samples of rocks can be obtained from drilling and expeditions of small submarines to the ocean floor. Numerous samples have been recovered and studied. Most of the magmatism is basaltic composition.

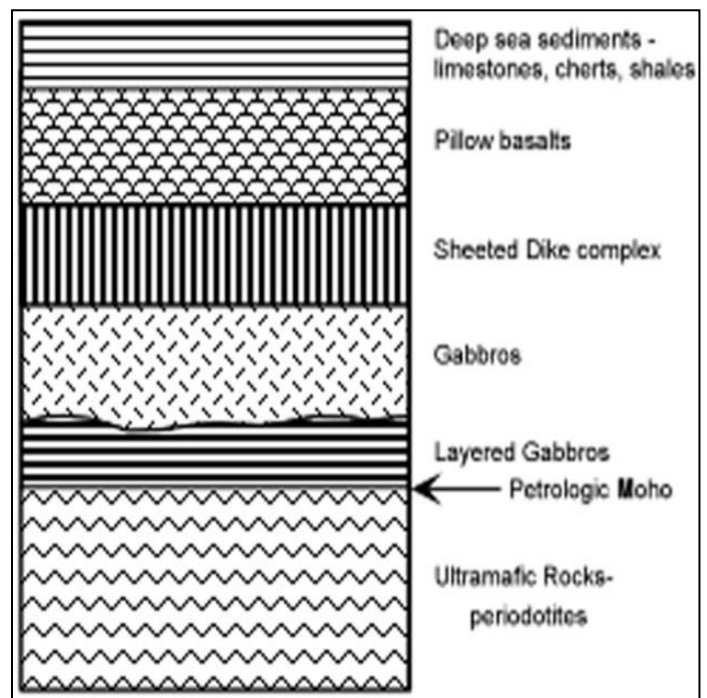
We can now identify basaltic rocks and their advanced series and relate them to their tectonic setting by the following terms:

1. Ophiolites

An ophiolite is a section of the Earth's oceanic crust together with the underlying upper mantle that has been uplifted and exposed above sea level and often emplaced onto continental crustal rocks. Ophiolites occur in areas where obduction (the opposite of subduction) has pushed a section of oceanic lithosphere onto continental crust.

During this process, most ophiolite sequences have been highly deformed and hydrothermally altered.

An idealized ophiolite sequence shows an upper layer consisting of deep-sea sediments (limestones, cherts, and shales), followed by a layer of pillow basalts. Such a pillow structure is typical of lavas erupted under water. The pillow basalts are followed by a layer consisting of numerous dikes, some of which were feeder dikes for the overlying basalts. Beneath the sheeted dike complex are gabbros that likely represent the magma chambers of basalts. The upper gabbros are massive, while the lower gabbros show layering that might have resulted from crystal settling. At the base of the



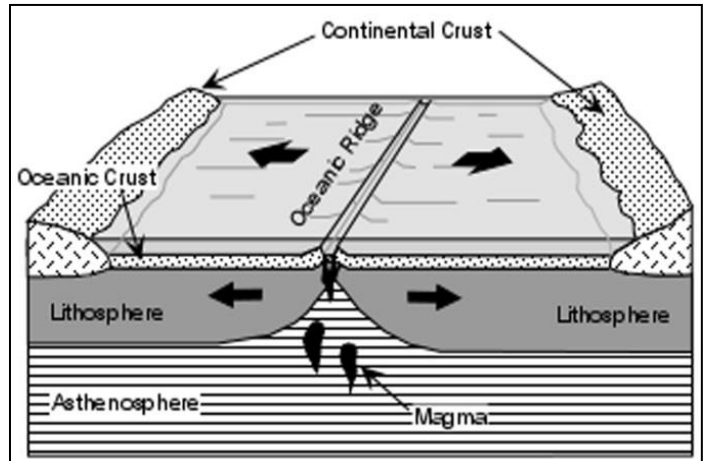
layered gabbros, there is a sharp increase in the density of the rocks, and the composition changes to ultramafic rocks (peridotite). This sharp change in density is correlated with what would be expected at the base of the crust and is thus referred to as the petrologic moho.

Ophiolites' great significance relates to their occurrence within mountain belts such as the Alps or the Himalayas, where they document the existence of former ocean basins that have now been consumed by subduction because ophiolite represents oceanic crust that had been emplaced on the continent.

2. Mid Oceanic Ridge Basalt (MORB)

Oceanic ridges are probably the largest producers of magma on the Earth. Yet, much of this magmatism goes unnoticed because it all takes place below the oceans. This magmatism is responsible for producing oceanic crust at divergent plate boundaries. Some contents of the asthenosphere transfer to substitute for the deficit that occurs as a result of the divergence of the lithosphere plates.

Magma is both erupted and intruded near the central depressions that form the oceanic ridges. Thus, both basalts and gabbros are produced. But little is known of the gabbros since they are rarely exposed, and most oceanic lithosphere eventually is subducted. The main melting mechanism is likely decompression melting as rising convection cells move upward through the mantle beneath the ridges.



At most mid-ocean ridges, the erupted basalts are predominantly tholeiitic basalts, commonly referred to as NMORBs (Normal Mid-Ocean Ridge Basalts). It differs from the alkaline basalt that formed far from spreading centers. Moreover, tholeiitic basalt is generated by relatively high degrees of partial melting of the mantle and is geochemically characterized by higher SiO_2 , CaO , and MgO and lower TiO_2 , K_2O , and P_2O_5 contents, whereas alkaline basalt forms from lower degrees of partial melting and exhibits lower SiO_2 but enrichment in alkali elements (Na_2O and K_2O) along with comparatively higher TiO_2 and P_2O_5 .

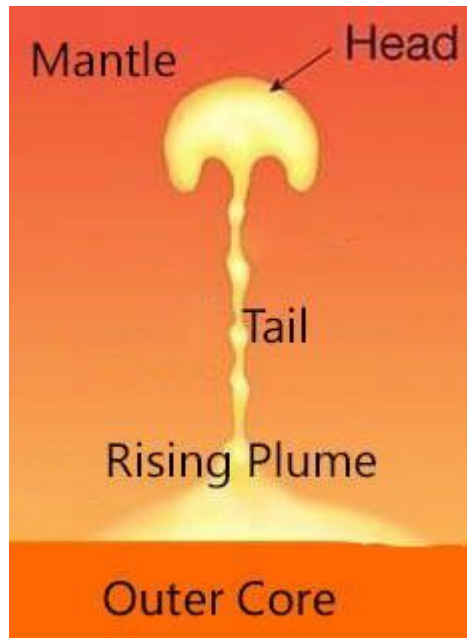
3. Oceanic Island Tholeiite (OIT)

Oceanic Island Tholeiites (OITs) are formed from hot spots, occurring when an oceanic plate moves over a deep, stationary **mantle plume**. These tholeiitic lavas, a major component of some oceanic islands like Hawaii and Iceland.

A hotspot is a volcanically active area on the Earth's surface that results from a stationary plume of hot mantle material rising from deep within the planet. This plume creates a region of exceptionally hot, buoyant mantle rock that melts and forms magma. The magma then rises through cracks in the tectonic plate above, erupting at the surface to form volcanoes. As the tectonic plate moves over the fixed hotspot, a chain of volcanoes forms, with older volcanoes carried away from the hotspot location.

- The mantle plume is shaped like a mushroom with a long conduit (tail) connecting the bulbous head to its base. The head expands in size as the plume rises.

- The plume rises through the Earth's mantle, becoming a **diapir** (dome-like intrusion forced into brittle overlying rocks) in the upper mantle (lower parts of the lithosphere).

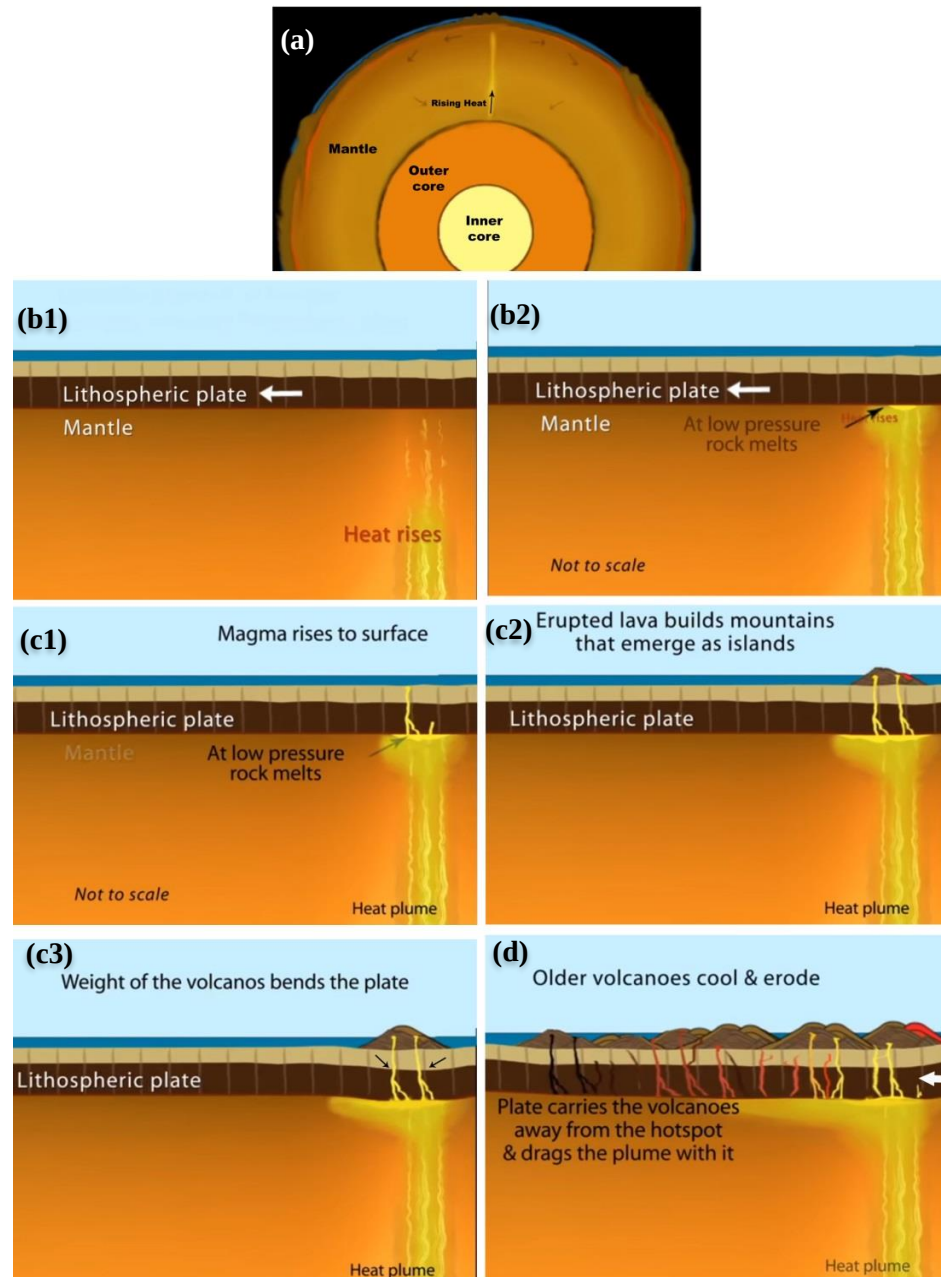


- Mantle plumes (a few hundred kilometres in diameter) rise slowly towards the upper mantle.
- When a plume head encounters the base of the lithosphere, it flattens out and undergoes widespread decompression melting to form large volumes of basalt magma.
- Hot spots are characterized by basaltic volcanoes where thermal energy (plume) travels from the depths. The hot spots occur within oceanic crust, and 50% of them occur near the MOR, for example, Iceland and Hawaii.
- A hotspot is a localized source of high heat energy that sustains volcanism.
- One theory holds that hot spots may begin as a blowtorch-like thermal perturbation in a zone between the liquid outer core and overlying mantle about 2900 km deep.

Let's zoom in to look at hot spot volcanism beneath a moving plate (Hawaiian Island Style):

- The plume rises through the Earth's mantle (Fig. a).
- The heat is transferred to the adjacent rocks; this process continues to the base of the tectonic plate, where decreased pressure facilitates rock melting (Fig. b1 and b2).
- The magma that forms at the base of the plate rises through the plate in a network of cracks and shallow chambers and erupts on the surface (Fig. c1 and c2).

- Over 100s of thousands of years, larger volcanoes built atop the plate; the weight of the volcanoes bends the plate downward (Fig. c3).
- Volcanoes that spent their constructive life over the thermal plume slowly get rafted away on the moving plate and new volcanoes build in their place. Multiple dikes can feed several volcanoes from separate conduits; the moving plate drags the thermal plume with it (Fig. d). This can explain why volcanoes can erupt again after centuries of quiescence, even after they have moved off the center of the hot spot.



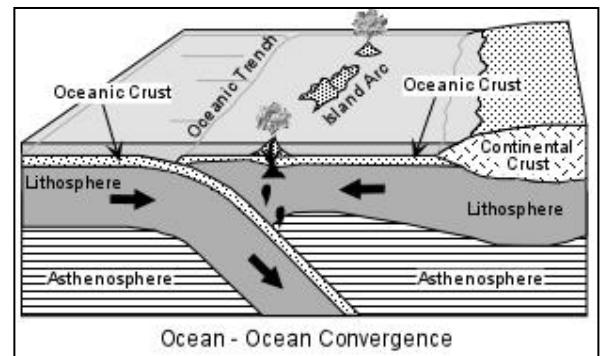
4. Supra Benioff Zone (SBZ)

Active subduction is taking place along the convergent plate boundaries, as evidenced by the zone of earthquakes, called a Benioff Zone, that begins near the oceanic trenches and extends to deeper levels in the direction of plate motion. Earthquake focal depths reach a maximum of about 700 km in some areas. Volcanism occurs on the upper plate about 100 to 200 km above the Benioff Zone. For this reason, volcanism in these areas is often referred to as subduction-related volcanism.

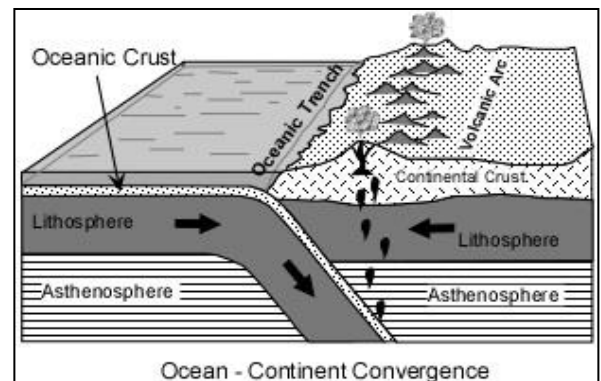
As an oceanic plate subducts, it is subjected to great heat and pressure and forms magma. The magma starts to rise up towards the crust, and then the magma pushes through the crust and forms a volcano. The volcano expands, and then more volcanoes begin to form from other parts of the subduction zone. All the volcanoes gradually grow larger, and they continue to grow larger to form the island arcs or volcanic arcs above continents or oceans. These arcs consist of volcanic rocks formed above the Benioff Zone, where they are called by supra Benioff zone series.

Two situations occur:

1- In areas where oceanic lithosphere is subducted beneath another oceanic lithosphere, the volcanism is expressed on the surface as chains of islands referred to as island arcs. These include, for example, Caribbean Arc, Japan, Philippines, Indonesian Arc, and Marianas.



2- In areas where oceanic lithosphere is subducted beneath continental lithosphere, volcanism occurs as chains of volcanoes near the continental margin, referred to as a continental margin arc. For example, Andes Mountains, Central American Volcanic Belt, Mexican Volcanic Belt, and North Island of New Zealand.



Benioff zone series are characterized by their clear variation in potassium content. The rocks that have less K content are called **low K tholeiite (LKT)** or **island arc**

tholeiite (IAT), and those of medium K content represent the **Calc-alkaline series**; while those of high K content are called **Shoshonite**.

This volcanic series is related to the age of the subduction zone and the depth. The tholeiitic magma series is well represented above young subduction zones formed by magma from relatively shallow depth. The calc-alkaline series is seen in mature subduction zones and is related to the magma of greater depths.

Continental Igneous Rocks

A wide variety of igneous rocks occur in the continental lithosphere, a reflection of its heterogeneous nature compared to the oceanic lithosphere. In addition, because the continents are not subducted and are subject to uplift and erosion, older plutonic rocks are both preserved and accessible to study.

Granitic Rocks

Types of Granitic Rocks:

1. S-type Granites

S-type granites are thought to originate from the melting of a pre-existing metasedimentary or sedimentary source rock. These are peraluminous granites [i.e. they have molecular $\text{Al}_2\text{O}_3 > (\text{Na}_2\text{O} + \text{K}_2\text{O})$]. Since many sedimentary rocks are enriched in Al_2O_3 as a result of their constituents having been exposed to chemical weathering near the Earth's surface (particularly rocks such as shales that contain clay minerals), melting of these rocks is a simple way of achieving the peraluminous condition.

Many S-type granites are found in the deeply eroded cores of fold-thrust mountain belts formed as a result of continent-continent collisions, such as the Himalayas and the Appalachians, and would thus be considered orogenic granites.

2. I-type Granites

I-type granites are granites considered to have formed by the melting of an original igneous type source. These are generally metaluminous granites, expressed mineralogically by the absence of peraluminous minerals and the absence of peralkaline minerals.

I-type granites are found in the Himalayas, which are related to continent-continent collisions and would thus be considered orogenic granites.

3. A-type Granites

A-type granites are generally peralkaline in composition ($\text{Na}_2\text{O} + \text{K}_2\text{O} > \text{Al}_2\text{O}_3$). A-type granites form in extensional or post-collisional, typically anorogenic (non-mountain-building) settings, often originating from either mantle-derived basaltic magmas that undergo extensive fractional crystallization and assimilation, or by crustal melting of a previously metasomatized (altered by fluids) crust.

A-type granites are characterized by highly ferroan and potassic major element compositions, and by strong enrichment in incompatible trace elements, unlike I- and S-type granites.