Geography Optional 2024

NEETU SINGH

THEORIES ON MOUNTAIN BUILDING AND VOLCANISM

Continents and Ocean basins being the fundamental relief features of the globe are the **relief features of first order**. About 70.8% of total surface area of globe is represented by the oceans whereas remaining 29.2% is represented by continents. The distributional aspects however is different in the hemispheres. There is overwhelming dominance of land areas in Northern Hemisphere, with more than 75% of the total land area of globe situated to the north of equator. Water bodies on the other hand is dominate in Southern Hemisphere. **Continents** are also identified with **typical triangular** arrangements. Most of them have their apices in south and base in north. Except Australia and Antarctica this norm is applicable to all the continents. Eurasia has base along Arctic and apexto to East Indies, North-South Americas forms equilateral triangle with base as Cape Horn. Similarly Africa has triangular apex as Cape of Good Hope. **Oceans** are also **triangular** however the alignment is opposite to that of continents, i.e. their apices is towards north. Atlantic Ocean has its base between Cape Horn and Cape of Good Hope and apex east of Greenland. Indian Ocean has two apexes as in Arabian Sea and Bay of Bengal. Pacific Ocean has its apex near Aleutian islands. North pole has oceanic and south pole has continental surroundings. There is **antipodal arrangement** of continents and oceans. Only 44.6% oceans are situated opposite to land area. More than 95% of land is situated diametrically opposite to water bodies. The two exceptional cases includes – Patagonia being opposite to north China and New Zealand to Iberian Peninsula. **Pacific Ocean basin** occupies one third of entire surface area of globe.

Several attempts to explain the origin and evolution of the continent and ocean basin have been registered. The hypothesis still recognized with scientific validity includes

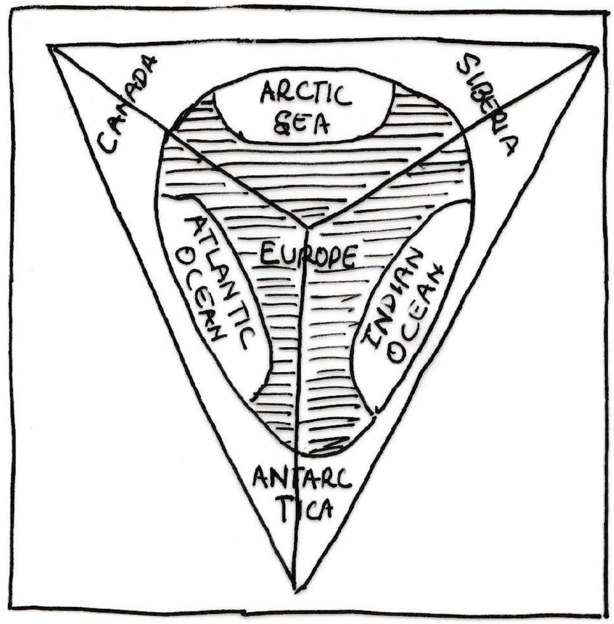
(a) Tetrahedral hypothesis of Lowthian Green

(b) Continental drift theory of F.B. Taylor

(c) Continental drift theory of Alfred Wegner

(d) Plate Tectonic theory

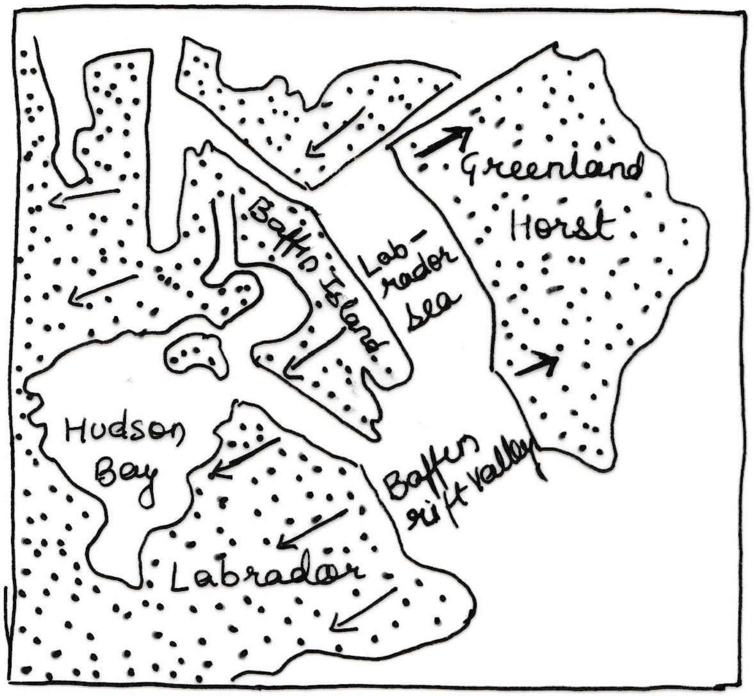
Tetrahedral Hypothesis: It is the hypothesis based on the fundamental principal of geometry. In 1875 it was propounded by Lowthian Green. He based his hypothesis on the characteristics of the distributional pattern of land and water. The two principles of geometry – a sphere is that body which contains the largest volume with respect to its surface area and a tetrahedron is that body which contains the least volume with respect to its surface area – have been the basis of the hypothesis. According to the scholar, when the earth originated, it was in the form of sphere. Eventually, the outer part cooled down to form crust. Inner part left molten was subjected to more contraction and thus there was marked reduction in the volume of the inner part. The absence of contraction of crust resulted in possible gap between the upper and inner parts of the earth. The eventual collapse led to the initiation of shape of a tetrahedron. The process of cooling is still underway and earth cannot attain the shape of true tetrahedral because of its structural variations. In case of earth the oceans represents the plane faces and land mass the apices, though not as sharpened as in real geometric figure rather they are flat and convex. Four oceans were created on four plane faces of terrestrial tetrahedron. These plane faces could retain water because of the fact that these were lower than the level of apices.



Lowthian claimed to see a tetrahedral arrangement in the distribution of continents and oceans in such a way that the earth was linked to a tetrahedron having four flat faces and standing on one point. The upper flat face represents the Arctic while others the rest of the oceans. The three vertical meridianal edges represent North and South Americas, Europe, Africa, Asia, while the lower point being Antarctica. The presence of water in North Pole and continental South Pole is thus proved. The three apex present the oldest rigid masses around which the present continents have grown. Laurentian, Baltic and Siberian shields the fourth being Antarctica. All the continents developed along the edges taper southward proving triangular shape. This positioning also proves antipodal position of land and water. In the present context however, it is being discarded on several lines.

It is argued that the balance of the earth in the form of a tetrahedron while rotating on an apex cannot be maintained. Rotating earth cannot take the shape of tetrahedron on contraction. Moreover the hypothesis believes in permanency of basins.

Continental Drift Theory of Taylor: F.B. Taylor postulated his concept of horizontal displacement of the continents in 1908. The hypothesis was to explain the problem of origin of the folded mountain of tertiary period. He attempted to explain the arrangement of the mountains. Taylor identified that in Cretaceous period, there were two land masses. Lauratia and Gonwana land were located near the north and south poles respectively. Continental crust was identified to be made up of sial. The continents due to tidal force moved towards equator and westward. Lauratia started moving away from north pole because of tidal force of moon in radial manner.The thus created splitting and rupture of land masses developed. Baffin Bay, Labrador Sea and Davis Strait. In similar manner displacement of Gondwana land from south pole led to the disintegration of it leading to Great Australian Bight, Ross Sea. Arctic Ocean, Indian and Atlantic oceans were supposed to be filled up gaps. Mountains and island arcs were formed in the frontal part of the drifting continents. Himalayan Cordilleras, Alpine Cordilleras were formed due to equator ward drift whereas Rockies and Andes due to westward drift. The significance of the concept is that it proved absence of permanency of crystal basins and has forcefully objected the contraction theory.

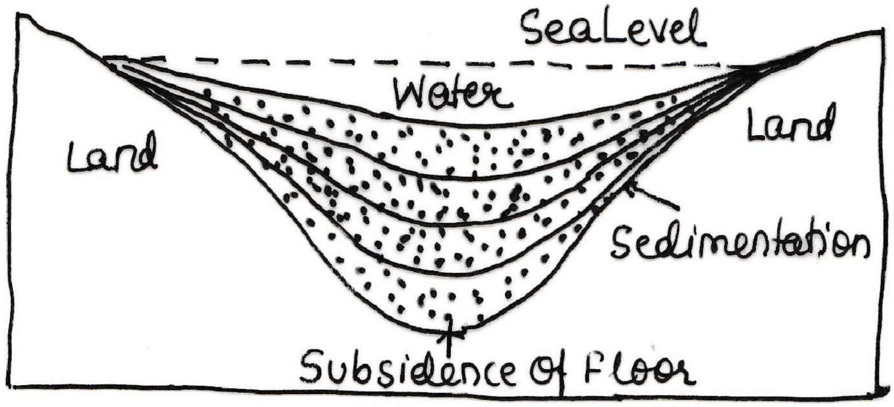


It was however the amended attempt of Alfred Wegner and ultimately the Plate Tectonic theory that led to the explanation of the development of ocean and continental crust.

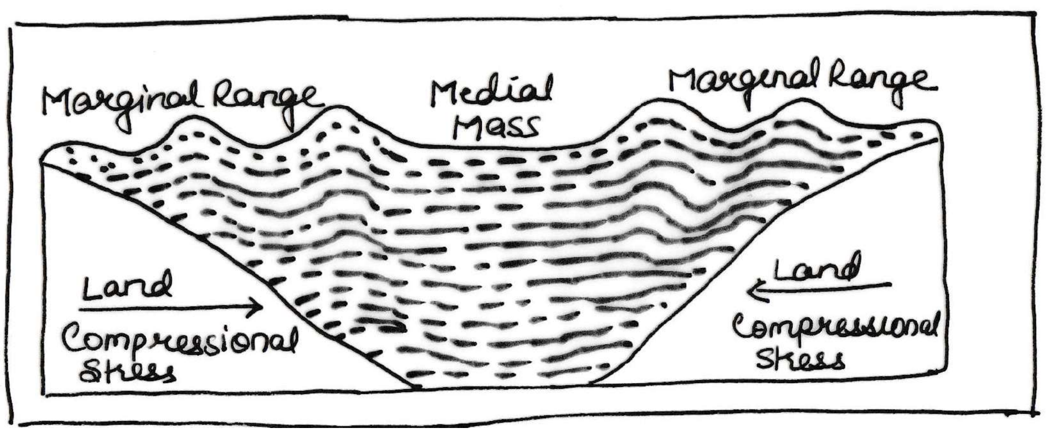
Most of the theories of mountain building have been oriented towards analysis the origin of folded mountain. The common factor for most of the theories has been based on horizontal forces.

The **Geosyncline concept of Kober** – the German geologist presented detailed and systematic description of surface features. He aimed at explaining relation between ancient rigid masses and more mobile zones or geosynclines. The theory also explained geological history and evolution and development. The theory is based on the forces of contraction produced by cooling of the earth. According to him, there were mobile zones of water in place of mountains – the geosyncline. Mid pacific geosyncline separated north and south pacific forelands which were later on foundered to form Pacific Ocean. Eight morphotectonic units can be identified on the basis of description of surface features during Mesozoic era. Six major periods of mountain building periods have been referred. Three mountain periods were of pre-Cambrian. Paleozoic era had two major mountain building periods. The last activity known as Alpine orogeny was completed during tertiary epoch. Geosyncline, the mountain formation places are long and wide water areas characterized by sedimentation and subsidence.

The stage development of mountains is referred with **lithogenesis** – the geosyncline surrounded by rigid masses the fore lands. The forelands subjected to erosion leads to deposition of sediments in syncline.



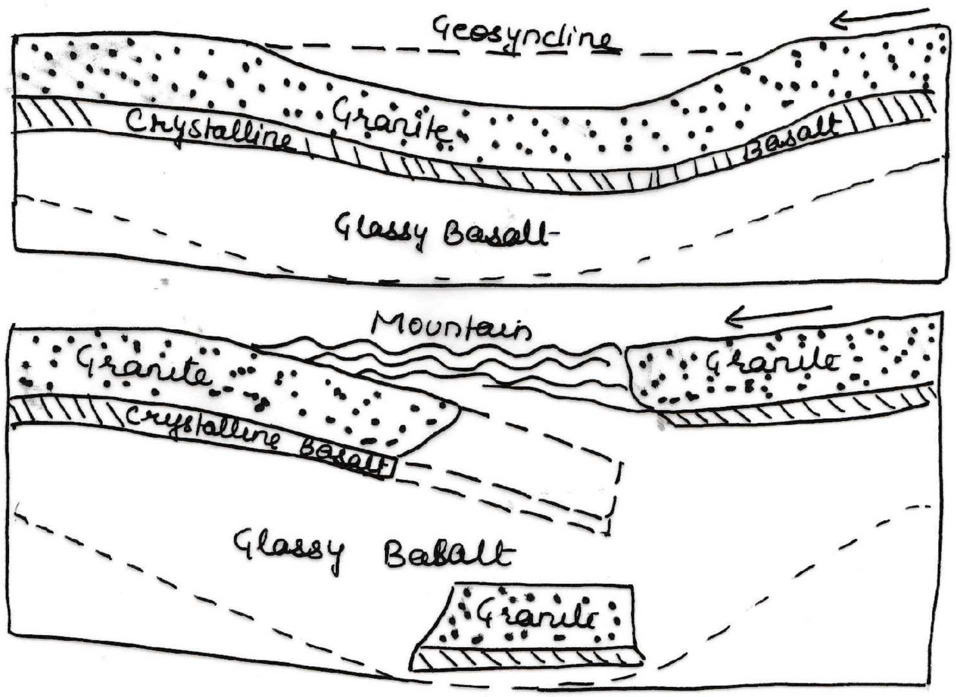
The load of sediments leads to gradual subsidence. **Orogenesis** – the stage when the forelands start to move towards each other because of horizontal movements caused by the force of contraction resulting from the cooling of the earth. The compressive forces generated by the movement of forelands together cause contraction, squeezing and folding geosyncline. The folding of entire sediments of the geosyncline depends upon the intensity of compressive forces. The sediments of geosyncline are folded to form two marginal and middle portion of it remains unaffected called **median mass.**



The ultimate **glyptogenesis** results in full development and complexity in the mountains because of acute compression. The idea of medial mass of Kober fully explains the process of mountain building. The sediments of Tethys Geosyncline were compressed and folded due to the movements of European land mass foreland and African rigid mass together in the form of Alpine mountain system. According to Kober Asiatic Alpine folded mountain can be grouped into – ranges which were formed by the northward compression include Caucasus Pontic and Tauraus, Kunlun, Yunnan, Annan ranges and ranges which were formed by the southward compression include Zagros, Elbruz of Iran.

Thermal contraction of Jeffreys: Jeffreys was strongly in favour of the contraction theory to explain origin and evolution of major relief of the earth's surface and also the distributional pattern. Jeffreys used the force of contraction resulting partly from cooling of the earth due to loss of heat through radiation and partly from the decrease of the speed of earth's rotation (about 1600 million years ago, earth completed its one rotation in about 0.84 hour whereas presently it is about 24 hours). The decrease in rotational speed caused contraction in equatorial circumference of the earth. A decrease in temperature upto 400°C in 400 km thick outer shell of the earth would cause shortening of the diameter of earth by 20 km and circumference by 130 km due to cooling and contraction. This cooling however was effective only upto 700 km. Moreover, upper layer cooled earlier and more than the layer beneath. After maximum cooling and resultant contraction, the lower layer first lying underneath to top layer began to cool and contract. As a result already cooled and contracted upper layer becomes too large to fit. Hence the upper layer has to collapse on the lower layer. This results in decrease in the radius of earth which causes horizontal compressive stress leading to bucking and folding of rocks of upper layer. The mountains thereby are formed. The lower layer remains too short to fit with core and thus spreads horizontally. This lateral spread and thinning out introduces a state of stress which causes breaking of rocks, leading to further rise of the mountain. Jeffreys also identified that the process has not been active throughout the geological **periods**. It is only marked when accumulated compressive and tensile force exceeds the rock strength. This causes folding, faulting and process of mountain building. The **zones** of mountain building has been the region of hard and less elastic rocks. Here cooling of oceanic regions have been recognized to be more active. The force of contraction is thus directed from the oceanic crust to continental crust. Formation of Rockies and Andes very well proves it. The theory, however has been criticized on several grounds. The force of contraction resulting from the cooling of the earth is not sufficient enough to account for origin of major surface features, cooling of earth in system of concentric shells, impact of decrease in rotational speed on mountain building. Moreover the uniform distribution of continents and oceans is doubious.

Sliding Continent Theory of Daly: Theory postulated by Daly in 1926 to explain causes and process of mountain building. The main force of gravity was implied for origin of mountain. The entire theory is based on the nature and rate of downward slide of continents. To present his theory, Daly presented some axioms. A solid crust was formed just after the origin of earth – **the primitive crust**. These ancient rigid masses were generally located near poles or around equator – **the polar** and **equatorial domes**. These collectively made three masses of primitive crust. The rigid masses were separated by depressed region called **Mid latitude furrows** and **Primeval Pacific Ocean** (the geosyncline). He recognized the granitic crust and basaltic substratum. He also identified that Tethys geosyncline (northern mid latitude furrow between north polar dome and equatorial dome) was a marked feature throughout much of geological time. Land masses projected above the water bodies and the polar and equatorial domes were sloping towards mid latitude furrows and the pacific ocean. The collapse of primitive crust has been the basic assumption, however has not been explained by the scholar. It appears that the mid latitudinal furrows were formed as geosynclines due to collapse of outer crust on the contracting interior of the earth and due to the gravitational force coming from the center of the earth. The sediments derived through the erosion of polar and equatorial domes were deposited. By rivers into the mid latitudinal furrows and the pacific ocean.



Continuous sedimentation and weight of oceanic water exerted enormous pressure on beds of the oceans – geosyncline, with the result their beds experiences continuous subsidence. This caused lateral pressure on the continental masses, with the result they were transformed into broad continental domes known as polar and equatorial domes. As the oceanic beds were depressed downwards due to gravitational force of the earth's center and weight of oceanic water and geosynclinal sediments, the size of domes continued to increase. This expansion led to the oceanic beds rupture and break. Thus the support of continental domes was removed which introduced strong tensional movements due to which larger blocks of continental mass began to slide towards the geosyncline giving birth to mountains. This explains the distributional patterns of mountains as east-west (temperate geosyncline) and north-south (pacific geosyncline). The theory however fails to present coherent account of the mountain building. The theory does not go into details and is based on the self proved axioms.

GEOSYNCLINE

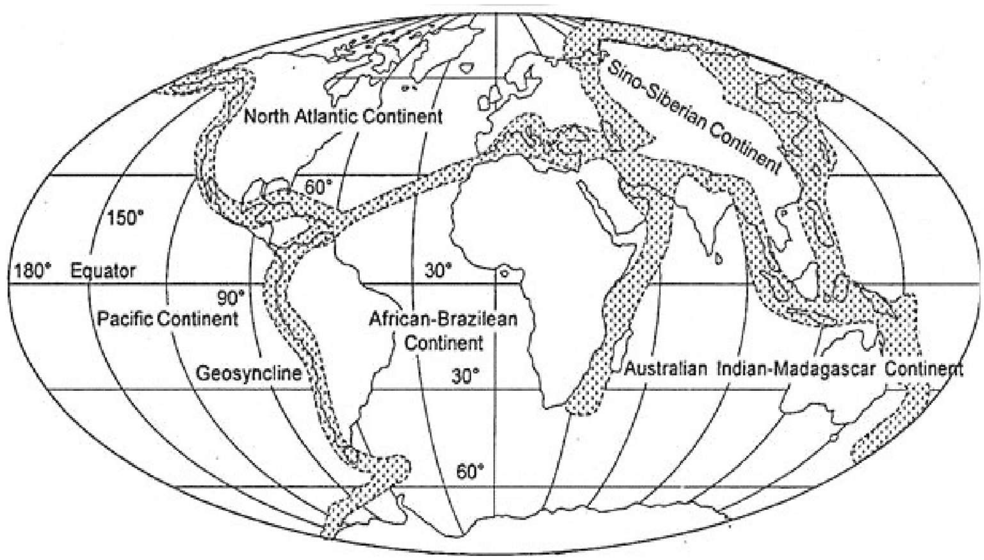
The geological history of the earth denotes presence of two important features - the rigid masses and the geosyncline, the former representing the ancient nuclear of the present continents have remained stable for considerably longer periods of time. These were surrounded by mobile zones of water characterized by extensive sedimentation - geosyncline**. Geosynclines** are a long but narrow shallow water depression that undergoes continuous subsidence. These are mobile zones of water, which are generally bordered by two rigid masses called **forelands**. The nature and patterns of geosynclines have remained same throughout the geological history, rather these have widely changed. The location, shape, dimension and extent of geosynclines have considerably changed due to earth movements and geological process.

The concept of geosyncline was given by **James Hall** and **Dana**. It was elaborated by **Haugh**. The concept of **Hall and Dana** was based on the studies of folded mountain. They concluded that the sediments of the rocks of folded mountains were of marine origin. These rocks were deposited in long, narrow and shallow seas. Dana named such water bodies as **geosynclines**. He thus defined for the first time that geosynclines are long narrow, shallow sinking sea beds. Hall elaborated the concept by presenting ample of evidences to show relationship between geosynclines and folded mountain. He viewed that the rocks of folded mountains were deposited in shallow seas. The beds of geosynclines are subjected to subsidence due to continuous sedimentation but the depth of water in geosyncline remains the same.

Concept of E. Haug

According to him, geosynclines are relatively deep water areas and they are much longer than they are wide. He developed a **paleogeographical map** of world and depicted long, narrow oceanic tracts to demonstrate that these waters were subsequently folded into mountain ranges. The geosynclines existed as mobile zones of water between rigid masses. He identified 5 major rigid masses during Mesozoic era - North Atlantic mass, Sino Siberian mass, Africa Brazil mass, Australia-India-Madagascar mass and Pacific mass. He located 4 geosynclines between these ancient rigid masses which were - **Rockies geosyncline, Ural geosyncline, Tethys geosyncline** and **Circum Pacific geosyncline**. According to Haug, there is systematic sedimentation in the geosynclines.

The littoral margins of the geosynclines are affected by transgressional and regressional phases of the seas. The marginal areas of the geosynclines have shallow water where the larger sediments are deposited whereas finer sediments are deposited in central parts of geosyncline. The sediments are squeezed and folded into mountain ranges due to compressive forces induced from the margins. He further remarked that it is not always necessary that all the geosynclines may pass through the complete cycle of the processes of sedimentation, subsidence, compression and folding of sediments. Though the contribution of Haug in this regard is prominent, the scholar could not explain the status of larger extent of rigid masses after Mesozoic era. His geosynclines were deep oceanic tracts but the marine fossils found in the folded mountains belong to the group of marine organisms of shallow seas.



Concept of J.W. Evans

According to him, the geosynclines are so varied that it becomes difficult to present their definite form and location. The beds of geosynclines are subjected to gradual subsidence because of sedimentation.

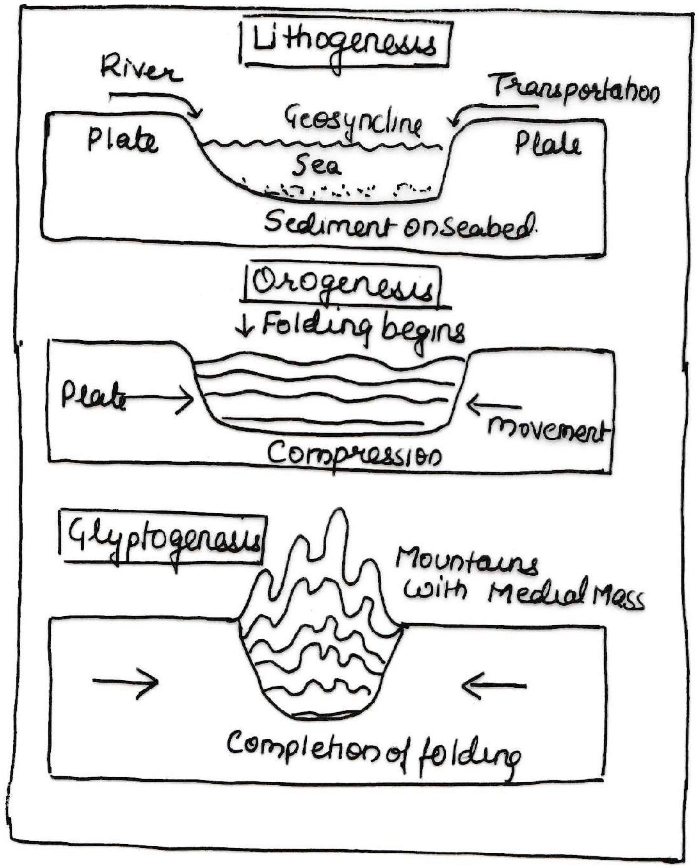
The form and shape of geosyncline change with changing environmental conditions. There are various alternate situations of geosynclines between two land masses - **Tethys between Laurasia and Gondwanaland**, in front of a mountain or a plateau - **resultant long trench after the origin of Himalayas**, along margins of continents. According to him, all the geosynclines irrespective of their varying forms, shapes and locations are characterized by twin processes of sedimentation and subsidence. These after long period of sedimentation, gets squeezed to form Fold Mountains.

Views of Schuchert

He attempted to classify geosynclines on the basis of their size, location, evolutionary history. He divided geosynclines into 3 categories – **Monogeosynclines, Polygeosynclines** and **Mesogeosynclines**.

Monogeosynclines are exceptionally long and narrow but shallow water tracts. The geosynclinal beds are subjected to gradual sedimentation and resultant load. Such geosynclines are situated either within a continent or along its borders. These are called **mono** because they pass through only one cycle of sedimentation and mountain building. **Appalachian** geosyncline present during Pre Cambrian period is the best example. This geosyncline was borded by highland mass called Appalachian. The sediment of this geosyncline was folded from Ordovician to Permian Periods.

The **Polygeosynclines** were long and wide water bodies. These were broader than mono geosyncline. They also existed for longer period and had complex evolutionary history. These are considered to have experienced more than one phase of orogenesis. Consequently they may have been diversified by the Production of one more parallel anticlines arising from their floors. Rockies and Urals are good examples. **Mesogeosynhclines** are long, narrow and mobile ocean basins which are bordered by continents from all sides. They have great abyssal depth and long complex geological history. These pass through **phases** of sedimentation, subsidence and folding. **Tethys geosynline** is typical example. This folded into Himalayas and Alps. The unfolded remnant is Mediterranean Sea.



Arther Holmes Concept

This approach is credited in availing the details of characteristics as well as **causes of origin** of different types of geosynclines. He identified four major type of geosyncline

(a) Formation due to migration of magma,

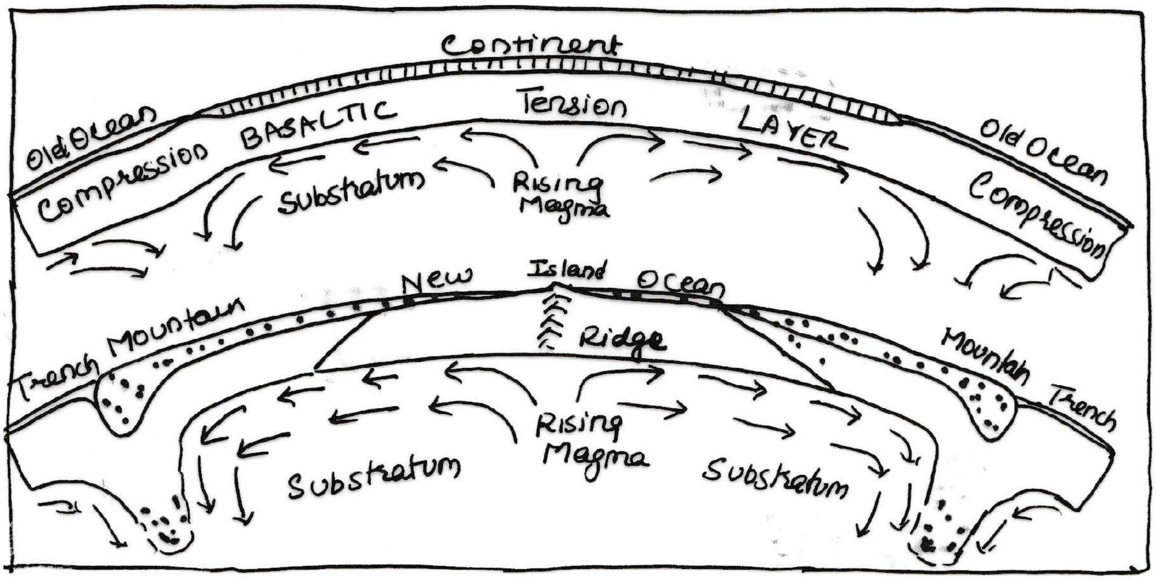
(b) Formation due to metamorphism,

(c) Formation due to compression, and

(d) Formation due to thinning of scale layer.

The crust of the earth is composed of three shells of rocks - beneath the outer thin sedimentary layer is outer granodiorite (10-12km) followed by amphibolite (20-25 km) and lower layer of eclogite with peridotite. The migration of magmas from intermediate layer to neighbouring areas causes collapse and subsidence of upper or outer layer forming geosyncline. Coral Sea, Tasman Sea Arafura Sea and Weddell Sea are quoted as examples. The rocks of lower layers of crust are metamorphosed due to compression caused by converging convective currents. This metamorphism increases the density of rocks causing subsidence and thus formation of geosyncline. Carribean Sea and Banda Sea is quoted as examples. Due to compression, the subsidence of outer layer of the crust causes geosyncline formation. Persian Gulf and Indo Gangetic trough are examples. The sialic layer stretched apart due to the tensional forces exerted by diverging convective currents causes the formation of geosyncline as the Tethys Sea.

As contributed by different scholars, the Geosynclinal history can be divided into three stages.



1. **Lithogenesis** - the stage of creation of geosyncline, sedimentation and subsidence.
2. **Orogenesis** - the stage of folding of sediments into mountain ranges and
3. **Glyptogenesis** is the stage of gradual rise of mountains with closing of geosynclines.

BUOYANCYAND THE PRINCIPLE OF ISOSTASY

According to earthquake studies, the crust is thin beneath the oceans and thickest below high mountain belts. The crust is consequently thin where its surface is at a low elevation, and thickest where it is high. This means that the base of the crust (the Moho) has a shape that mirrors in an exaggerated fashion the overlying shape of the Earth's surface topography. In short, the higher the crustal elevation, the deeper the crustal "root".

The reason behind this curious relationship is one of buoyancy. The level at which any object floats depends upon its buoyancy. The greater the object's buoyancy, the higher the level at which it will float. An empty cargo ship, for example, is more buoyant than a laden one and so rides higher in the water. For the same reason, lighter continental crust rides higher than denser oceanic crust. The relationship between crustal thickness and elevation therefore shows that the crust of the Earth is in a state of buoyant equilibrium and is effectively" floating". The principle that describes this condition is called **isostasy** from the Greek for "equal standing". But to fully understand how it works, we must examine buoyancy more closely.

The buoyancy of an object actually depends upon two factors, the object's thickness and its density. The relationship of buoyancy to thickness is best illustrated by examining the floating behavior of objects of the same density but different size. Take, for example, floating icebergs. All icebergs float such that only 10 percent of their volume is exposed above sea level. This is because the buoyancy of an iceberg depends on its density contrast with respect to ocean water, and the density of ice (0.9) is 10 percent less than that of water (1.0). The well-known expression "the tip of the icebergs" therefore comes from the fact that 90 percent of any iceberg is always nine times larger than its exposed portion, larger iceberg not only ride higher, but also extend to greater depths than smaller ones. For example, an iceberg 10 m (33 ft) thick will float such that only 1 m (3 ft) stands above sea level, whereas a 100 m-(330 ft) thick iceberg will stand 10 m (33 ft) above sea level. In other words, for an iceberg to stand high in the water it must have a deep, submerged portion to support it.

Continents behave in much the same way in that they "float" on the pliable asthenosphere below. They stand highest where there are mountains and so must be thickest below major mountain belts. Hence, mountain belts are supported by buoyant "roots" that project deep into the mantle. For continents, the depth to which this root projects below the average thickness of continental crust is about four and a half times more than the mountain's elevation. So for Mt. Everest to stand 8 km (5 mi) high, it must be supported by a crustal root that extends the average thickness of continental crust (35 km or 22 mi) by a further 36 km (22.2 mi). The thickness of the crust beneath the Himalayas actually approaches 80 km (50 mi).

This floating model also explains the contrast in thickness and surface elevation between oceanic and continental crust. The contrast occurs because both continental and oceanic crusts effectively "float" on the denser mantle beneath. But oceanic crust is thin and has no anomalously thick roots. Instead, its thickness is relatively uniform. It is also much denser than continental crust because its composition is largely basaltic so that it is rich in heavy iron-and magnesium-bearing (mafic) minerals. Continental crust, on the other hand, is composed of rocks of broadly granitic (felsic) composition that are rich in relatively light-weight alumina-bearing silicates. Because oceanic crust is both thin and heavy, it is not surprising that it occurs in those areas where elevations are lowest. As water collects at the lowest elevations, those areas have also become the world's ocean basins.

Viewed from space, the contrasting elevation of the continents and oceans is one of the most striking features of Planet Earth. That we live on a split-level planet is most clearly displayed on a graph known as the **hypsometric curve**. This shows the proportion of the Earth's surface that stands at or above a given elevation or depth. From the curve it is clear that much of the earth's surface stands at one of two elevations: either between 1000 m (3300 ft) and sea level, or between 4000 m and 5000 m (13,000 to 16,400 ft) below sea level. Representing 20.8 percent and 22.6 percent of the Earth's surface, these two elevation ranges mark the **continental platforms** (0 to 1000 m above sea level) and the **oceanic abyssal plains**

(4000 to 5000 m below sea level) respectively, and demonstrate the remarkable control that crustal density and thickness exert on the planet's surface elevation.

Thus the Earth's crust is in a state of buoyant equilibrium, the continents stand highest where they are thickest, and the oceans have formed in regions floored by denser basaltic crust. It is this balance or "equal standing" between crustal elevation, crustal thickness and crustal density, that is described by the principle of isostasy. Not only does isostasy explain why mountains stand high, but it also accounts for the subdivision of the Earth's surface into continents and ocean basins. According to the principle of isostasy, the edge of a continent occurs where the crust thins as it changes its composition from a broadly granitic one of the basaltic composition that makes up the ocean floor. This boundary between continental and oceanic crust does not necessarily mark the edge of the physical ocean. This is because ocean water is not confined by the boundary, but instead moves freely on top of the lithosphere. In fact, ocean waters tend to flood the feather edges of continents so that continents are bordered by areas covered by shallow water known as the **continental shelves**.

According to the principles of isostasy, the Earth's major topographic variations are a function of crustal thickness and the density of crustal rocks. If either of these is changed, the crust responds by establishing a new "floating" balance or **isostatic equilibrium.** During the last Ice Age, for example, the crust beneath the advancing continental ice sheets was first depressed under the weight of the ice, only to rebound again when the ice sheet retreated.

In a similar fashion, as the summits of mountains are lowered by erosion, so the crust rises in response to the reduced load, and the crustal root supporting the mountains shrinks. This response is known as **isostatic rebound**. The net result is a loss of elevation due to erosion which is offset by the rise towards the surface of the guts of the mountain chain in such a fashion that isostatic equilibrium is maintained. It is this process of erosion compensated by uplift by which progressively deeper levels of the crust are brought to the surface that makes the rock cycle possible. Hence, ancient mountain belts that have undergone long periods of erosion often expose metamorphic rocks that once resided deep within the root of the mountains. The process of erosion therefore causes readjustments to isostatic equilibrium that slowly reduce the mountain belt to normal crustal thickness. When this is achieved, once deeply buried portions of the mountain belt will be exposed at the surface.

In summary, the principle of isostasy describes the state of buoyant equilibrium that exists in the Earth's crust. It accounts for the contrasting elevations of the continents and ocean floors, and the striking relationship between the crustal thickness and surface elevation of the continents. It also demonstrates that the Earth's crustal fragments and the plates in which they are embedded effectively "float" on a pliable mantle below. Crustal erosion is consequently compensated by isostatic rebound. This rebound not only drives the rock cycle but has also eliminated entire mountain belts that may have once rivaled the Himalayas. In the process, the crust may be uplifted by as much as 50 km (30 mi). Yet this distance is tiny compared to the horizontal distances moved by plates. Because plates effectively "float" they are also free to move sideways and can be carried in this way for thousands of kilometers by circulating currents within the Earth's heated interior.

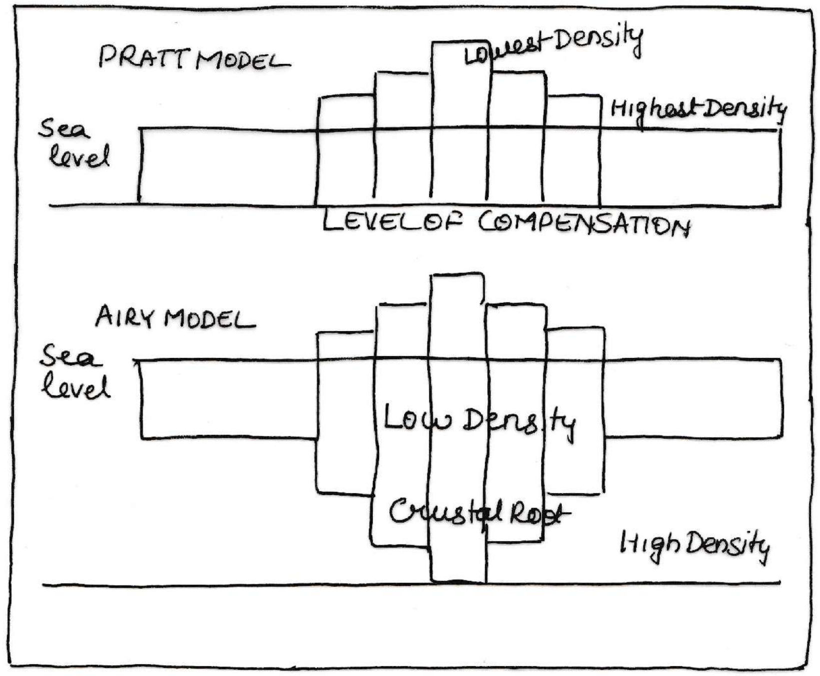
Isostacy represents the mechanical stability between the upstanding parts and low lying basins on a rotating earth. The term is derived from a German word **isostasios** (in equipoise). It was first proposed by American geologist Dutton in 1859 to express his view to indicate the state of balance which he thought must exist between large upstanding areas of the earth's surface, mountain ranges plateaus and contiguous lowlands, submarine features etc. According to him, the upstanding parts of the earth must be compensated by lighter rock material from beneath so that the crustal reliefs should remain in mechanical stability. That is wherever equilibrium exists on the earth's surface, equal mass must underline equal surface areas.

The concept of isostacy gradually grew out of the empirical observations of montane regions. Pierre Bouger in 1735 concluded from his expedition of Andean cordilleras that peak of Chimborazo was not attracting the plumb line. Similar discrepancies were noted during geodetic survey of the Indo-Gangetic plain for the determination of latitudes. Pratt calculated the difference of the gravitational deflections brought another fact that the Himalayas was not exerting the attraction according to its enormous mass. These discrepancies of the gravitational deflection resulted into numerous explanations as:

Airy's Views

Sir George B. Airy (1801-92) - the Astronomer Royal in 1851 opined that the continents which are made of lighter material sial are floating over the substratum which is made of denser material sima. The suggestion was put forward to account for certain features concerning the gravitative attraction of the Himalayas. During the Trigonmetrical and Geodetic Survey of India, the difference of latitude between two stations, Kalianpur and Kaliana, was obtained both by direct triangulation and by astronomical methods. The difference in the latitude obtained by the two means amounted to 5.236. It is important to note that Kaliana, the northern of the two stations, is only about 100 km (60 miles) from the Himalayas. He opined that the lighter sial of the Himalayas is floating over the denser material of the sima lying underneath. He also made it vividly clear that the Himalayas were not just surface feature but that the light rocks part of the mountain extended as roots deep down into the denser rocks below. It is just like as a large part of the boat remains immersed in water to keep it afloat, so are the Himalayas floating on the denser below and the weight of the mountains is balanced by light materials penetrating into considerable depths.

In fact, the principle of isostasy is really nothing else than that of ordinary floatation, and the example of an iceberg floating in water may help stress the fundamental concept of the doctrine. Ice floats in water in such a way that, approximately, for every one part above water level there are nine parts below. That is to sea, the ratio of free board to draught is as 1 to 9. On this analogy, if we assume the average density of the continental rocks to be 2.67 and that of the sub-stratum as 3, as suggested by Joly, then nearly eight times the height of the rocks above the sub-stratum should penetrate into the denser sub-stratum. In other words, the density of the rocks must be relatively low down to considerable depths below these mountains. The important point, however is that they are compensated as a whole, and the individual peaks and valley are not separately compensated. To take a somewhat far-fetched example, it would be quite wrong to assume that, if Mount Everest is about 30,000 feet high, and if the ratio assumed of draught to freeboard are correct, then there is a downward projection of lighter material beneath that mountain reaching to about 240,000 feet. By stating of mountain areas being compensated, it is implied that the mountains are regarded as a great plateau whose height is equal to that of the mean height of the mountain chain. The same reasoning must also apply to the continents. Joly estimates their mean heights and concludes that the continental material is about 31 km thick on an average.



Airy established his point with the help of an illustration of wooden blocks of different heights floating in water with each block moving vertically and independently of its neighbour. All blocks are of equal density but different heights, and they float, the longest blocks extending deepest into the mantle. At a certain depth, equal to or greater than the thickest crust, the pressure is everywhere constant and below it the mantle is in a state of hydrostatic equilibrium. The blocks emerge by amounts which are proportional to their heights, so that the block which rises highest above the water is also the block which goes deepest in the water. These blocks are said to be in a stare of hydrostatic balance or equilibrium. Similarly, the landmasses are composed of similar density of rocks, but they penetrate deep into the sub-stratum in proportion to their height. Thus, Airy assumed that the continents and islands are resting, or rather floating, in denser mass, and that excess of matter above the upper surface of the sub-stratum is balanced by deep projection of the lighter material into the sub-stratum. In short, the sial masses are in hydrostatic equilibrium.

The fundamental concept of Airy, i.e., the continental masses floating as lighter (*sial*) blocks in a heavier (*sima*) sub-stratum, has been rejuvenated by Heiskanen's work, so that it is now probably true to say that most geologists favour Airy's explanation.

Pratt's Views

The data obtained from the trigonometrical and geodetic survey of Kalianpur and Kaliana in Indian plains were computed by J.H. Pratt. According to Pratt, the gravitational attraction of the Himalayas was less than the mass represented by these mountains, because of mountains were made of much lighter materials, i.e., rocks of much lower density. He stipulated that the rocks of the mountain chains should have a lower density than those of the plateaus, the rocks of the plateaus lower than the plains and the plains lower than the rocks of the ocean floor. In his opinion, there was an inverse relationship between height and density - higher the column lesser the density, and smaller the column greater the density. Pratt visualized that there was a level above which these density changes were found and below that level the density was uniform. In other words, the density of a particular column was the same from top to bottom but the density of the different columns were different.

Pratt's concept of isostasy was related to 'the law of compensation' and not to 'the law of floatation'. According to Pratt, different relief features are standing only because of the fact that their respective mass is equal along the line of compensation because of their varying densities. The Pratt's law of compensation has been shown in the figure.

It may be seen from the figure that columns of lead, iron, antimony and zinc, having different densities, are placed in a jar, filled with mercury. The height above the mercury level of the floating columns is different but inside the mercury they are at a uniform depth. He, however, does not believe in the 'root formation', thus, the fundamental difference between Airy's and Partt's views is that the former postulated a uniform density with varying thickness, while the latter a uniform depth with varying density.

Views of Hayford and Bowie

The views expressed by Hayford and Bowie, about isostasy were in agreement with that of Pratt. According to them, there is a plane where there is a complete compensation of the crustal parts. Densities vary with elevations of columns of crustal parts above this plane of compensation. Thus, the density of the mountain is less than the ocean floor. In other words, the earth's crust is composed of lighter material under the mountain than under the floor of the oceans. According to Hayford, and Bowie, there is an inverse relationship between the height of columns of the earth's crust and their respective densities above the line of compensation. The plane or level of compensation is supposedly located at the depth of about 100 km. he columns having the rocks of lesser density stand higher than the columns having the rocks of higher density.

Joly's views

The views advocated by Hayford and Bowie were criticized by Joly. His main objection was about the depth of compensation (100 km). In his opinion, the temperatures would be so high that all rocks would melt and become liquid at such a depth. According to Joly, there is a 16 km (10 miles) thick layer, below the areas having similar low density. The areas of low density penetrate into this thick layer, while where the surface rocks are of higher density, the heavier materials below rise to higher levels. Joly, thus, conceived the level of compensation not as a straight line surface but as a zone of compensation. This view is much closer to the floatation theory of Airy. In the opinion of Joly, the earth's crust consists of lighter materials (*sial*) whose average density is 2.67. Below this is the *sima* whose density is 3. The sial is floating over the sima like iceberg. Thus, these views are in conformity with the model of the earth's crust in which the lighter continental masses 'float' on a denser sub-stratum.

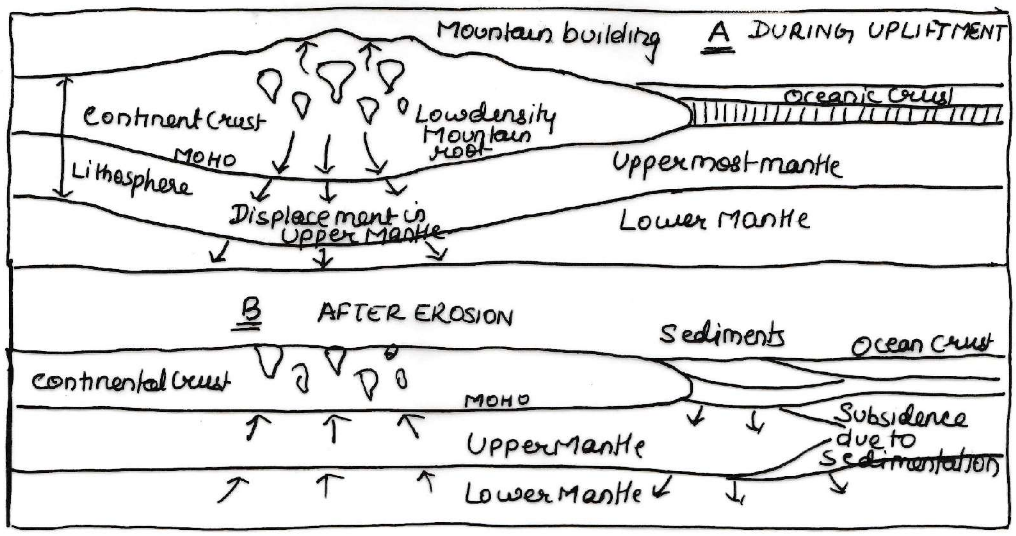
Holmes' Views

The views of Arthur Holmes were also similar to that of Airy. Holmes was of the opinion that the higher relief features of the earth's surface are composed of lighter materials and their portions lie buried in the heavier and denser rocks below to keep them in a state of hydrostatic balance. He further opined that mountain ranges have roots largely composed of sialic rocks, going down to depths of 50 to 60 km. In coastal plains the thickness of the sial is either extremely thin or totally absent. According to Holmes, the lighter columns are standing because of the fact that there is lighter material below them for greater depth whereas there is lighter material below the smaller columns upto lesser depth.

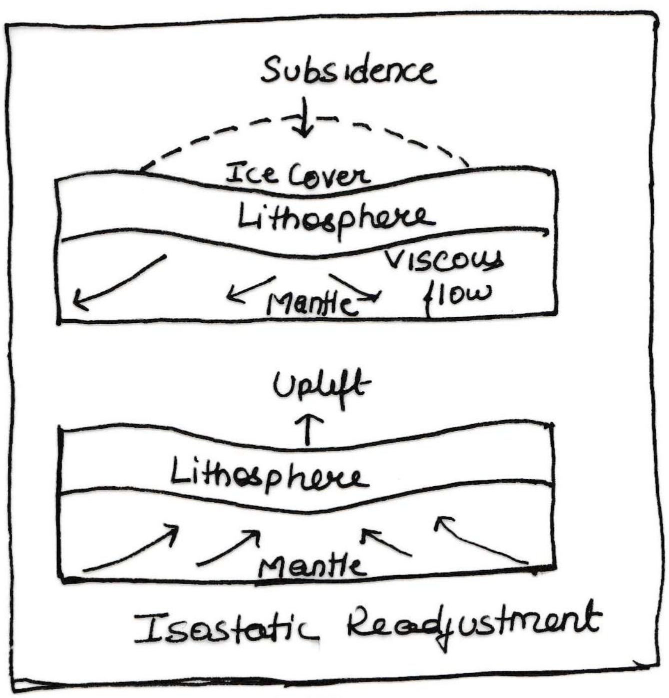
Isostatic Adjustment

A perfect isostatic adjustment is possible only theoretically. In fact, the earth is unstable and unresting as the endogenetic and exogenetic forces continuously disturb the isostatic adjustment. In fact, the endogenetic forces and the resultant tectonic events cause disturbances in the ideal condition of isostasy but the natur always tends towards the isostaic adjustment, if not at the local, at the regional level. For example, a newly formed mountain due to tectonic activities is subjected to severe denudation. Consequently, there is continuous lowering of the height of the mountain. On the other hand, eroded sediments are deposited in the oceanic areas, with the result there is continuous increase of weight of sediments on the sea floor. Due to this mechanism, the mountainous area gradually becomes lighter and the oceanic floor becomes heavier, and thus the state of balance or isostasy between these two areas gets distributed but the balance has to be maintained.

In brief, when an uplifted landmass or mountain is worn down by the agents of erosion, the load on the underlying column of the crust is reduced by the weight of the material that has been eroded away. At the same time, a neighbouring column underlying a region of delta and sea floor where the denuded material is being deposited, receives a corresponding increase of load. At the base of the crust the pressure exerted by the unloaded column is increased. In response to this pressure difference in the mantle there is a sub-crustal slow flow of sima from under the loaded column towards the base of the unloaded column. The loaded column therefore, sinks, while the unloaded column rises.



This process, whereby isostatic equilibrium is resorted, is called *isostatic adjustment*. This is made possible by a compensating transfer of material in the sub-crust. For example, extensive parts of North America and Eurasia were subsided under the enormous weight of accumulation of thick ice sheets during Pleistocene glaciation but the landmasses began to rise suddenly because of release of pressure of superincumbent thick load of ice sheets due to deglaciation and consequent melting of ice sheet about 25,000 years ago, and thus the isostatic balance was disturbed. The raised beaches of Finland and Scandinavia show that an uplift of about 250 meters has already taken place during the last 8000 years and the region is still out of isostatic balance and is rising



The theories discussed above and the given example illustrate several important facts about gravity and isostatic adjustments:

1. Gravity is the driving force for all isostatic adjustments. All types of loading and unloading, therefore, cause vertical movements. Isostasy is involved in all of the processes that shift material on earth's surface. Some of the more obvious isostatic adjustments to be expected are as follows:

(a) In mountains and highlands, as erosion removes material, the crust should rebound.

(b) In deltaic areas, where sediment is deposited, the added weight should cause the crust to subside.

(c) In areas of volcanic activity, the added weight of excursions should cause the crust to subside.

(d) In regions of continental glaciation, the thick ice sheet should cause the crust to subside. As the ice is removed, the crust should rebound.

2. Very small loads, such as water a few hundred meters deep, are also sufficient to cause isostatic adjustments.

3. Isostatic adjustments can occur very rapidly in a geological time frame (60 meters in fewer than 20,000 years).

VULCANISM

Volcanic activity is commonly perceived as a process that produces a picturesque, cone-shaped structure that periodically erupts in a violent manner, like Mount St. Helens. Although some eruptions may be very explosive, many are not. The primary factors include the magma's *composition*, its *temperature*, and the amount of *dissolved gases* it contains. To varying degrees, these factors affect the magma's mobility, or **viscosity**. The more viscous the material, the greater its resistance to flow. (For example, syrup is more viscous than water). The viscosity of magma associated with an explosive eruption may be five times more viscous than magma that is extruded in a quiescent manner.

Factors Affecting Viscosity

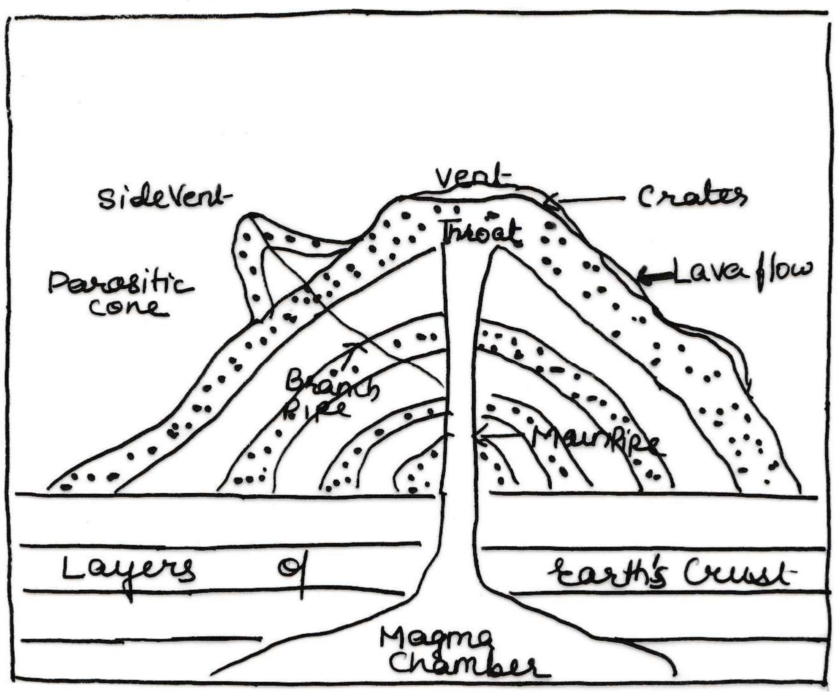
The effect of temperature on viscosity is easily seen. Just as heating syrup makes it more fluid (less viscous), the mobility of lava is strongly influenced by temperature. As lava cools and begins to congeal, its mobility decreases and eventually the flow halt.

A more significant factor influencing volcanic behavior is the chemical composition of the magma. Magmas that produce mafic rocks such as basalt contain about 50 percent silica, whereas magmas that produce felsic rocks (granite and its extrusive equivalent, rhyolite) contain over 70 percent silica. The intermediate rock types - andesite and diorite, contain about 60 percent silica.

Magma's viscosity is directly related to its silica content . In general, the more silica in magma, the greater its viscosity. The flow of magma is impeded because silica structures link together into long chains, even before crystallization begins. Consequently, because of high silica content, felsic lavas are very viscous and tend to form comparatively short, thick flows. By contrast, mafic lavas, which contain less silica, tend to be quite fluid and have been known to travel distance of 150 kilometers (90 miles) or more before congealing.

Importance of Dissolved Gases

The gas content of magma also affects its mobility. Dissolved gases tend to increase the fluidity of magma. Of far greater consequence is the fact that escaping gases provide enough force to propel molten rock from a volcanic vent.



Volcanoes inflate before an eruption, indicating buildup in gas pressure directly below in a shallow magma chamber. When an eruption starts, gas-charged magma moves from the magma chamber and rises through the volcanic conduit or vent. As the magma nears the surface, the confining pressure is greatly reduced. This reduction in pressure allows the dissolved gases to be released suddenly, just as opening a warm soda bottle allows carbon dioxide gas bubbles to escape. At temperatures of 1000°C and low, near-surfaces pressures, these gases will expand to occupy hundreds of times their original volume.

Very fluid basaltic magmas allow the expanding gases to migrate upward and escape from the vent with relative ease. As they escape, the gases may propel incandescent lava hundreds of meters into the air, producing lava fountains. Although spectacular, such fountains are mostly harmless and not generally associated with major explosive events that cause great loss of life and property. Rather, eruptions of fluid basaltic lavas, such as those that occur in Hawaii, are generally quiescent.

As magma in the upper portion of the vent is ejected, the pressure on the molten rock directly below drops. Thus, rather than a single "bang", volcanic eruptions are really a series of explosions. This process might logically continue until the magma chamber is emptied, much like a geyser empties itself of water. However, this generally does not happen. The soluble gases in a viscous magma migrate upward quite slowly. Only within the uppermost portion of the magma body does the gas content build sufficiently to trigger explosive eruptions. Thus, an explosive event is commonly followed by the quiet emission of "degassed" lavas. However, once this eruptive phase ceases, the process of gas buildup begins anew. This time lag may explain the sporadic eruptive patterns of volcanic that eject viscous lavas.

To summarize, the viscosity of magma, plus the quantity of dissolved gases and the ease with which they can escape, determined the nature of a volcanic eruption.

Materials Extruded During an Eruption

Volcanoes extrude lava, large volumes of gas, and pyroclastic materials (broken rock, lava "bombs," fine ash, and dust).

Lava Flows

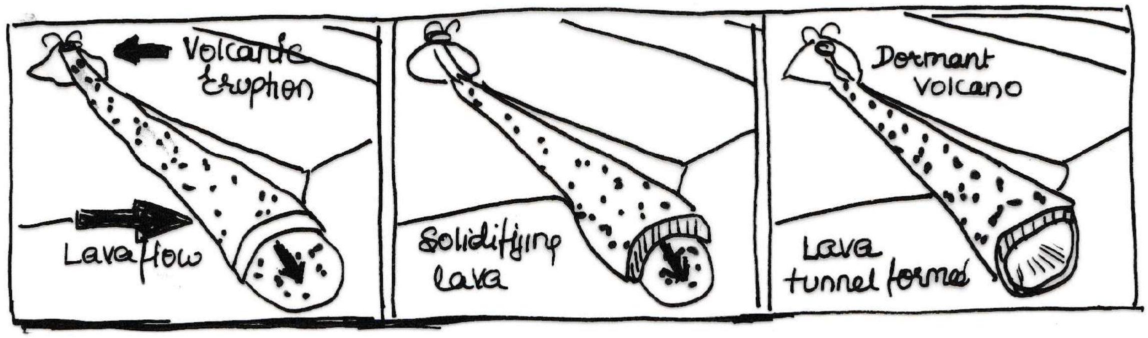
Because of their low silica content, basaltic lavas are usually very fluid. They flow in thin, broad sheets or stream-like ribbons. On the island of Hawaii, such lavas have been clocked at speeds of 30 kilometers per hour are more common. Further, basaltic lavas have been known to travel distances of 150 kilometers 990 miles) or more before congealing. In contrast, the movement of silica-rich (felsic) lava may be too slow to perceive.

When fluid basaltic lavas of the Hawaiian type congeal, they commonly form a relatively smooth skin that wrinkles as the still-molten subsurface lava continues to advance. These are known as **pahoehoe flows** (pronounced *pah-hoy-hoy*) and resemble the twisting braids in ropes.

Another common type of basaltic lava, called **aa** (pronounced *ah-ah*), has a surface of rough, jagged blocks with dangerously sharp edges and spiny projections. Active *aa* flows are relatively cool and thick and advance at rates from 5 to 50 meters per hour. Further, escaping gases fragment the cool surface and produce numerous voids and sharp spines in the congealing lava. As the molten interior advances, the outer crust is broken further, giving the flow the appearance of an advancing mass of lava rubble.

The lava that flowed from the Mexican volcano Paricutin and buried the city of San Juan Parangaricutiro was of the *aa* type. At times one of the flows from Paricutin moved only 1 meter per day, but it continued to advanced day in and day out for more than 3 months.

Hardened lava flows commonly contain tunnels that once were horizontal conduits carrying lava from the volcanic vent to the flow's leading edge.



These openings develop in the interior of a flow where temperatures remain high long after the surface congeals. Under these conditions, the still-molten lava within the conduits continues its forward motion, leaving behind the cavelike voids called **lava tubes**. Lava tubes can play an important role in allowing fluid lavas to advance great distances from their source.

When lava enters the ocean, or when outpourings of lava actually originate in the ocean basin, the flows' outer zones quickly congeal. However, the lava is usually able to move forward by breaking through the hardened surface. This process occurs over and over, generating a lava flow composed of elongated structures resembling large bed pillows stacked one upon the other. These structures, called **pillow lavas**, are useful in the reconstruction of Earth history. Whenever pillow lavas are located, they indicate that deposition occurred in an underwater environment.

Gases

Magmas contain varying amounts of dissolved gases held in the molten rock by confining pressure, just as carbon dioxide is held on soft drinks. As with soft drinks, as soon as the pressure is reduced, the gases begin to escape. Obtaining gas samples from an erupting volcano is difficult and dangerous, so geologists usually estimate the amount of gas originally contained within the magma.

The gaseous portion of most magmas makes up from 1 to 6 percent of the total weight, with most of this in the form of water vapor. Although the percentage may be small, the actual quantity of emitted gas can exceed thousands of tons per day.

The composition of volcanic gases is important because they contribute significantly to the gases that make up our planets' atmosphere. Analyses of samples taken during Hawaiian eruptions indicate that the gases areabout 70 percent water vapor, 15 percent carbon dioxide, 5 percent nitrogen, 5 percent sulfur dioxide, and lesser amounts of chlorine, hydrogen, and argon. Sulfur compounds are easily recognized by their pungent odour. Volcanoes are a natural source of air pollution, including sulfur dioxide, which readily combines with water to form sulfuric acid.

In addition to propelling magma from a volcano, gases play an important role in creating the narrow conduit that connects the magma chamber to the surface. First, the intense heat from the magma body cracks the rock above. Then, hot blasts of high-pressure gases expand the cracks and develop a passageway to the surface. Once the passageway is completed, the hot gases armed with rock fragments erode its walls, producing a larger conduit. Because these erosive forces are concentrated on any protrusion along the pathway, the volcanic pipes that are produced have a circular shape. As the conduit enlarges, magma moves upward to produce surface activity. Following an eruptive phase, the volcanic pipe often becomes choked with a mixture of congealed magma and debris that was not thrown clear of the vent. Before the next eruption, a new surge of explosive gases may again clear the conduit.

Pyroclastic Materials

When basaltic lava is extruded, dissolved gases escape quite freely and continually. These gases propel incandescent blobs of lava to great heights. Some of this ejected material may land near the vent and build a cone-shaped structure, whereas smaller particles will be carried great distances by the wind. By contrast, viscous (felsic) magmas are highly charged with gases, and upon release they expand a thousand-fold as they blow pulverized rock, lava, and glass fragments from the vent. The particles produced in both of these situations are referred to as **pyroclastic materials** (meaning "fire fragments"). These ejected fragments range in size from very fine dust (less than 0.063 mm in diameter) and sand-sized volcanic ash (less than 2 mm in diameter) to pieces that weigh more than a ton.

Ash and *dust* particles are produced from gas-laden, viscous magma during an explosive eruption. As magma moves up in the vent, the gases rapidly expand, generating a forth of melt that might resemble froth which flows from a just-opened bottle of champagne. As the hot gases expand explosively, the forth is blown into very fine glassy fragments. When the hot ash falls, the glassy shards often fuse to form welded tuff. Sheets of this material, as well as ash deposits that later consolidate, cover vast portions of the western United States. Sometimes the forthlike lava is ejected as *pumice*, a material having so many voids (air spaces) that it often floats in water.

Also common are walnut-sized pyroclasts termed *lapilli* ("little stones"), and pea-sized particles called *cinders*. Particles larger than lapilli are called *blocks* when they are made of hardened lava and *bombs* when they are ejected as incandescent lava. Because bombs are semi-molten upon ejection, they often take on a stream lined shape as they hurtle through the air. Because of their size, bombs and blocks usually fall on the slopes of a cone; however, they are occasionally propelled far from the volcano by the force of escaping gases.

Fine volcanic debris can be scattered great distances from its source. Dust, in particular may be blasted high into the atmosphere, where it can remain for extended periods. When present, dust produces brilliant sunsets and has on occasion slightly lowered Earth's average temperature.

Volcanoes and Volcanic Eruptions

Successive eruptions from a central vent build a mountainous accumulation we call a volcano. Located at the summit of many volcanoes is a steep-walled crater. The crater is connected to a magma chamber via a circular conduit, or **pipe**, which terminates at an opening called a **vent**. Some volcanoes have unusually large summit depressions that exceed 1 kilometer in diameter and are known as **calderas**.

When fluid Hawaiian-type lava leaves a conduit, it is often stored in the crater or caldera, until it overflows. Conversely, viscous lava forms a plug in the pipe, which rises slowly or is blown out, often enlarging the crater.Lava does not always issue from a central crater. Sometimes the magma or escaping gases push through fissures located on the volcano's flanks. Continued activity from a flank eruption may build a smaller **parasitic cone**. Mount Etna in Italy, for example, has more than 200 secondary vents. Some of these emit only gases and are appropriately called **fumaroles**.

The eruptive history of each volcano is unique, so volcanoes vary in size and form. Nevertheless, volcanologists recognize three general eruptive patterns and characteristic forms: shield volcanoes, cinder cones, and composite cones (strato-volcanoes).

Shield Volcanoes

When fluid Hawaiian-type lava is extruded, the volcano takes the shape of a broad, slightly domed structure called a **shield volcano**. They are so-called because they thoroughly resemble the shape of a warrior's shield. Shield volcanoes are built primarily of basaltic lava flows and contain only a small percentage of pyroclastic material.

Mauna Loa is one of five shield volcanoes that together make up the island of Hawaii., its base rests on the ocean floor 5000 meters (16,400 feet) below sea level, and its summit is 4170 (13,677 feet) above the water, giving it a total height approaching 6 miles, greater than the height of Mount Everest. Nearly a million years and numerous eruptive cycles built this truly gigantic pile of volcanic rock. Many other volcanic structures, including Midway Island and the Galapagos Islands, have been built in a similar manner from the ocean's depths.

Cinder Cones

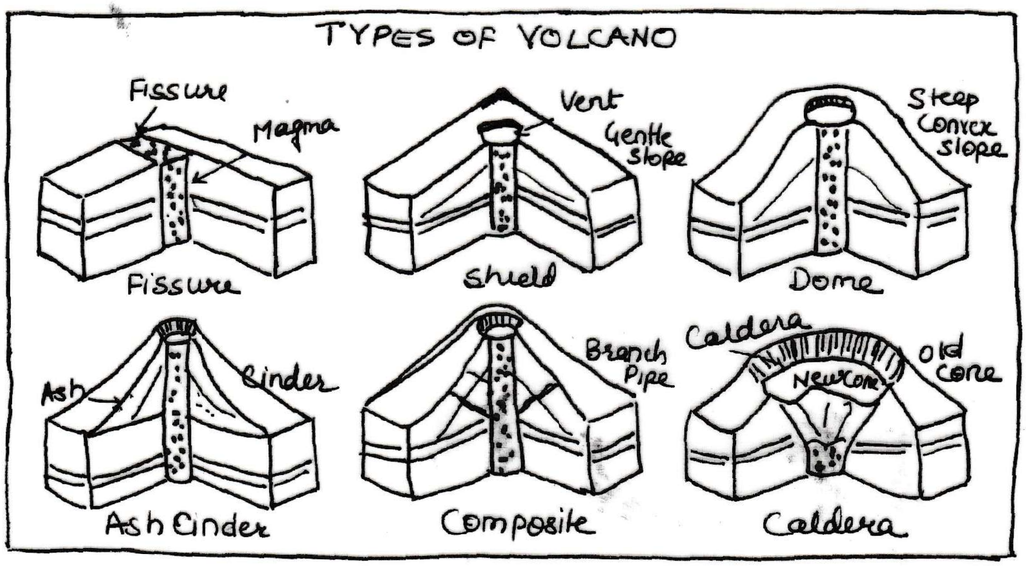
As the name suggests, **cinder cones** are built from ejected lava fragments. Loose pyroclastic material has a high angle of repose (between 30 and 40 degrees), the steepest angle at which the material remains stable. Thus, volcanoes of this type have very steep slopes. Cinder cones are rather small, usually less than 300 meters (1000 feet) high, often forming near larger volcanoes, and often in groups.

One of the very few volcanoes observed by geologists from beginning to end is the cinder cone called Paricutin about 200 miles west of Mexico City.

Composite Cones

Earth's most picturesque volcanoes are composite cones. Most active composite cones are in a narrow zone that encircles the Pacific Ocean, appropriately named the *Ring of Fire*. In this region are Fujiyama (Mt. Fuji) in Japan, Mount Mayon in the Philippines, and the picturesque volcanoes of the Cascade Range in the northwestern United States, including Mont St. Helens, Mount Rainer and Mount Shasta.

A **composite cone** or **stratovolcano** is a large, nearly symmetrical structure composed of alternating lava flows and pyroclastic deposits, emitted mainly from a central vent. Just as shield volcanoes owe their shape to the highly fluid nature of the extruded lavas, so too do composite cones reflects the nature of the erupted material.



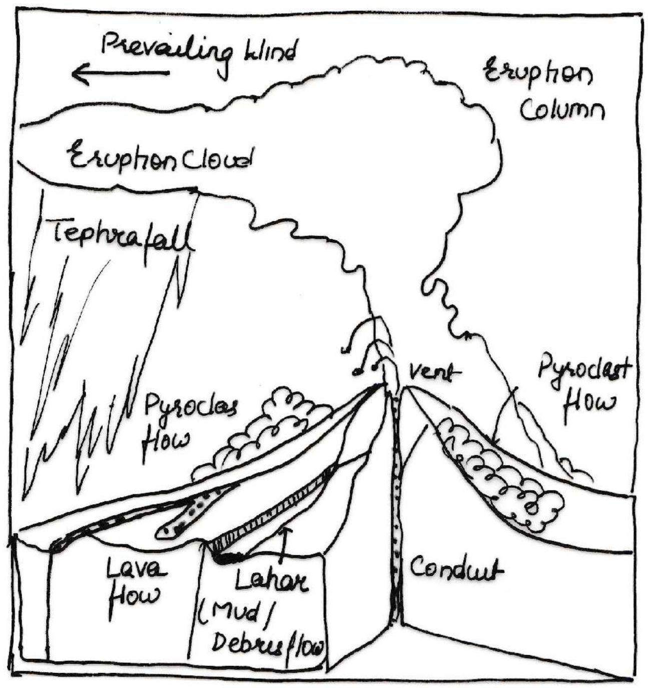
Composite cones are produced when relatively viscous lavas of andesitic composition are extruded. A composite cone may extrude viscous lava for long periods. Then, suddenly, the eruptive style changes and the volcano violently eject pyroclastic material. Occasionally, both activities occur simultaneously. The resulting cone consists of alternating layers (strata) of lava and pyrocalstic materials, giving rise to the name *stratovolcano*. Two of the most perfect cones, Mount Mayon in the Philippines and Fujiyama in Japan, exhibit the classic from of the stratavolcano with its steep summit and more gently sloping flanks.

Nuee Ardente; A Deadly Pyroclastic Flow

Although the destruction of Pompeii was catastrophic, even more devastating eruptions may occur when a volcano ejects hot gases infused with incandescent ash. Such events produce a fiery pyroclastic flow called a **nuee ardente**. Also referred to as *glowing avalanches*, these turbulent steam clouds and companion ash flows race down steep volcanic slopes at speeds that can approach 200 kilometers (125 miles) per hour. The ground-hugging portions of glowing avalanches are rich in particulate matter, which is suspended by hot, buoyant gases. Thus, these flows, which can include larger rock fragments in addition to ash, travel downslope in a nearly frictionless environment cushioned by expanding volcanic gases. This explains why some nuee ardente deposits extend more than 100 kilometers (60 miles) from their source.

Lahar

In Addition to their violent eruptions, large composite cones often generate a mudflow called by its Indonesian name **lahar**. These destructive flows occur when volcanic ash and debris become saturated with water and flow down steep volcanic slopes, generally following stream valleys. Some lahars are produced when rainfall saturates volcanic deposits, whereas others are triggered as large volumes of ice and snow melt during an eruption.



Other Volcanic Landforms

The most obvious volcanic landform is a cone. But other distinctive landforms are also associated with volcanic activity.

Calderas and Pyroclastic Flows

Most volcanoes have a steep-walled *crater*. A crater is called a *caldera* when it exceeds 1 kilometer in diameter. Calderas are roughly circular and most form when the summit of a volcano structure collapses into a partially emptied magma chamber below.

Crater Lake in Oregon, located in such a structure, is 10 kilometers (6 miles) at its widest and 1175 meters (over 3800 feet) deep. The formation of Crater Lake began about 7000 years ago when the volcano, later to be named Mount Mazama, violently extruded 50 to 70 cubic kilometers of pyroclastic material.

Although most calderas are produced by *collapse following an explosive eruption*, some are not. For example, Hawaii's active shield volcanoes, Mauna Loa and Kilauea, have large calderas (3 to 5 kilometers, or 2 to 3 miles across, and nearly 200 meters, or 650 feet deep). They formed by gradual subsidence as magma slowly drained from the summit magma chambers during flank eruptions.

The formation of a large caldera begins when a granitic (felsic) magma body is emplaced near the surface, up-warping the overlying rocks. Next, fracturing of the roof allows the highly viscous, gas-rich magma to reach the surface, where it explosively ejects huge volumes of pyrocalstic materials, mainly ash and pumice fragments. Typically, this material, called a **pyroclastic flow**, avalanches across the landscape at speeds that may exceed 100 kilometers (60 miles) per hour, destroying most living things in its path. After coming to rest, these hot fragments often fuse to form a welded tuff that closely resembles a solidified lava flow. Finally, with the loss of support the roof collapses generating a caldera. The cycle of caldera formation can repeat itself numerous times in the same location.

Perhaps the best-known caldera in the United States is located in the Yellowstone Plateau of northwestern Wyoming.

Fissure Eruptions and Lava Plateaus

We think of volcanic eruptions as building a cone or mountain from a central vent. But by far the greatest volume of volcanic material is extruded from fractures in the crust called **fissures**. Rather than building a cone, these long, narrow cracks pour forth low-viscosity Hawaiian-type lava, blanketing a wide area. The extensive Columbia Plateau in the northwestern United States was formed this way. Here, numerous **fissure eruptions** extruded very fluid basaltic lava. Successive flows, some 50 maters thick, buried the existing landscape as they built a lava plateau that is nearly a mile thick in places. The fluidity is evident, because some lava remained molten long enough to flow 150 kilometers (90 miles) from its source. The term **flood basalts** appropriately describe these flows.

Lava Domes

In contrast to mafic lavas, silica-rich lavas near the felsic end of the compositional spectrum are so viscous they

hardly flow. As the thick lava is "squeezed" out of the vent, it may produce a bulbous mass of congealed lava called a **lava dome**. Because domes develop from viscous magma, most are composed of rhyolite, and many consist of obsidian.

Most volcanic domes develop following an explosive eruption of gas-rich magma. This is exemplified by the volcanic dome that continues to "grow" from the vent that produced the 1980 eruption of Mount St. Helens. Although most volcanic domes form in association with preexisting composite cones, some form independently, such as the line of rhyolotic and obsidian domes at Mono Craters, California.

Volcanic Pipes and Necks

Most volcanoes are fed magma through short conduits, called **pipes** that connect a magma chamber to the surface. In rare circumstances, pipes may extend tubelike to depths exceeding 200 kilometers. When this occurs, the ultramafic magmas that migrate up these structures produce rocks that are thought to be samples of the mantle that have undergone very little alteration during their ascent. Geologists consider these unusually deep conduits to be "windows" into Earth, for they allow us to view rock normally found only at great depth.

The best-known volcanic pipes are the diamond-bearing structures of South Africa. Here, the rocks filing the pipes originated at depths of at least 150 kilometers (90 miles), where pressure is high enough to generate diamonds and other high-pressure minerals. The task of transporting essentially unaltered magma (along with diamond inclusions) through 150 kilometers of solid rock is exceptional. This fact accounts for the scarcity of natural diamonds.

Volcanoes on land are continually being lowered by weathering and erosion. Cinder cones are easily eroded, because they are composed of unconsolidated materials. However, all volcanoes will eventually succumb to relentless erosion over geologic time. As erosion progresses, the rock occupying the volcanic pipe is often more resistant and may remain standing above the surrounding terrain long after most of the cone has vanished. Shiprock, New Mexico, is such a feature, and is called a **volcanic neck**. This structure, higher than many skyscrapers, is but one of many such landforms that produce conspicuously from the red desert landscape of the American Southwest.

Plutonic Igneous Activity

Although volcanic eruptions can be among the most violent and spectacular events in nature and therefore worthy of detailed study, most magma is emplaced at depth. Thus, an understanding of intrusive igneous activity is as important to geologists as the study of volcanic events.

The structures that result from the emplacement of igneous material at depth are called **plutons**, named for Pluto, the god of the lower world in classical mythology. Because all plutons form out of view beneath Earth's surface, they can be studied only after uplifting and erosion have exposed them. The challenge lies in reconstructing the events that generated these structures millions or even hundreds of millions of years ago.

Nature of Plutons

Plutons are known to occur in a great variety of sizes and shapes. Some of these structures have a tabular (tabletop) shape, whereas others are quite massive and some of these bodies cut across existing structures, such as layers of sedimentary rock, others form when magma is injected between sedimentary layers. Because of these differences, intrusive igneous bodies are generally classified according to their shape as either **tabular** (sheetlike) or **massive** and by their orientation with respect to the host rock. Plutons are said to be **discordant** if they cut across existing structures and **concordant** if they form parallel to features such as sedimentary strata. Plutons are closely associated with volcanic activity. Many of the largest instructive bodies are the remnants of magma chambers that once fed ancient volcanoes.

Dikes

Dikes are tabular discordant bodies that are produced when magma is injected into fractures. The force exerted by the emplaced magma can be great enough to separate the walls of the fracture further. Once crystallized, these sheet-like structures have thicknesses ranging from less than a centimeter to more than a kilometer. The largest have lengths of hundreds of kilometers. Most dikes, however, are a few meters thick and extend laterally for no more than a few kilometers.

Dikes are often found in groups that once served as vertically oriented pathways followed by molten rock that fed ancient lava flows. The parent pluton is generally not observable. Some dikes are found radiating, like spokes on a wheel, from an eroded volcanic neck. In these situations, the active ascent of magma is thought to have generated fissures in the volcanic cone out of which lava flowed.

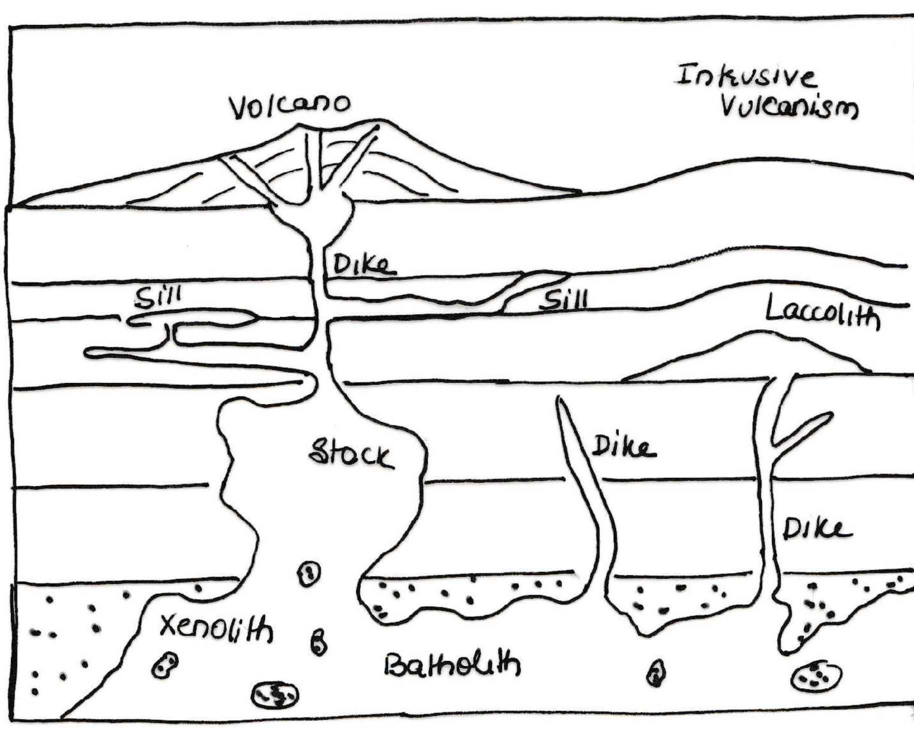
Dikes often weather more slowly that the surrounding rock. When exposed by erosion, these dikes have the appearance of a wall.

Sills

Sills are tabular plutons formed when magma is injected along sedimentary bedding surfaces. Horizontal sills are the most common, although all orientations, even vertical, are known to exist. Because of their relatively uniform thickness and large areal extent, sills are likely the product of very fluid magmas. Magmas having low silica content are more fluid, so most sills are composed of the rock basalt.

The emplacement of a sill requires that the overlying sedimentary rock be lifted to a height equal to the thickness of the sill. Although this is a formidable task, in shallow environments it often requires less energy than forcing the magma up the remaining distance to surface. Consequently, sills form only at shallow depths, where the pressure exerted by the weight of overlying rock layers is low. Although sills are intruded between layers, they can be locally discordant. Large sills frequently cut across sedimentary layers and resume their concordant nature at a higher level.

One of the largest and most studied of all sills, in the United States is the Palisades Sill. Exposed for 80 kilometers along the west bank of the Hudson River in southeastern New York and northeastern New Jersey, this sill is about 300 meters thick. Because of its resistant nature, the Palisades Sill forms an imposing cliff that can be seen easily from the opposite side of the Hudson.



In many respects, sills closely resemble buried lava flows. Both are tabular and often exhibit columnar jointing. **Columnar joints** form as igneous rock cool and develop shrinkage fractures that produce elongated, pillar-like columns. Further, because sills generally form in near-surface environments and may be only a few meters thick, the emplaced magma often cools quickly enough to generate an aphanites texture.

When attempts are made to reconstruct the geologic history of a region, it becomes important to differentiate between sills and buried lava flows. Fortunately, under close examination these two phenomena can be readily distinguished. The upper portion of a buried lava flow usually contains voids produced by escaping gas bubbles. Further, only the rocks beneath a lava flow show evidence of metamorphic alternation. Sills, on the other hand, form when magma has been forcefully intruded between sedimentary layers. Thus, fragments of the overlying rock can be found only in sills. Lava flows, conversely, are extruded before the overlying strata are deposited. Further, "baked" zones in the rocks above and below are trademarks of a sill.

Laccoliths

Laccoliths are similar to sills because they form when magma is intruded between sedimentary layers in a near-surface environment. However, the magma that generates laccoliths is more viscous. This less fluid magma collects as a lens-shaped mass that arches the overlying strata upward. Consequently, laccoliths can occasionally be detected because of the dome-shaped bulge it creates at the surface.

Most large laccoliths are probably not much wider than a few kilometers. The Henry Mountains in southwestern Utah are largely composed of several laccoliths believed to have been fed by a much larger magma body emplaced nearby.

Batholiths

By far the largest intrusive igneous bodies are **batholiths**. Most often, batholiths occur in groups that form linear structures several hundreds of kilometers long and up to 100 kilometers wide. The Idaho batholith, for example, encompasses an area of more than 40,000 square kilometer and consists of many plutons. Indirect evidence gathered from gravitational studies indicates that batholiths are also very thick, possibly extending dozens of kilometers into the crust. Based on the amount exposed by erosion, some batholiths are at least several kilometers thick.

By definition, a plutonic body must have a surface exposure greater than 100 square kilometers (40 square miles) to be considered batholiths. Smaller plutons of this type are termed **stocks**. Many stocks appear to be portions of batholiths that are not yet fully exposed.

Batholiths usually consist of rock types having spectrum, although diorite is commonly found. Smaller batholiths can be rather simple structures composed almost entirely of one rock type. However, studies of large batholiths have shown that they consist of several distinct plutons that were intruded over a period of millions of years. The plutonic activity that created the Sierra Nevada batholiths, for example, occurred nearly continuously over a 130-million-year period that ended about 80 million years ago during the Cretaceous period.

Batholiths may compose the core of mountain systems. Here uplifting and erosion have removed the surrounding rock, thereby exposing the resistant igneous body. Some of the highest peaks in the Sierra Nevada, such as Mount Whitney, are carved from such a granitic mass.

Large expanses of granitic rock also occur in the stable of North America. These relatively flat exposures are the remains of ancient mountains that have long since been leveled by erosion. Thus, the rocks that make up the batholiths of youthful mountain ranges, such as the Sierra Nevada, were generated near the top of a magma chamber, whereas in shield areas, the roots of former mountains and, thus, the lower portions of batholiths, are exposed.

Emplacement of Batholiths

An interesting problem that forced geologists was trying to explain how large granitic batholiths form within largely unaltered sedimentary rocks. One group of geologists supported the idea that batholiths originated from magma that formed at depth and then migrated upward to its present position. This idea, however, presents a space problem. Further, the problem of explaining how magma is able to force its way through several kilometers of solid rock also plagued those supporting the magmatic origin of batholiths.

The group opposing this hypothesis suggested that granite batholiths originate when hot ion-rich fluids and gases migrated through sedimentary rock and chemically altered the rock's composition. This essentially metamorphic process of converting rock into granite without passing through a molten stage is called **granitization**. Although granitization undoubtedly generates small quantities of granite, this process is clearly not capable of generating these large intrusive bodies.

This controversy was resolved when careful studies were made of structures called **salt domes**. These structures are of economic importance because they are found in close association with major oil-producing areas in the Gulf Coast states and in the Persian Gulf region. Salt domes are produced where extensive salt deposits were buried by thousands of meters of sediment. Salt, which is less dense than overlying sediments, migrates very slowly upward. This is possible because salt behaves like a mobile fluid when it is subjected to stress over a long period of time. Because salt beds are not perfectly uniform, the zone of upward movement is thought to originate at a high spot. As the salt moves slowly upward, the stress exerted on the overlying sediments causes them to mobilize and be pushed aside. Occasionally the salt breaches the surface, where it begins to flow outward, not unlike a very thick lava flow.

It is now generally accepted that batholiths are emplaced in a manner similar to salt domes. Because magma is less dense than the surrounding rock, its buoyancy propels it upward. At depths of several kilometers, the overlying rocks are subjected to very high temperatures and pressures; thus they deform plastically as the rising magma forcibly makes room for itself. As the magma continues to move upward, some of the host rock that was shouldered aside will fill in the space left by the magma body as it passes. As a magma body nears the surface, it encounters relatively cool, brittle rocks that resist deformation. Further upward movement, if any, is accomplished by a process called stoping, where the injected magma dislodges blocks of host rock from the roof of the magma chamber and incorporates them into the magma body. Evidence for this process are inclusions called **xenoliths**, the unmelted remnants of the host rock.

Magma gradually cools during its ascent, which reduces its rate of upward mobility. Further, because movement through the brittle uppermost crust is greatly restricted, most magma accumulates in chambers several kilometers below the surface. As a result, roughly 10 to 1000 times more magma is emplaced at depth than is involved in volcanic output.

Plate Tectonics and Igneous Activity

For many years geologists have realized that the global distribution of igneous activity is not random, but rather exhibits a definite pattern. In particular, volcanoes that extrude mainly intermediate to felsic lavas are confined largely to continental margins. By contrast, most volcanoes locate within the ocean basins, such as those in Hawaii and Iceland, extrude lavas that are of mafic composition. Moreover, basaltic rocks are common in both oceanic and continental settings, whereas granitic rocks are rarely observed in the oceans. This pattern puzzled geologists until the development of the plate tectonics theory, which greatly clarified the picture.

Many of the more than 800 known active volcanoes are located along continental margins adjacent to oceanic trenches. Further, volcanic activity occurs along the oceanic ridge system. This later activity, although extensive, is hidden from view by the world's oceans.

In this section we will examine three zones of igneous activity and relate them to global tectonics. These active areas are along the oceanic ridges (spreading centers), adjacent trenches (subduction zones), and within the plates themselves.

Igneous Activity at Spreading Centers

The greatest volume of volcanic rock is produced along the oceanic ridge system, where seafloor spreading is active. As plates of rigid lithosphere pull apart, pressure on the underlying rocks is lessened. This reduced pressure, in turn, lowers the melting temperature of the mantle rocks. Partial melting of these mantle materials (primarily peridotite) produces large quantities of basaltic magma that move upward to fill the newly formed cracks between the diverging plates. In this way new slivers of oceanic crust are generated.

Some of the molten basalt reaches the ocean floor, where it produces extensive lava flows or occasionally grows into a volcanic cone. Sometimes this activity produces a volcanic structure large enough to rise above sea level, such as the islands of Vestmann off the south coast of Iceland. Numerous submerged volcanoes also dot the flanks of the ridge system and the adjacent deep-ocean floor. Many of these formed along the ridge crest and gradually moved away as new oceanic crust was created by the seemingly unending process that generates new seafloor.

Igneous Activity at Subduction Zones

Deep-ocean trenches are sites where slabs of water-rich oceanic crust are bent and descend into the mantle. As a slab sinks, volatiles are driven from the ocean crust and migrate upward into the wedge-shaped piece of mantle located directly above. At a depth of 100 to 150 kilometers, these water-rich fluids reduce the melting point of the mantle's peridotitie sufficiently to promote partial melting. In some environments, silica and other components of the subducted sediments may become incorporated into the magma body. This process generates basaltic magma, and in some cases, small amounts of andesitic magma.

After a sufficient quantity of magma has accumulated, it slowly migrates upward because it is less dense than the surrounding rock. When igneous activity occurs along a subduction zone in the ocean, a chain of volcanoes called a **volcanic island arc** is produced. These structures, which usually form 200 to 300 kilometers from the oceanic trench, include such island chains as the Aleutians, the Tongas, and the Marianas. When subduction of oceanic crust occurs beneath a continent, the magma that forms may become contaminated with silica-rich rocks as it moves through the crust. Magmatic differentiation and the assimilation of crustal fragments into the ascending mantle-derived basaltic magma will change it into one exhibiting an andesitic to granitic composition. The *continental margin volcanic arc* consisting of South America's Andes Mountains is one place where andesitic magma having such an origin is extruded. Many subduction-zone volcanoes border the Pacific Basin. Because of this pattern, the region has come to be called the *Ring of Fire*. Here volcanism is associated with subduction of the Pacific seafloor. As oceanic plates sink, they carry sediments and oceanic crust containing abundant water to great depths. The presence of water contributes to the high gas content and explosive nature of volcanoes that make up the Ring of Fire. The volcanoes of the Cascade Region in the northwestern United States, including Mount St. Helens, Mount Rainier, and Mount Shasta, are all of this type.

Intraplate igneous Activity

We know why igneous activity occurs along plate boundaries. But why do eruptions occurs in the middle of plates? Equally perplexing is the activity in Yellowstone National Park where felsic pumice and ash flows actually overlap basalt flows that cover vast portions of the Pacific Northwest.

Because basalts having relatively similar compositions are found in the ocean basins as well as on the continents, partial melting of mantles rocks is the most probable source for many of these rocks. The sources of some intraplate basaltic magma are hot **mantle plumes**, which may originate at the core-mantle boundary. Upon reaching the crust, these structures begin to spread laterally. The result is localized volcanic regions a few hundred kilometers across called **hot spots**. More than 100 hot spots have been identified and most appear to have persisted for tens of millions of years. One hot spot is situated beneath the island of Hawaii. Another may be responsible for the large outpourings of lava that make up Iceland.

With few exceptions, lavas and ash of felsic composition are restricted to vents located landwards of the continental margins. This suggests that remelting of the continental crust may be the mechanism responsible for the formation of these silica-rich magmas. One explanation is that a thick segment of continental crust occasionally becomes situated over a rising plume of hot mantle material. Rather than producing vast outpourings of basaltic lava as occurs at oceanic sites such as Hawaii, the magma from the rising plume is emplaced at depth. Here melting and assimilation of the surrounding host rock, coupled with magmatic differentiation, result in the formation of a highly evolved *secondary magma*. As this buoyant magma of intermediate to felsic composition slowly migrates upward, continued hot-spot activity supplies heat to the rising mass, thereby aiding its ascent. Volcanism in the Yellowstone region may have resulted from this process.

Although the plate tectonics theory has answered many questions regarding the distribution of igneous activity, many new questions have arisen. These and other questions are the subject of continuing geologic research.