FOUR THEORIES TO EXPLAIN LITHOSPHERE DYNAMICS

While in 1800 geologists thought that Earth was immobile and static, at the beginning of 1900 three theories spread to support the dynamism of the planet:
(a) the Isostasy Theory
(b) the Continental Drift
(c) the Seafloor Spreading.

These three theories are laying the foundations for the theory of Plate Tectonics (d), which is the most important model of modern geology.

A) THE ISOSTASY PRINCIPLE

In 1855 the English astronomer Airy suggested that the Earth's crust is floating on mantle below, like ice on liquid water, reaching a balance based on weight. An analogy may be made with an iceberg: it always floats with a certain proportion of its mass below the surface of the water. If more ice is added to the top of the iceberg, the iceberg will sink lower in the water. If a layer of ice is somehow sliced off the top of the iceberg, the remaining iceberg will rise. Similarly, Earth's lithosphere "floats" in the asthenosphere. So isostasy is the principle of buoyancy wherein an object immersed in a fluid is buoyed with a force equal to the weight of the displaced fluid.

When large amounts of sediment are deposited on a particular region, the immense weight of the new sediment may cause the crust below to sink. Similarly, when large amounts of material are eroded away from a region, the land may rise to compensate.

Also the formation of ice sheets can cause Earth's surface to sink. Conversely, isostatic post-glacial rebound is observed in areas once covered by ice sheets that have now melted, such as around the Baltic Sea and Hudson Bay. As the ice retreats, the load on the lithosphere and asthenosphere is reduced and they rebound back towards their equilibrium levels.
B) CONTINENTAL DRIFT THEORY

In 1915 Wegener, a German meteorologist and geophysicist, wrote his hypothesis, called continental drift, on his book entitled “The origin of continents and oceans”.

He suggested that a single supercontinent consisting of all Earth’s landmasses once existed. He called it “Pangea”, while the only huge ocean that surrounded it was named “Pantalassa”. Then he hypothesized that about 200 million years ago it began to fragment into smaller landmasses and to move up to the current positions, forming the present continents.

This point of view was supported by some evidence:

1. **the continental jigsaw puzzle**: the similarity between the coastlines on opposite sides of the Atlantic Ocean; combining together the edges of the continental shelves of South America and Africa Bullard (another geophysicist) obtained a very precise fit;
2. **fossils matching across the seas**: the discovery of identical fossil organisms in rocks from South America and Africa: the organisms were Mesosaurus (a small aquatic freshwater reptile), Cynognathus (a carnivorous reptile) and Glossopteris (a very tall seed fern);
3. **rock types and geologic features:** rocks found on Brazil closely match in age and type those found in adjacent positions on Africa to form a nearly continuous belt;
4. ancient climates: about 300 million years ago vast ice sheets covered South Africa, South America, Australia and India, while large tropical swamps existed in several location in the Northern Emisphere, to show that every land was positioned at a different latitude.

Wegener wasn’t able to identify a mechanism for continental drift: he though that gravitational forces or centrifugal forces could move the continents (but it couldn’t be true, because they are too weak). So at the beginning most of the scientific community rejected this theory or treated it with skepticism.
Before investigating the third theory, we have to consider some studies about seabeds and the discovery of some important oceanic structures.

Bathymetric techniques are born in the late 1800s, when the British ship Challenger for the first time explored seabeds and performed depth measurements by the sounder. At the beginning of 1900 the sonar was invented, which uses sound waves to measure the sea depth \[ h = \frac{1}{2} \times (1500 \text{ m/s} \times \text{transit time}) \]. In the 1950s and 1960s, oceanographers equipped with these new marine tools started a period of important oceanographic exploration and marine geologists such as Heezen, Tharp, and Menard used data from echo sounders to map ocean floors. Current research vessels, as the great Chikyu, can accomplish drilling up to 7000 meters deep and use multibeam technology that allows to obtain bathymetric surveys and map the ocean floor along a strip of a few tens of kilometers.

Based on these studies a global oceanic ridge system was discovered: it consists of various mountains linked in chains that wind through all the major oceans. It is the longest topographic feature on Earth’s surface, exceeding 70,000 kilometers in length. Some segments of the global ridge system have been named: the Mid Atlantic Ridge, the East Pacific Rise and the Mid Indian Ridge. While the crest is commonly 2-3 kilometers high, ridges vary in width from 1000 to 4000 Km; further along the crest there is a deep V-shaped canyonlike structure called “rift valley”, from 30 to 50 Km wide. The ocean ridges are generally characterized by volcanic activity with basaltic lavas and a high heat flux; the hips are slightly pendants, but the upper part sometimes emerges from the ocean forming volcanic islands such as Iceland and Azores.

Between the foot of a continental rise and a mid-ocean ridge, abyssal plains lay, usually at depth between 3,000 and 6,000 meters. But the maximum oceanic depths occur in the deep-ocean trenches, that are long, narrow and steep-sided.
depressions. They have a length of thousands of kilometers, width from 100 to 200 km, and depths greater than 6000 m; the deepest known is the Mariana Trench in the western north Pacific, that reaches more than 11,000 m at its deepest point. The longest is the Peru-Chile Trench, which extends 5,900 Km along the west coast of South America, but the deep trenches are more than 20; others are partially buried by sediments accumulated over time.
C) THE SEAFLOOR SPREADING HYPOTHESIS

The seafloor spreading hypothesis was proposed by Harry Hess, a petrologist, and Robert Dietz, an oceanographer. They went to say that new ocean floor is continuously generated along the crests of oceanic ridges. The molten material erupted by volcanoes produce new slivers of seafloor: so, while adjacent plates spread apart, new oceanic lithosphere forms between them and oceanic ridges are considered crustal spreading centers. As soon as new lithosphere forms, it is continually displaced away from the zone of upwelling; thus, it begins to cool and contract, thereby increasing in density. Typical rates of spreading average around 5 cm per year, roughly the same rate at which human fingernails grow, but spreading rates exceeding 15 cm for year have been measured along sections of the East Pacific Rise.

However our planet is not growing larger and its total surface area remains constant. The balance is maintained because older and denser portions of oceanic lithosphere descend toward the hot mantle and eventually sink down and melt into oceanic trenches. Therefore these sites are called subduction zones: here Earth’s crust parts are destroyed at a rate equal to seafloor production. This theory states that ocean floors are constantly being renewed: on one side they are reformed, on the other they will be destroyed.
It is confirmed by three data:
- oceanic sediments never are older than 200 million years;
- the sediment layer increases regularly and becomes thicker as you move away from the ridge;
- as you move away from the ridge as you find older sediments: the oldest are in the vicinity of the trenches.
THE EARTH’S MAGNETIC FIELD

All magnetic objects produce invisible lines of force that extend between the poles of the object. Conventionally the lines of force enter the south pole and get out of the north pole. The Earth can be considered a magnet with two poles: today’s north geographic pole, however, corresponds to the magnetic south pole and vice versa, even if we traditionally call north pole the one located in the northern hemisphere. Moreover, these magnetic poles do not coincide exactly with the geographic ones, but they are shifted by 15°-20°. The magnetic needle becomes aligned with the lines of force and points toward the north pole. The compass needle is then diverted to the direction of the local meridian by a corner called magnetic declination.

The magnetic field on Earth’s surface is about 50 gauss. This magnetic field is justified by the presence of conductive fluids and materials in motion into the Earth’s core: the convective motions of metallic substances generate electric currents that can cause a magnetic field, which in turn facilitates the maintenance of this internal dynamo (this theory is called the dynamo self-excitation, Bullard 1948).

Particles with electric charge are trapped in the lines of force: therefore a magnetic region also exists around the Earth and it is called magnetosphere. It acts as a protective shield against cosmic radiation. It isn’t perfectly symmetrical, because the solar wind stretches the lines of forces forming a magnetic tail. The solar wind protons and electrons are captured by Earth magnetic field and remain inside a zone, called outer Van Allen belt, which extends up to 60 to 80,000 Km from Earth on the sun side, up to 300,000 Km on the opposite side. The inner band, however, contains charged particles derived from the interaction between cosmic rays and Earth’s atmosphere: it extends between 800 and 4,000 Km.
In addition to the main magnetic field, there is also another field, generated by magnetized rocks of the crust. In fact, the rocks are divided into:

- **diamagnetic**, that are not influenced by magnetic field;
- **paramagnetic**, that become aligned with magnetic field, but when the field ceases they lose magnetization;
- **ferromagnetic**, which are magnetized, regardless of the existence of an external magnetic field (for example rocks that contain magnetite and hematite).

All materials, however, lose the permanent magnetization if the temperature exceeds a threshold value called as the **Curie point**, which varies from ore to ore, but it is about 600°-700°. Consequently molten lava is not magnetic, but when it cools some rocks become magnetized and align themselves in the direction of the existing magnetic lines of force. So they point toward the position of the magnetic poles at the time of their formation.
PALEOMAGNETISM

Rocks that formed thousands or millions of years ago and contain a record of the direction of the magnetic poles at the time of their formation are said to possess paleomagnetism or fossil magnetism. It is an evidence of both continental drift (1) and seafloor spreading (2) theories.

(1) The magnetic alignment of iron-rich minerals in lava flows of different ages indicates that the position of the paleomagnetic poles had changed through time. In particular during the past 500 million years, the pole seems to have gradually wandered from a location near Hawaii northeastward to its present location over the Arctic Ocean. This idea is known as polar wandering, even if we know that the poles had remained in place and in reality the continents had drifted beneath them. In fact, if the magnetic poles remain stationary, their apparent movement is produced by continental drift and this demonstrates that North America and Europe were once joined.

(2) Studying paleomagnetism, geophysicists learned that over periods of hundreds of thousands of years, Earth's magnetic field periodically reverses polarity. During a magnetic reversal, the magnetic north pole becomes the magnetic south pole and vice versa. Lava solidifying during a period of reverse polarity will be magnetized with the polarity opposite that of volcanic rocks being formed today. When rocks exhibit the same magnetism as the present magnetic field, they are said to possess normal polarity, whereas rocks exhibiting the opposite magnetism are said to have reverse polarity.
After World War II, when magnetometers began to be used to survey the seafloor’s magnetic properties, scientists were surprised to learn that Earth’s magnetic field had flip-flopped many times over its history, with the north and south poles exchanging places. They discovered that the poles have reversed 171 times in the last 76 million years. The major divisions of the magnetic time scale are called chrons and last roughly 1 million years; several short-lived reversals (less than 200,000 years long) often occurred during a single chron. Over the past 5 million years there are 4 main chrons:

1) Gilbert (4-3.3 million years ago – reversed chron)
2) Gauss (3.3-2.5 million years ago – normal chron)
3) Matuyama (2.5-0.7 million years ago – reversed chron)
4) Brunhes (present chron – normal chron).

In the late 1960s, magnetometer data revealed an alternating “striped” pattern of seafloor rocks: rocks that formed when Earth’s magnetic field was in one position alternated with rocks that formed when the field was reversed. Vine and Matthews suggested that the stripes of high intensity magnetism are regions where the paleomagnetism of the ocean crust exhibits normal polarity and where, consequently, these rocks enhance Earth’s magnetic field. Conversely, the low intensity stripes are regions where the ocean crust is polarized in the reverse direction and therefore weaken the existing magnetic field.

The stripes ran parallel to the mid-ocean ridges and extended out hundreds of miles on either side of them. So we can see the pattern of stripes found on one side of an oceanic ridge to be a mirror image of those on the other side and stripes exhibiting a remarkable degree of symmetry in relation to the ridge axis. These seafloor’s permanent magnetic signatures showed that new ocean crust was created at the ridge crests and then spread outward in both directions.

During reversals the Earth would lose much of its magnetic protection and would be subject to greater cosmic bombardament of radiation and charged particles. Currently we believe that a reversal of the poles is happening now and it would complete in about 2000 years. In fact we found some convective cells in outer core and mantle with a reverse flow and in some areas (such as South Africa and close to the North Pole) the magnetic needle is already pointing toward the center of Earth, rather than toward the North Pole.
Plate Tectonics is a theory developed in the late 1960s, to explain how the outer layers of the Earth move and deform. The theory has caused a revolution in the way we think about the Earth. Since the development of the theory, geologists have had to reexamine almost every aspect of Geology. Plate tectonics has proven to be so useful that it can predict geologic events and explain almost all aspects of what we see on the Earth.

In 1965, a Canadian geophysicist, J. Tuzo Wilson, combined the continental drift and seafloor spreading hypothesis to propose the theory of plate tectonics. Tuzo said that Earth’s lithosphere, consisting of the crust and the uppermost part of the mantle, was divided into large, rigid pieces called plates.

While the continents do indeed appear to drift, they do so only because they are part of larger plates that float and move horizontally on the upper mantle asthenosphere. In the asthenosphere, rocks are under such tremendous heat and pressure that they are very near their melting temperature and they behave like a viscous liquid (like very thick honey). The term “continental drift” was no longer fully accurate, because the plates are made up of continental and oceanic crust, which both “drift” over Earth’s surface.

Oceanic lithosphere is about 100 km thick in the deep ocean basins but is considerably thinner along the crest of the oceanic ridge system. Oceanic crust is composed of rocks that have a mafic composition, and therefore it has a greater density than continental one.

Continental lithosphere averages about 150 Km thick but may extend to depths of 200 Km or more beneath the stable interior of the continents. Continental crust is composed largely of less dense felsic rocks, making continental lithosphere less
dense than its oceanic counterpart. The lithosphere is broken into about two dozen segments of irregular size, but seven major plates are recognized and account for 94 percent of Earth’s surface area: they include an entire continent plus a significant amount of ocean floor.

They are:
1. North American
2. South American
3. Pacific
4. African
5. Eurasian
6. Australian-Indian
7. Antarctic plates.

Intermediate-sized plates, that are composed mostly of oceanic lithosphere, include:
- Caribbean
- Nazca
- Philippine
- Arabian
- Cocos
- Scotia
- Juan de Fuca.
In addition, several smaller plates, called microplates, have been identified. The plates behave as rigid bodies with some ability to flex and they move independently, but deformation occurs mainly along the boundaries between plates.

There are three distinct types of boundaries, which are differentiated by the type of movement they exhibit:

1. Divergent plate boundaries or constructive margins
2. Convergent plate boundaries or destructive margins
3. Transform plate boundaries or conservative margins.