3. The Earth system

Our planet is composed of three complex natural systems (Figs. 1 & 2): (1) the ***climate system***, (2) the ***plate tectonic system***, and (3) the ***geodynamo system***. The first is driven by an external source of heat (the Sun), whereas the second and the third are driven by an internal source of heat (original heat accumulated during Earth's formation and heat being generated by the decay of radioactive elements inside the Earth).

(1) The ***climate system*** involves all the components of the Earth whose interactions control Earth's climate:

Atmosphere (layer of gas around the Earth)
Cryosphere (surface ice and snow; e.g., ice caps, glaciers)
Hydrosphere (liquid surface waters, including groundwater)
Lithosphere (rigid rocky outer layer of Earth)
Biosphere (all living things on Earth)

Recent global warming calls to our attention the impact of human activities on climate. The anthropogenic influence on nature has become so significant that it is nowadays adequate to define yet another component of the climate system: the ***anthroposphere*** (sum of all human activities influencing the environment).

(2) The ***plate tectonic system*** involves all the components of the Earth which control the movements of continents, the formation of mountains and ocean basins, and events such as volcanic eruptions and earthquakes. These components are the ***lithosphere***, the ***asthenosphere***, and the ***deep mantle***. The principles of plate tectonics are described in section 3.2 (see slides for additional figures and further information on subjects related to plate tectonics).

(3) The ***geodynamo system*** produces and maintains Earth's magnetic field and involves movements of charged particles in the liquid outer core.

Figure 1: Illustrations of the climate system (typhoon, A), the plate tectonic system (lava, B), and the geodynamo system (compass, C). Sources: A. NOAA, B. Encyclopaedia Britannica, C. Wikipedia.

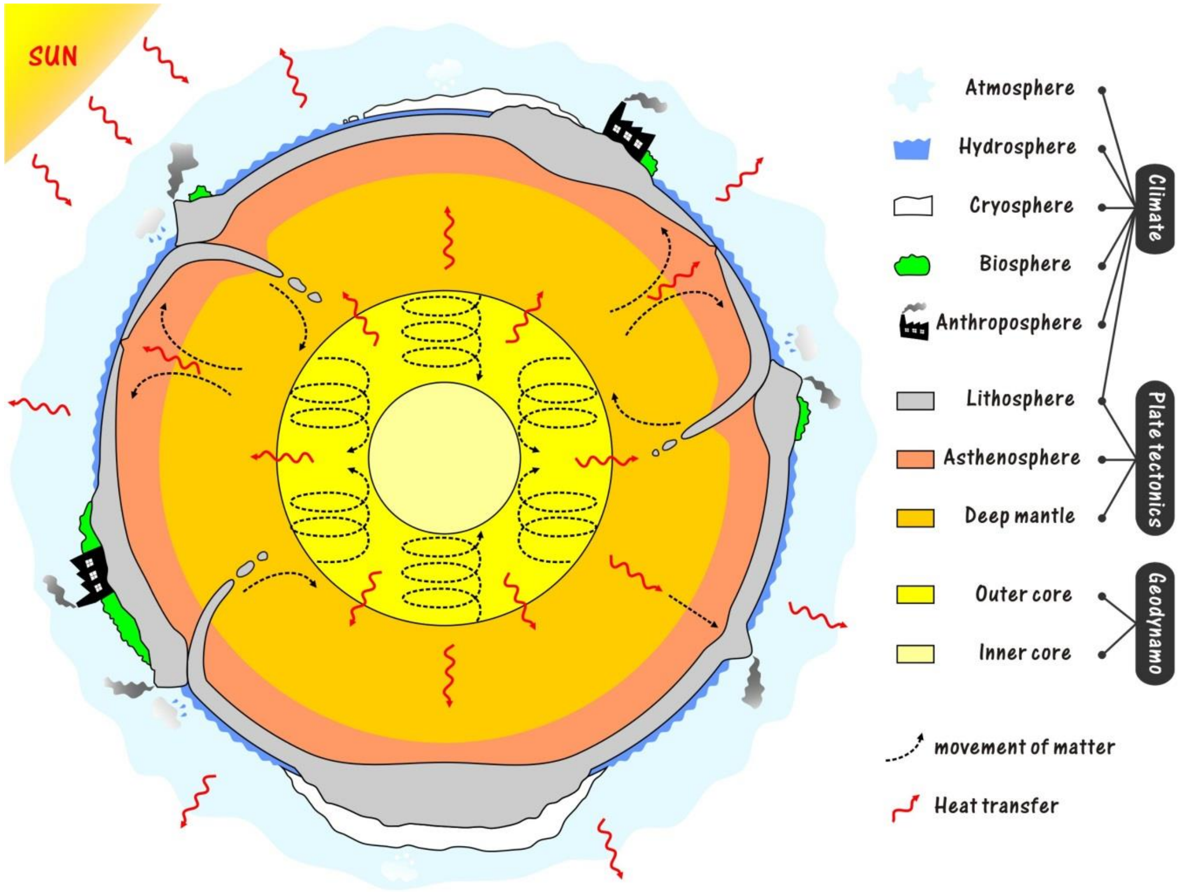

Figure 2: Model of the Earth and the three systems: climate, plate tectonics, and the geodynamo.
Reference: John Grotzinger, and Thomas H. Jordan, *Understanding Earth 6th edition, Boston, Bedford,, Boston, Bedford, 2010.*

3.1. **The age and structure of the Earth**

The exact age of the Earth cannot be determined directly but a good approximation can be obtained by measuring the age of meteorites. Meteorites are rocks from space falling on the surface of the Earth. They originate primarily from the collision and fragmentation of asteroids. Asteroids are the leftover of the process of planetary accretion. In other words they did not aggregate with other asteroids to form planets when the solar system formed. The age of the Solar System (and the Earth) derived from meteorites is 4.6 billion years.

During the first 700 million years or so, the solar system was not yet cleared of the majority of its asteroids which means there was a higher probability of collision among asteroids and planets, and therefore a higher number of meteorites falling on Earth. This period of Earth's history is referred to as the ***Heavy Bombardment***. Heat energy released by the collision between Earth and large meteorites was high enough to melt Earth's surface. Other important sources of heat were provided by gravitational contraction (conversion of gravitational potential energy, i.e. heat released by friction) and by the decay of radioactive elements contained within Earth's interior. Consequently our planet was occasionally in a molten ("soft") state during which elements could migrate freely, and matter redistributed according to density. Heavier elements (e.g., Fe, Ni) migrated toward the center of the Earth to form the core, whereas lighter elements (e.g., Al, K, Na, Mg) remained closer to the surface. The process by which Earth became a layered planet is called ***gravitational differentiation***.

Earth is composed of three main layers: the ***crust***, the ***mantle*** and the ***core*** (Fig. 3A). Each layer has a distinct chemical composition. Temperature and pressure increase toward the center. Only the ***outer core*** is in a liquid state. The ***inner core*** is solid because the pressure is extremely high and keeps matter into a solid state despite the very high temperature.

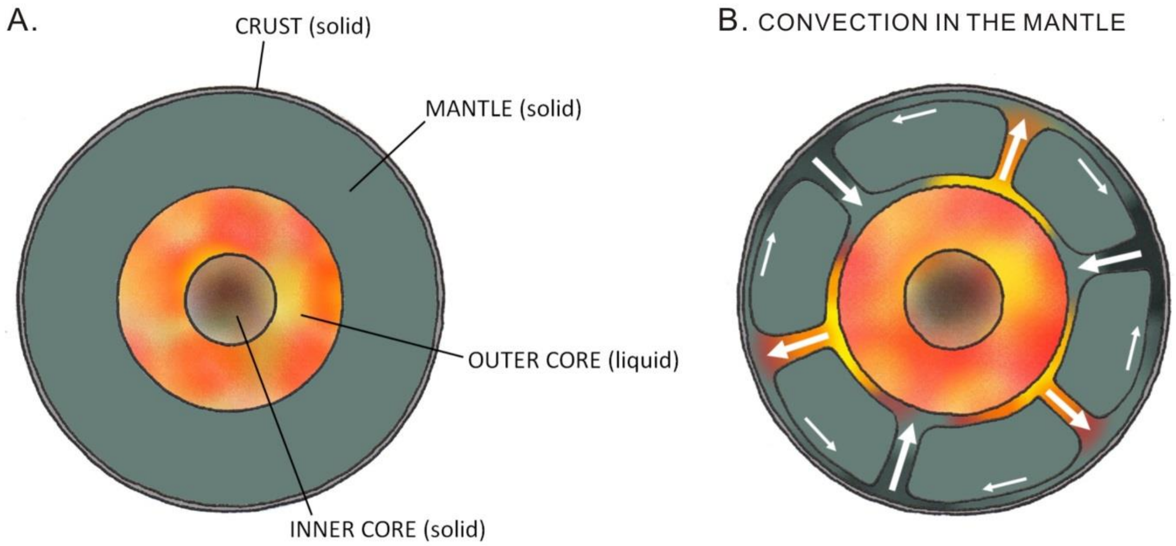

Figure 3: Schematic cross section of the Earth. (A) Earth's main layers and (B) convection movements in the mantle (dark green = colder material sinking, yellow-orange = hotter material rising).
Reference: John Grotzinger, and Thomas H. Jordan, *Understanding Earth 6th edition, Boston, Bedford, 2010.*

Most of the Earth's volume consists of the solid mantle. Rocks of the crust and mantle are composed primarily of minerals of the silicate family. The basic structural unit of silicate minerals is $[SiO_4]^{4-}$ in which each of the four oxygen atoms shares one electron with the silicon atom. The core is Earth's densest layer and composed mostly of an iron-nickel alloy. The mantle is slightly denser than the crust and composed of silicates rich in Fe and Mg. The crust is divided into the **oceanic and continental crust**. The former is thinner (**up to 7 km thick**), heavier, and enriched in Fe and Mg*. The oceanic crust lies beneath the ocean floor. The latter is thicker (**up to 40 km thick**), lighter and enriched in Al, K and Na (Fig. 4). The continental crust forms the continents and their continental shelves (shallow seabed adjacent to the coast). *Where does the evidence supporting the model of a layered Earth come from?* Sources of evidence include: (1) the study of meteorites originating from the fragmentation of larger objects which have been subject to gravitational differentiation, (2) the study of seismic waves traveling inside the Earth (see Fundamental of Earth Science II), (3) the analysis of fragments of rocks from the mantle brought to Earth's surface by volcanic eruptions, (4)

* Note that the chemical composition of the oceanic crust is close to that of the mantle because the oceanic crust is derived from the partial melting of mantle rock (see chapter on igneous rocks).

deep drilling (see project of drilling the oceanic crust down to the mantle by the Japanese drilling vessel *Chikyu*), and (5) high-pressure lab experiments.

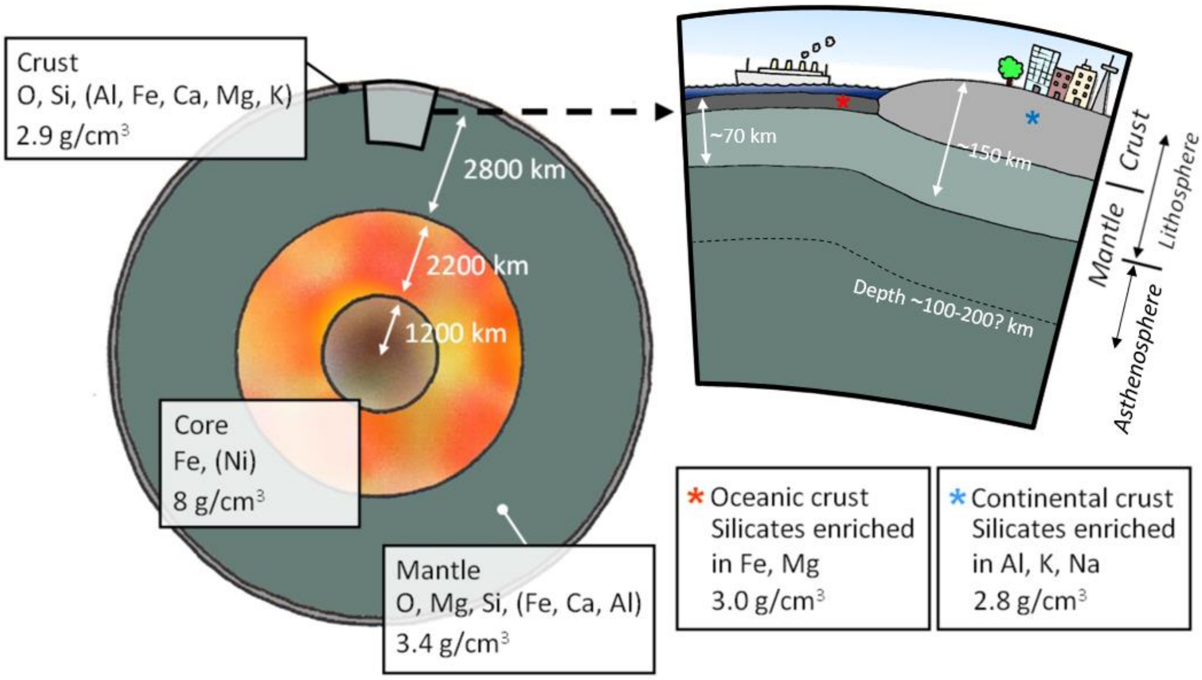

Figure 4: Thickness, composition and density of Earth's layers. Note the distinction between crust and mantle and between the lithosphere and the asthenosphere.
Reference: John Grotzinger, and Thomas H. Jordan, *Understanding Earth 6th edition, Boston, Bedford, 2010.*

3.2. **A dynamic Earth: the theory of plate tectonics**

The crust and the uppermost part of the mantle form a rigid layer called the ***lithosphere*** (Figs. 4). The lithosphere beneath the oceans (i.e., ***oceanic lithosphere***) is **about 70 km thick**. The lithosphere that forms the continents (i.e., ***continental lithosphere***) is **about 150 km thick**. Directly below the lithosphere lies the ***asthenosphere*** (or asthenospheric mantle), a layer of the upper mantle reaching depths of up to ~200 km. The physical properties of the lithosphere and asthenosphere are very different. The lithosphere is rigid and brittle. The asthenosphere is weak and ductile. Slow, plastic deformations can take place in the asthenospheric mantle, allowing matter "to move around". The rock "flow" inside the mantle is driven by differences in density. Hotter material rises toward the surface whereas cooler material sinks (Fig. 3B). This vertical motion is called ***convection*** (like convection taking place in a hot miso soup in which denser, colder soup in contact with the bowl sinks and lighter, hotter soup rises until the temperature/density inside the soup becomes uniform).

The ***lithosphere*** is broken into plates called ***tectonic plates*** (Figs. 5 & 6). Tectonic plates move relative to one another and slide over the asthenosphere. The energy that fuels the process of plate tectonics originates from Earth's internal heat. Three major types of plate boundaries can be identified: (1) ***divergent***, (2) ***convergent***, and (3) ***transform-fault*** plate boundaries.

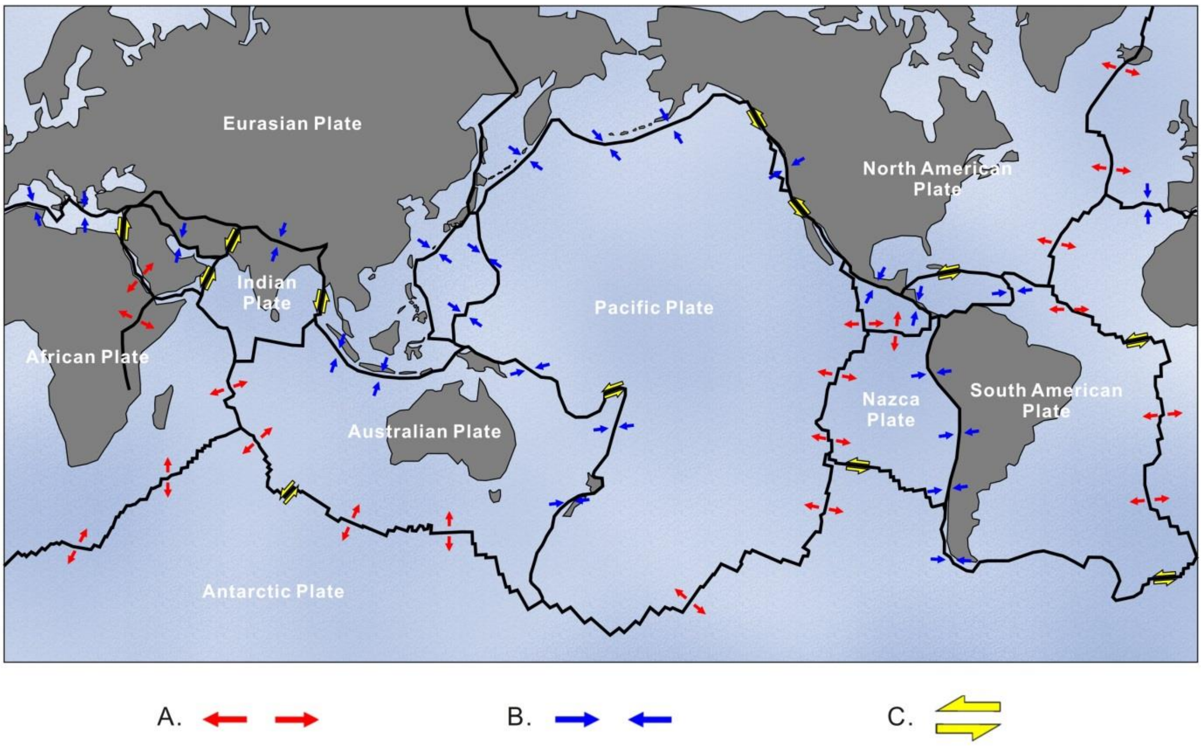

Figure 5: The main tectonic plates. A, B and C are the 3 types of plate boundary: (A) divergent boundary, (B) convergent boundary, and (C) transform-fault boundary (note that only major transform faults are indicated by yellow arrows on this figure).
Reference: John Grotzinger, and Thomas H. Jordan, *Understanding Earth 6th edition, Boston, Bedford, 2010.*

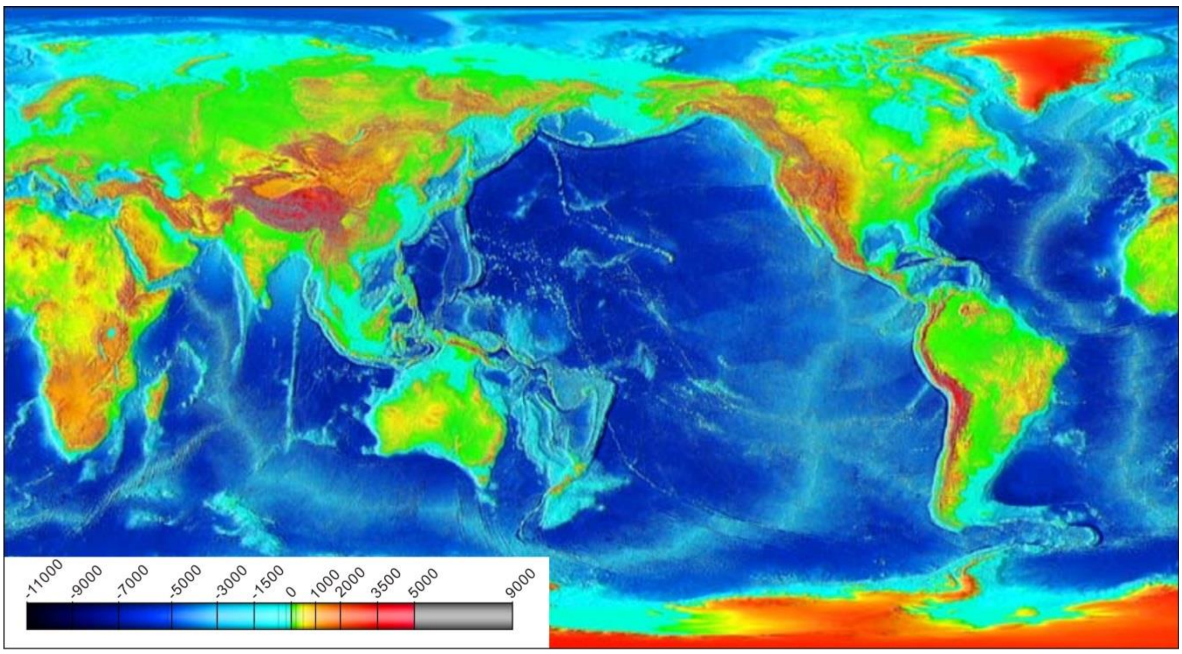

Figure 6: Global relief map of Earth. Note the correspondence between the location of plate boundaries and Earth's topography. Source: NOAA.

(1) *Divergent boundaries*

Along divergent boundaries two plates are pulled apart and a large valley forms in between. This is a zone where mantle rock rises toward the Earth's surface and partially melts[*]. Some of the molten rock (***magma***) solidifies before reaching the surface. Some magma reaches the surface and forms a volcanic chain in the middle of the valley. This process is responsible for the formation of new oceanic crust along plate boundaries called ***mid-ocean ridges*** (e.g., the Mid-Atlantic Ridge, Figs. 6 & 7A). The divergence of oceanic plates at mid-ocean ridges and the production of new oceanic crust is a process referred to as ***seafloor spreading*** (average spreading rate of mid-ocean ridges = 50 mm/yr). The other type of divergent boundary is the ***continental rift*** where continental crust is being pulled apart (e.g., the East African Rift, Fig. 7B) eventually leading to the formation of a new ocean basin.

(2) *Convergent boundaries*

Since the surface area of the Earth's crust does not increase over time, the continuous production of oceanic lithosphere at mid-ocean ridges means that oceanic lithosphere must be destroyed somewhere else. This happens at ***subduction zones*** (Figs. 7C). At subduction zones, two plates converge (two oceanic plates or one oceanic and one continental plate). The heavier oceanic plate slips under the other one[**] and sinks deeper into the mantle where it is "recycled". The subducting oceanic plate sinks because it is colder and denser than the surrounding asthenospheric mantle. Subduction zones are characterized by a deep ***oceanic trench*** on the subducting plate side (e.g. the Mariana Trench) and by a ***mountain chain*** on the overriding plate side (e.g. the Andes, Fig. 6). Subduction zones are also associated with volcanic activity[***] (e.g., Mount Fuji). The other type of convergent boundary involves the collision between two continents: ***continental collision*** (Fig. 7D). In this case, the converging plates are both continental, hence light compared to the mantle, and no subduction takes place. Instead, a large mountain chain builds up where the two continents collide (e.g., the Himalayas, Fig. 6).

(3) *Transform faults*

The last type of plate boundary is called a ***transform fault*** (Figs. 7E-F). Along transform-fault boundaries, two plates slip past one another. They most commonly offset mid-ocean ridges but they can also be found on land (e.g., San Andreas Fault).

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[*] In this context, the partial melting of mantle rock is due to the decrease in pressure during its ascension toward the Earth's surface (*decompression melting*). The melting temperature of a rock is lowered when pressure decreases.

[**] In case of a convergence between two oceanic plates, the older, cooler, hence denser plate subducts beneath the other one.

[***] Rock melting at subduction zones is facilitated by the presence of H_2O contained in sedimentary rock pores and minerals. The effect of water is to lower the melting point of rocks because water molecules helps break chemical bonds.

Earthquakes occur along all plate boundaries, whereas the majority of ***volcanoes*** are located along subduction zones and mid-ocean ridges.

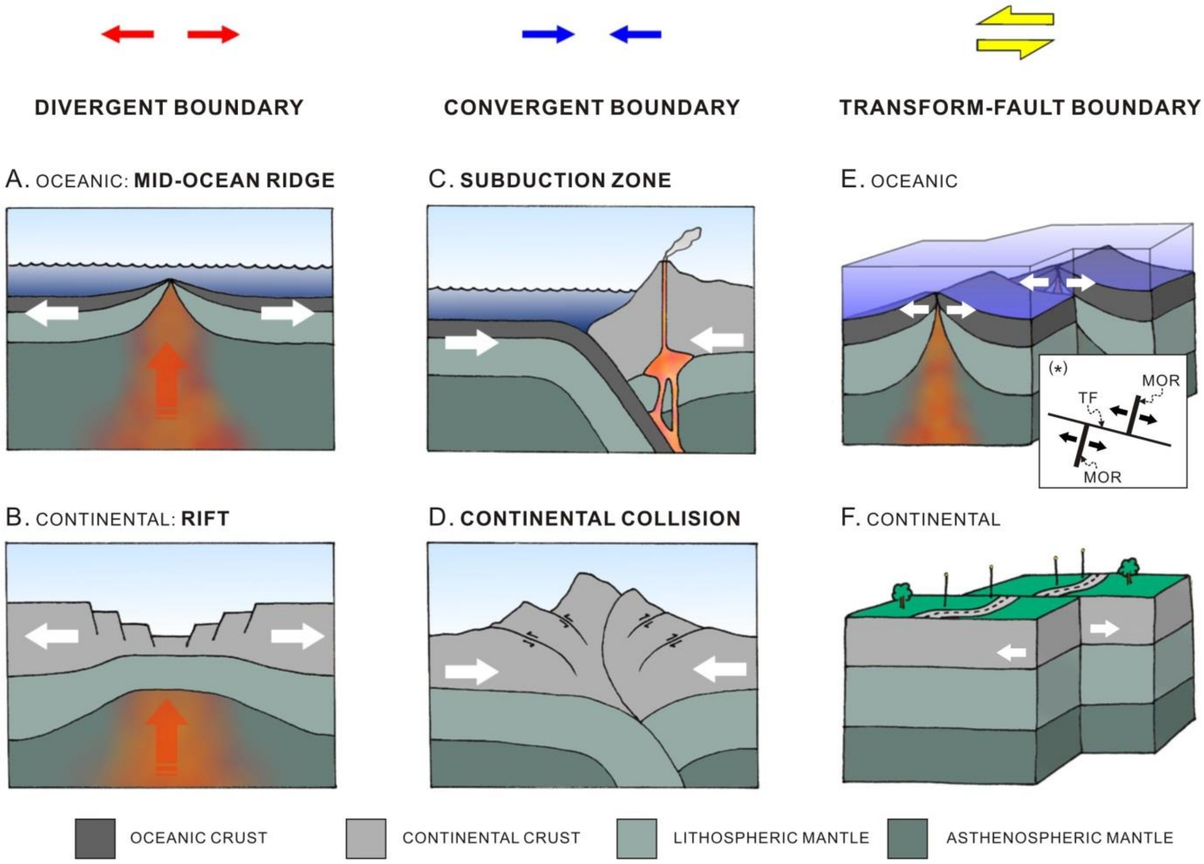

Figure 7: Schematic cross section of tectonic plate boundaries. (*) Oceanic transform fault viewed from above (TF = transform fault, MOR = mid-ocean ridge). Note the motion of plates in opposite directions between the two segments of mid-ocean ridge.
Reference: John Grotzinger, and Thomas H. Jordan, *Understanding Earth 6th edition, Boston, Bedford, 2010.*