1. The Earth system

1.1. introduction

The Earth system can be divided into three subsystems: (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 －heat accumulated at the beginning of Earth’s history and generated by the decay of radioactive elements.

(1) The ***climate system*** includes all the components of the Earth system whose interactions control Earth’s climate: the ***atmosphere*** (layer of gas surrounding the Earth), the ***cryosphere*** (surface ice and snow, e.g. polar ice caps, mountain glaciers, permafrost), the ***hydrosphere*** (liquid surface water, including groundwater), the ***lithosphere*** (rigid rocky outer layer of Earth), and the ***biosphere*** (all living things). Recent global warming calls to our attention the role of human activities on climate change. So much so that it is adequate to define 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 movement of continents, the formation of mountains and ocean basins, and events such as volcanic eruptions and earthquakes. These components are the ***lithosphere***, ***asthenosphere***, and the deep ***mantle***. These terms will be described in the following paragraphs. As we will see later, characteristics of the lithosphere such as the position of continents, the presence of mountain chains or the shape of ocean basins influence the climate system.

(3) The ***geodynamo system*** produces and maintains Earth’s magnetic field and involves movements of matter within the Earth’s core.

Figure 1: Model of the Earth system and its three subsystems (i.e. climate, plate tectonics, and geodynamo).

1.2. Earth structure and plate tectonics

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 falling from space on the surface of the Earth. They originate from the collision and fragmentation of larger bodies. These larger bodies －asteroids－ are leftovers from the process of planetary accretion. In other words, they did not aggregate with other asteroids to form planets. The age of the Earth derived from meteorites is 4.6 billion years.

During the first billion years, the solar system was not yet cleared of the majority of its asteroids. This meant a higher probability of collision among asteroids and planets, and therefore a higher number of meteorites falling on the Earth. This period of Earth's history is referred to as the ***Heavy Bombardment***. Heat released by the collision between Earth and large meteorites was enough to melt Earth's surface. Another important source of heat was provided by the decay of radioactive elements contained inside the Earth. Consequently, our planet was occasionally in a molten ("soft") state, during which elements could migrate freely and matter redistributed according to its density. Heavier elements (Fe, Ni) migrated toward the center of the Earth, whereas lighter elements remained at the surface (Mg, Al, K). This process, by which Earth became a layered planet, is called ***gravitational differentiation***.

Earth is composed of 3 layers: the ***crust***, the ***mantle*** and the ***core*** (Fig. 2A). 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 "forces" matter into a solid state despite the very high temperature.

Figure 2: 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).

Most of the Earth's volume consists of the solid mantle. Solid does not mean totally rigid in this case. Slow, plastic deformations can take place, allowing matter to move. The rock "flow" inside the mantle is driven by differences of temperature/density. Hotter material rises toward the surface whereas cooler material sinks (Fig. 2B). This vertical motion is called ***convection*** (like convection taking place in a hot miso soup in which colder, denser soup in contact with the bowl sinks and hotter, lighter soup rises, creating convective cells).

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 oxygen atom shares one electron with the silicon atom. The crust is divided into an oceanic and continental crust. The former is thinner (up to 7 km thick), heavier and enriched in Fe and Mg[*], and lies beneath the ocean floor. The latter is thicker (up to 40 km thick), lighter and enriched in Al, K, and Na, and rises above sea level to form the continents (Fig. 3).

Figure 3: Thickness, composition and density of Earth's layers. Note the distinction between crust and mantle, and between lithosphere and asthenosphere.

The crust and the uppermost part of the mantle form a layer called the ***lithosphere*** (Figs. 3). The lithosphere beneath the oceans (oceanic lithosphere) has an average thickness of 70 km. Beneath continents (continental lithosphere), it can be more than 200 km thick. Directly below the lithosphere lies the ***asthenosphere***, a portion of the mantle a few hundred kilometers thick. The

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[*] Note that the mantle is also rich in iron and magnesium. The chemical composition of the oceanic crust is very similar to that of the mantle because the oceanic crust is derived from the partial melting of mantle rock (see page 3).

physical properties of the two layers are very different. The lithosphere is rigid and brittle. The asthenosphere is weak and ductile.

The lithosphere is broken into plates called ***tectonic plates*** (Figs. 4 & 5). Tectonic plates move relative to one another and slide over the asthenosphere. The motion of plates is driven by convective movements inside the mantle. Three major types of plate boundary can be identified: (1) divergent, (2) convergent, and (3) transform-fault.

Figure 4: 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 on this figure).

Figure 5: Global topographic map. Note the correspondence between the location of plate boundaries and Earth's topography. The deepest places on Earth consist of oceanic trenches along subduction zones and submerged mountain chains correspond to mid-ocean ridges (see text for explanations). Source: NOAA.

(1) ***Divergent boundaries***: two plates are pulled apart where hot mantle material rises and a large valley (***rift***) forms in between. Mantle rock rising toward the surface partially melts[*]. Some of the molten rock (magma) solidifies before reaching the surface; some reaches the surface forming a volcanic chain in the middle of the valley. This process is responsible for the formation of new oceanic lithosphere along plate boundaries called ***mid-ocean ridges*** (e.g. the Mid-Atlantic Ridge, Figs. 5 & 6A). The divergence of oceanic plates at mid-ocean ridges and the production of new oceanic lithosphere is a process referred to as ***sea-floor spreading*** (average spreading rate of mid-ocean ridges = 50 mm/yr).

The other type of divergent boundary is the ***continental rift*** where continental lithosphere is being pulled apart (e.g. the East African Rift, Fig. 6B), eventually leading to the formation of a new ocean basin.

(2) ***Convergent boundaries***: since the Earth's surface does not increase in time, the continuous production of oceanic lithosphere at mid-ocean ridges means that it must be destroyed somewhere else. This happens at ***subduction zones*** (Figs. 6C). 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 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

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[*] In this setting, 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.

plate side (e.g. the Andes, Fig. 5). 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. 6D). In this case, the converging plates are both continental, hence light compared to the mantle, and no subduction can take place. Instead, a large mountain chain builds up where the two continents collide (e.g. the Himalayas, Fig. 5).

(3) ***Transform faults***: along transform-fault boundaries, two plates slip past one another (Figs. 6E-F). They most commonly offset mid-ocean ridges but they can also be found on land (e.g. San Andreas Fault).

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

Figure 6: 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, which triggers earthquakes.

1.3. Minerals: building blocks of rocks

Rocks are usually composed of an aggregate of different minerals although they can be composed of a single mineral too. Minerals are solid inorganic substances with atoms arranged in a regular, repeating pattern (***crystal lattice***). They have a specific chemical formula (e.g. $NaCl$, $CaCO_3$; Fig. 7). The external shape of mineral crystals reflects the internal order of atoms.

Figure 7: Crystal structure of halite (table salt). The green cube represents the repeating structural unit of the crystal lattice of halite (unit cell). Note the cubic shape of crystals of halite. Source (photograph): Understanding Earth 6th edition.

The structure of a mineral (the way atoms are stacked) depends on its chemical composition as well as the conditions of temperature and pressure during crystallization (Fig. 8).

Figure 8: Two minerals with the same chemical composition (carbon) but with different crystal structures. (A) Diamond formed at high temperature and pressure, and (B) graphite formed at much lower temperature and pressure. Source: modified from Understanding Earth 6th edition.

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

Three basic processes are responsible for the formation of minerals:

(1) Minerals form in saturated fluids when dissolved ions have reached their solubility threshold (e.g. precipitation of salts as water evaporates in a saline lake, Fig. 9A).
(2) Minerals form by solidification (liquid-solid transition) or deposition (gas-solid transition) (e.g. crystallization of a cooling magma, Fig. 9B)
(3) Minerals form by biological processes (***biomineralization***, e.g. corals, mollusk shells; Fig. 9C)

Figure 9: Illustration of the three processes of mineral formation. (A) Salts deposited at the bottom of a saline lake in southeastern Tunisia (scale bar = 2.5 km, source: Nasa Earth Observatory website), (B) rock composed of an aggregate of minerals crystallized during the slow cooling of a magma within the Earth's crust (granite, scale bar = 1 cm), and (C) coral skeleton composed of calcium carbonate (the specimen is 11 cm across).

1.4. Rocks and the rock cycle

The study of rocks is important because their mineral and chemical compositions and fossil contents can be used to reconstruct Earth's history and understand how life evolved. Rocks contain groundwater used for agriculture, public consumption and industrial purposes. They also contain mineral resources, such as gas, oil, coal and ore minerals, which are important from an economic and technological viewpoint. Their study is also crucial to solve environmental problems, such as the storage of radioactive substances and carbon dioxide, and the underground diffusion of pollutants.

Rocks can be classified into three families:

(1) ***Igneous rocks*** form by solidification of a cooling magma (molten rock). The size of mineral grains depends on the cooling rate (Figs. 10). Fine-grained igneous rocks are those which form near or at the surface of the Earth's crust when magma cools down rapidly (***extrusive igneous rocks***). Volcanoes form where magma reaches the surface (more or less violently). If the cooling rate is extremely high (e.g. magma in contact with air or water), crystals may not even have time to form, leading to the formation of a rock called ***volcanic glass***. Coarse-grained igneous rocks are those which form deep within the Earth's crust (***intrusive igneous rocks***). They result from the slow cooling of magma within the lithosphere (***magmatic intrusion***).

Figure 10: Examples of igneous rocks (hand-size specimens, scale bar = 2 cm, and photomicrographs taken in cross-polarized light, scale bar = 1 mm). (A) Intrusive igneous rock (granite) with large crystals formed in a slowly cooling magma, (B) extrusive igneous rock (basalt) with tiny crystals formed in a rapidly cooling magma, and (C) extrusive igneous rock (basalt) with tiny crystals mixed with volcanic glass (in black on the photomicrograph) resulting from a very high cooling rate (note the shiny surface of the sample). Source: Imperial College Rock Library.

(2) ***Sedimentary rocks*** form by accumulation and subsequent ***lithification***[*] of ***sediments*** (fragments of preexisting rocks or elements of biological origin, Figs 11A-C) or by precipitation of minerals from an aqueous solution (Fig. 11D). Sedimentary rocks forms in depressions of the Earth's crust where sediments can accumulate. Most originates in the largest depressions: the ocean basins. Sediments can be fragments of igneous, sedimentary or metamorphic rocks, or fragments of minerals (Fig. 11A). Sediments can also be of biological origin, such as mollusc shells, coral skeletons, bones and plant remains (Fig. 11 B-C). Other sedimentary rocks form by precipitation of minerals in evaporating lakes or embayments and are called ***evaporites*** (Fig. 11D).

Figure 11: Examples of sedimentary rocks (scale bar = 1 cm). (A) Conglomerate composed of rounded rock fragments (source: Imperial College Rock Library), (B) limestone composed of fragments of shells made of calcite ($CaCO_3$) (black arrows indicate shells of single-celled organisms called foraminifera), (C) coal (rock derived from an accumulation of plant debris, source: USGS) , and (D) evaporite composed of layers of anhydrite ($CaSO_4$) (source: Garcia-Veigas et al., 2013).

(3) ***Metamorphic rocks*** form by transformation of the chemical and/or mineralogical composition and/or texture[**] of a preexisting rock in a ***solid state*** due to changing conditions of temperature and/or pressure or due to interactions with hydrothermal fluids (Fig. 12). This process of rock transformation is called ***metamorphism***. Rocks caught in subduction zones or between two colliding continents are subject to tremendous changes in temperature and pressure causing rock metamorphism (***regional metamorphism***). In addition, wherever rocks are in contact with magma, these rocks, if not melted, are transformed (metamorphosed) —in this case "cooked"— by increasing temperature (***contact metamorphism***). Water heated in the vicinity of a magma circulates in the crust (***hydrothermal circulation***) and reacts with surrounding rocks, changing their chemical and mineralogical compositions (***metasomatism***). For instance, seawater which penetrates the oceanic crust through fractures near mid-ocean ridges is heated and leaches metals and sulfur from surrounding rocks. These elements precipitate as metal sulfides at underwater hot springs, forming large chimneys rising from the sea floor (***black smokers***).

Figure 12: Examples of metamorphic rocks (hand-size specimens, scale bar = 2 cm, and photomicrographs taken in cross-polarized light, scale bar = 1 mm). (A) gneiss showing an alternation of darker and lighter layers with different mineralogical compositions (layers are perpendicular to the direction of pressure —indicated by the arrows— affecting the rock during metamorphism), (B) schist with elongated minerals oriented at right angle to the direction of pressure (foliation), and (C) marble (metamorphosed sedimentary rock, usually limestone. Source: Imperial College Rock Library.

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[*] Lithification means solidification of a soft sediment (another word is ***induration***). This process occurs primarily by compaction (from the overlying sediment load) and precipitation of minerals in the space between sediment grains.

[**] The texture is determined by the size, shape and orientation of minerals.

The distribution of the different families of rocks is closely related to plate tectonics (Fig. 13). The formation of igneous rocks is linked to magma production and therefore to regions of the crust where rocks begin to melt. Rock melting takes place at mid-ocean ridges and subduction zones and at the root of large mountain chains related to continental collision. Most sedimentary rocks are produced in ocean basins whose formation is controlled by plate tectonics (i.e. the opening of ocean basins through sea-floor spreading). The distribution of metamorphic rocks too is of course closely linked to plate tectonics. Large variations of temperature and pressure affect rocks in convergence zones. Metasomatism related to hydrothermal circulation occurs in the vicinity of magmatic intrusions associated with plate boundaries.

Figure 13: Idealized cross section of the Earth's crust showing the regions of the crust where most igneous, sedimentary, and metamorphic rocks are produced. O-C SUBD. = ocean-continent subduction, HS = hot spot, O-O SUBD. = ocean-ocean subduction, MOR = mid-ocean ridges, CONT. COLL. = continental collision. Note that the hot spot location is not related to plate boundaries. Hot spots result from hot mantle material rising from great depths and producing volcanic activity at the surface (e.g. Hawaii).

Processes leading to the transformation of a rock of one family to a rock of another family can be described as a cycle called the ***rock cycle*** (Fig. 14). The rock cycle illustrates how each rock families can evolve from one another. The transformation of one rock family to another is controlled by plate tectonics and climate.

The control of plate tectonics on rock formation is clear when one looks at where the different types of rocks are being produced (see Fig. 13 and related text). Climate controls the production rate of sediments because the erosion of mountains depends on the amount of precipitation and other climatic factors (e.g. temperature). Hence, climate controls the production of sedimentary rocks. Plate tectonics also control the production rate of sediments because plate tectonics controls the formation of mountains from which sediments are derived. Moreover, plate tectonics influences the climate system through processes which will be discussed later in this course.

Figure 14: The rock cycle. Each arrow represents a transformation process from one rock family to another. Each transformation process is represented by a specific color. Note that metamorphic rocks themselves can also be metamorphosed.