5. Introduction to rocks

5.1. What is a rock?

A ***rock*** is a naturally-occurring solid material usually composed of an aggregate of mineral matter. Two exceptions are ***coal*** and ***volcanic glass*** (obsidian). The former is composed in large parts of organic compounds which cannot be regarded as minerals. The latter is a solid glassy material in which the arrangement of atoms displays irregularities and therefore does not match the definition of a mineral.

Properties of rocks that are commonly used to characterize them are their color, their texture (e.g., coarse-grained vs. fine-grained), and their mineralogical and chemical compositions.

5.2. Why study rocks?

We study rocks to learn about the history of the Earth. Rocks provide information about the origin and evolution of the terrestrial biosphere, lithosphere, atmosphere, and hydrosphere during the past 4.6 billion years. Information on past sea level and environmental changes can be used to assess the validity of predictive models aiming to determine the future course of the Earth global environment and sea level history. The study of rocks is not limited to our planet. By analyzing meteorites we can learn about the origin of the solar system. Samples of lunar rocks and soil (regolith) have been collected during the Apollo missions and by the Russian Luna spacecrafts in the late 60s and early 70s. More recently, NASA rovers have been analyzing Martian rocks to unravel the history of the red planet and to seek traces of present and past life.

Rocks are also important from an economic viewpoint because they may contain valuable minerals. The industrial revolution during the first half of the 19th century would not have been possible without coal. Coal and other rocks rich in organic compounds are associated with the production of oil and natural gas. Rocks contain minerals that can be exploited if their concentration is sufficiently high. These rocks are called ***ores*** (term usually used for metal-rich rocks). An example of iron ore is the banded iron formation (BIF) already mentioned in the previous chapter. Rocks are also quarried for various purposes in the construction industry (e.g. concrete manufacturing, construction aggregates, building stones). Therefore, understanding how rocks form and how they are distributed is essential for the mining industry.

The study of rocks can help solving environmental issues. For instance, plans to store carbon dioxide within certain rock formations with the purpose to alleviate the current rise in global temperature are now being evaluated by experts and tested in field experiments. The storage of highly radioactive waste deep underground is also considered a relatively safe way to dispose of this dangerous material.

Potable water is a fundamental resource for all countries. The presence/absence of groundwater reservoirs and their characteristics is determined by rock properties. The study of rocks is essential for the localization, characterization, and sustainable exploitation of groundwater reservoirs.

5.3. Classification of rocks

Rocks can be classified into three main families:

(1) ***Igneous rocks*** form by solidification of a cooling ***magma*** (molten rock). The size of mineral grains depends on the cooling rate (Fig. 1). Fine-grained igneous rocks are those which form near or at the surface of the Earth's crust where magma cools more 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 and ***volcanic glass*** is produced. Coarse-grained igneous rocks are those which form within the Earth's crust (= ***intrusive igneous rocks***). They result from the slow cooling of magma within the crust. Bodies of magma present in the crust are called ***magmatic intrusions***.

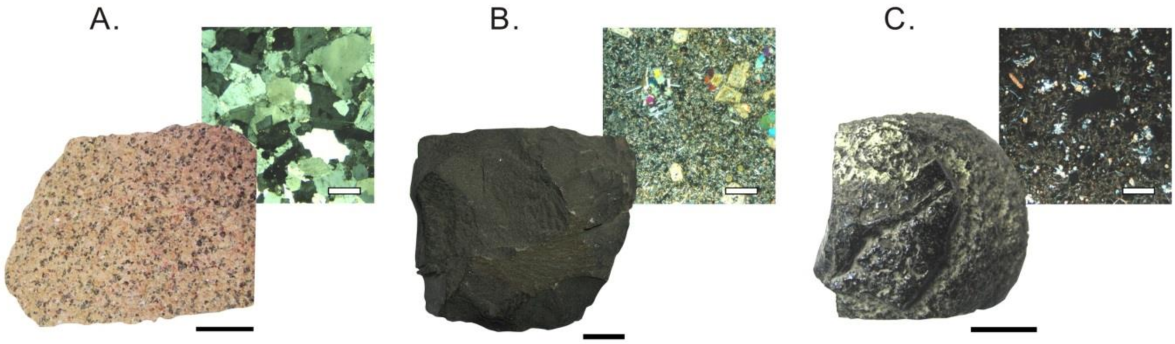

Figure 1: Examples of igneous rocks (hand-size specimens, scale bar = 2 cm, and photomicrographs taken in cross-polarized light, scale bar = 1 mm). (A) Intrusive igneous rock (granite) with large mineral grains crystallized in a slowly cooling magma, (B) extrusive igneous rock (basalt) with tiny mineral grains crystallized in a rapidly cooling magma, and (C) extrusive igneous rock (basalt) with tiny mineral grains 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 2A-C) or by precipitation of minerals from an aqueous solution (Fig. 2D). Sedimentary rocks form in depressions of the Earth's crust where sediments can accumulate. Most originate in the largest depressions, i.e. the ocean basins. Sediments can be fragments of igneous, sedimentary or metamorphic rocks, or fragments of individual minerals (e.g. quartz sand). Sediments can also be of biological origin, such as mollusk shells, coral skeletons, bones and plant remains. Sedimentary rocks formed by precipitation of minerals in saline lakes or an embayment subject to evaporation are called ***evaporites***.

* 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 (***cementation***).

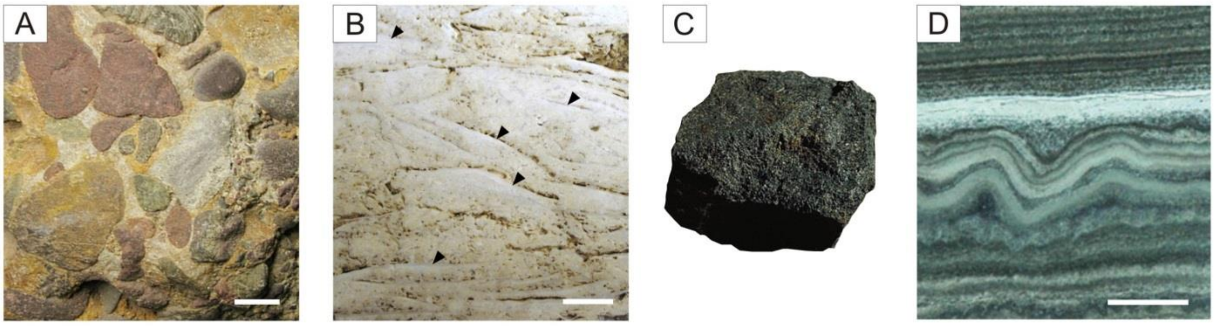

Figure 2: Examples of sedimentary rocks (scale bar = 1 cm). (A) Conglomerate composed of rounded rock fragments (source: Imperial College Rock Library), (B) limestone composed of fragments of shells made of calcite ($CaCO_3$) (black arrows indicate shells of single-celled organisms called foraminifera), (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. 3). 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 and can undergo various degrees of 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 increased temperature (***contact metamorphism***). In addition, water heated in the vicinity of magma circulates in the crust (***hydrothermal circulation***) and reacts with 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. This process also leads to the formation of new minerals in the basalt (e.g., hydrated minerals like chlorite or epidote which gives a dark green color to the rock ― hence this metamorphic rock is called ***greenstone***).

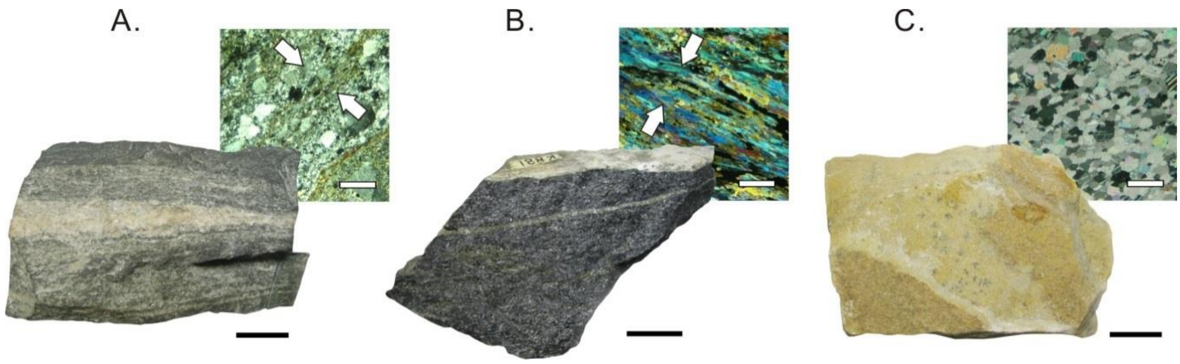

Figure 3: Examples of metamorphic rocks (hand-size specimens, scale bar = 2 cm, and photomicrographs taken in cross-polarized light, scale bar = 1 mm). (A) gneiss with alternation of darker and lighter layers (layers are perpendicular to the direction of pressure ―indicated by the arrows― affecting the 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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[*] The texture of metamorphic rocks 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. 4). The formation of igneous rocks is linked to magma production, and is therefore associated with regions of the crust where rocks begin to melt. Rock melting takes place at mid-ocean ridges and subduction zones, at hotspots, and at the root of large mountain chains resulting from 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 seafloor spreading). The distribution of metamorphic rocks is also closely linked to plate tectonics. Large variations of temperature and pressure affect rocks along convergent boundaries. Contact metamorphism occurs wherever rocks are in contact with magma. Metasomatism related to hydrothermal circulation occurs in the vicinity of magmatic intrusions associated with plate boundaries.

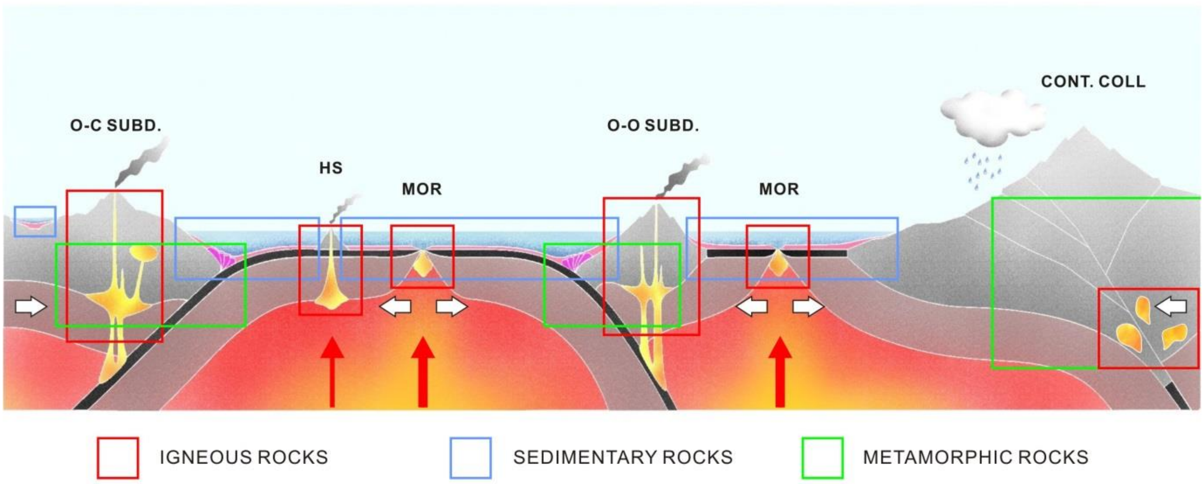

Figure 4: Idealized cross section of the Earth's crust showing the regions of the crust where most igneous, sedimentary, and metamorphic rocks are produced. O-C SUBD. = ocean-continent subduction, HS = hot spot, O-O SUBD. = ocean-ocean subduction, MOR = mid-ocean ridges, CONT. COLL. = continental collision. 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).
Reference: John Grotzinger, and Thomas H. Jordan, *Understanding Earth 6th edition, Boston, Bedford, 2010.*

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. 5). The rock cycle illustrates how each rock families can evolve from one another. The transformation of one rock family to another depends on 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. 5 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 controls the production rate of sediments because plate tectonics controls the formation of mountains from which most sediments are derived. Moreover, the long term evolution of Earth's climate (over millions of years) is influenced by plate tectonics: (1) global volcanism along plate boundaries influences the concentration of CO_2 in the atmosphere; (2) the formation of large mountain chains along convergent plate boundaries (e.g. Himalayas) influences the concentration of CO_2 in the atmosphere through the process of silicate weathering (see chapter on sedimentary rocks).

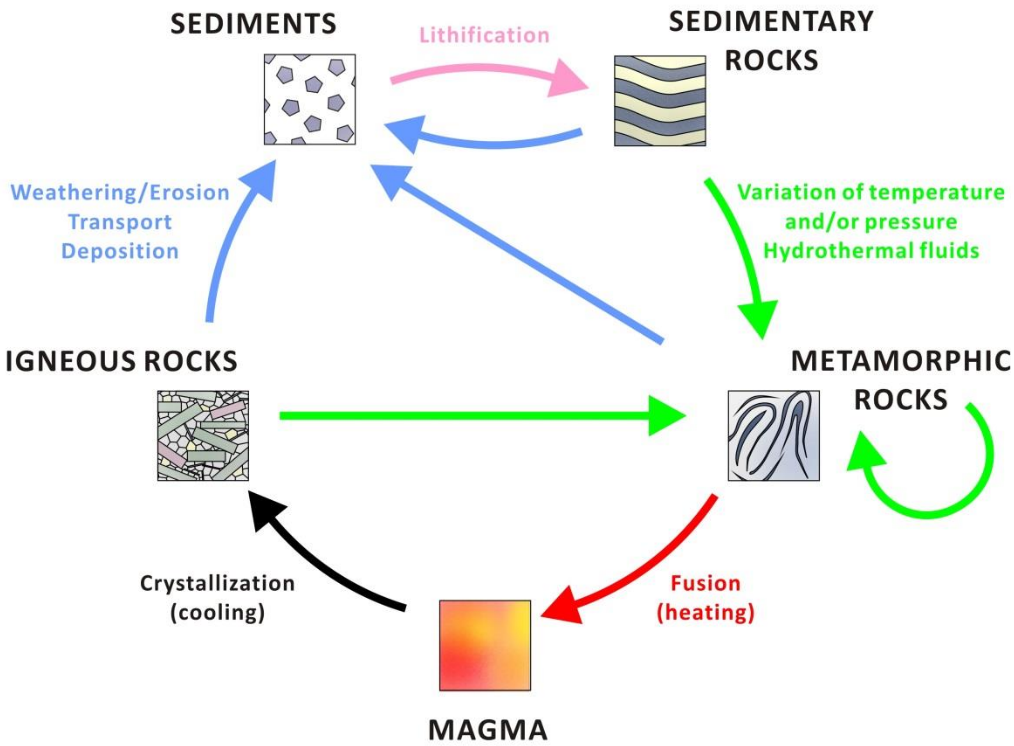

Figure 5: The rock cycle. Each arrow represents a transformation process from one rock family to another. Each transformation process is represented by a specific color. Note that metamorphic rocks themselves can also be metamorphosed.
Reference: John Grotzinger, and Thomas H. Jordan, *Understanding Earth 6th edition, Boston, Bedford, 2010.*