PETROLOGY OF METAMORPHIC ROCKS

SECTION I.

Basic notions about metamorphism

Contents

INTRODUCTION

The geological processes including plate's tectonic are fundamental for understanding the dynamic nature of Earth's surface. This concept of geodynamic explains how the lithosphere, which comprises the crust and the upper mantle, is divided into several large and small tectonic plates that float on the semi-fluid asthenosphere beneath. The interactions among these plates lead to various geological phenomena, including earthquakes, volcanic activity, and orogenesis causing the so called ''Metmorphism''. In this program, major aspects of the Metamorphism process will be undertaken.

I. DEFINITION: WHAT IS METAMORPHISM?

Metamorphism is defined as the modification of a rock's mineralogical, textural, and structural properties due to the variation of pressure and temperature and/or the presence or absence of a fluid phase. These changes take place in the solid state. As a result, there is no matter melt. General metamorphism equation is:

$\mathbf{P}_{\text{parent rock}} \rightarrow$ P+T+ fluid phase $\rightarrow$ **M** product ± Volatiles

minerals recrystallize, evolve, and change structure and chemical to adapt to the new conditions via two ways.

- Modifying the crystal lattice geometry (skeleton). Like the three alumina-silicate polymorphs "andalusite, sillimanite, and kyanite" with the same chemical formula (Al_2SiO_5), but different crystalline frame.
- Changing the chemical components, either partially (Chlorite → Biotite) or totally (clay minerals → micas).

  - ☒ The original rock subjected to the metamorphic process is known as "protolith." The protolith can be any form of rock.
  - ☒ During metamorphism, there is no matter loss except for water and CO_2, hence the chemical composition can remain unchanged (1) isochemical transformation, however, it can change partially or completely (2) allochemical transformation, as shown below.:

(1) $NaAlSi_3O_8 \rightarrow NaAlSi_2O_6 + SiO_2$

Albite Jadeite Quartz

(2) $3CaMg(CO_3)_2 + 4SiO_2 + H_2O \rightarrow Mg_3Si_4O_{10}(OH)_2 + 3CaCO_3 + 3CO_2$

Dolomite Quartz Talc Calcite

II. FACTORS OF METAMORPHIM

Pressure and temperature, as well as the presence of a fluid phase along with time, are the physical factors that govern the metamorphic process. A fluid phase of volatile constituents is also present during the metamorphism of carbonate rocks.

II.1 Pressure

Pressure varies from few megapascals (shallow crust) to 3.0 GPa high-pressure rocks of crustal origin (e.g. the Alps, Edough massif in Algeria...) until 6 GPa within the mantle in subducted zones (figure 2).

Pressure causes rock deformation and volume reduction, thus high-density recrystallization (foliation) and crystal system simplification. Silicates, for example, crystallize at the surface as "phyllo" and at depth as "tecto" (simple cubic structure). There are three sources of the pressure:

II.1.1 Lithostatic pressure (LP)

This form of pressure is generated by the huge mass of rocks on top of the rock undergoing metamorphism, it depends on rock density (ρ) and the depth (h). It is isotropic, and causes no deformation. Lithostatic pressure is calculated by the following formula : **LP = ρ g h:** **(**ρ = density of overlying layers, **g** = gravity, **h** = burial depth)

II.1.2 Tectonic pressure (Pt)

This form of pressure is caused by tectonic forces (compression) that occur during thrusting and orogenic processes. It has anisotropic and oriented properties. It causes deformation and the creation of new structures such as schistosity and foliation.

II.1.3 fluid pressure (Pf)

Fluid pressure applied at the level of rock pores improves circulation and enhances mineral transformation processes and matter exchanges.

II.2 Temperature

The low-temperature metamorphism limit has been estimated above 200°C or 300°C. The high-temperature limit recorded in crustal metamorphism oscillates between 1000 and 1150°C (figure 2). Temperature causes rock system instability. Increasing temperatures cause unstable low-temperature minerals to be replaced by more stable high-temperature minerals. Pressure at high temperatures flattens and stretches crystals or particles in igneous or sedimentary rock, causing them to align in schistosity or foliation planes.

II.3 Fluid phase

The presence of fluids (usually H_2O) shifts the solidus and facilitates chemical reactions (at a given pressure and temperature). The most complete recrystallizations take place in the deformed zones where water circulates more easily. The diagram below (figure 1) illustrates the lowering of a gabbro's melting temperature in the presence of H_2O.

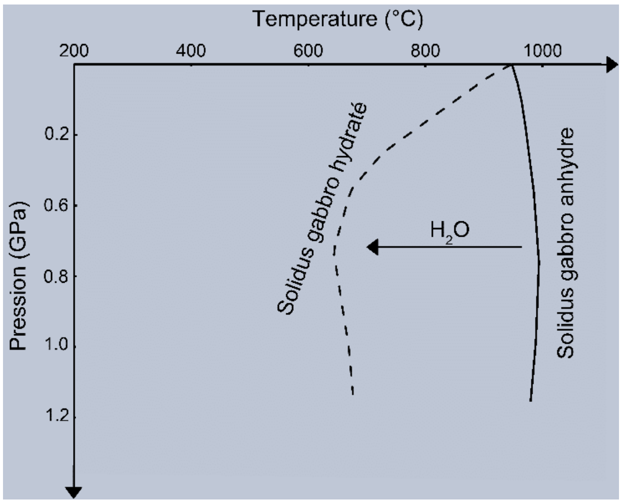


Figure 1 *Influence of the fluid phase (H2O) on gabbro melting conditions*.

II.4 Time

Time is an important factor, as metamorphic reactions occur at extremely low speeds. For most minerals to be metastable, physico-chemical conditions must be maintained over a long period of time to allow mineralogical and structural transformations to take place.

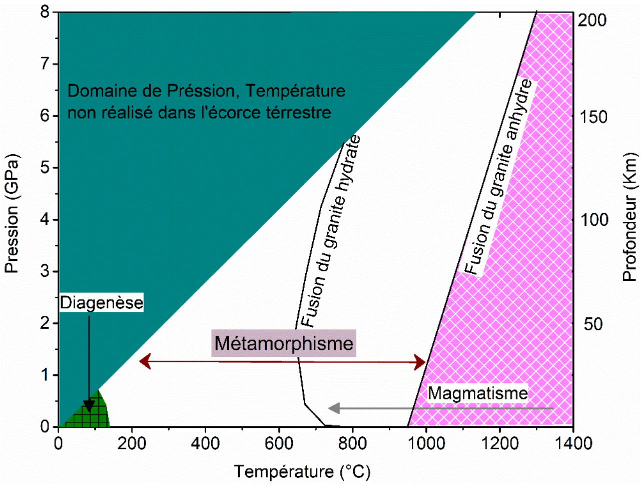
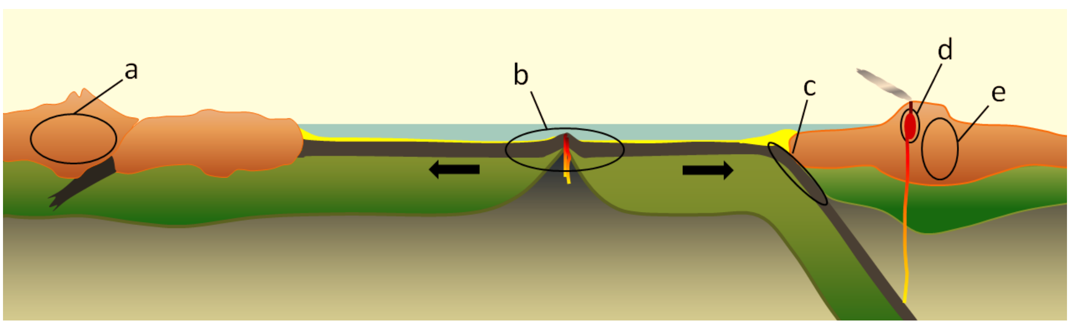


Figure 2 *Limits of the P and T conditions of the metamorphic process (approximate domains), according to K. Bucher and R. Grapes (2011).*

III. GEODYNAMIC CONTEXT OF METAMORPHIC PROCESS

The geodynamic context of metamorphism is primarily linked to plate tectonics. Key factors include:

- Subduction Zones: These are critical areas where oceanic plates descend beneath continental plates, leading to high-pressure, low-temperature metamorphism characterized by blueschist and eclogite facies. The interaction of fluids released from subducting slabs also plays a significant role in facilitating metamorphic reactions
- Continental Collision Zones: Here, intense pressure and temperature conditions arise due to the thickening of the crust during continental collisions. This results in significant regional metamorphism, often producing high-grade metamorphic rocks
- Volcanic Arcs: Associated with subduction zones, these regions experience both contact and regional metamorphism due to the additional heat from volcanic activity, which can steepen geothermal gradients compared to stable continental crusts.



a. Collision zones
b. Rift zones (heating)
c. Subducted zones

d. Arc zones – contact metamorphism
e. Arc zones regional metamorphism

IV. TYPES OF METAMORPHISM

Two broad types of metamorphism are distinguished based on the impact's extension (Figure II-1) :

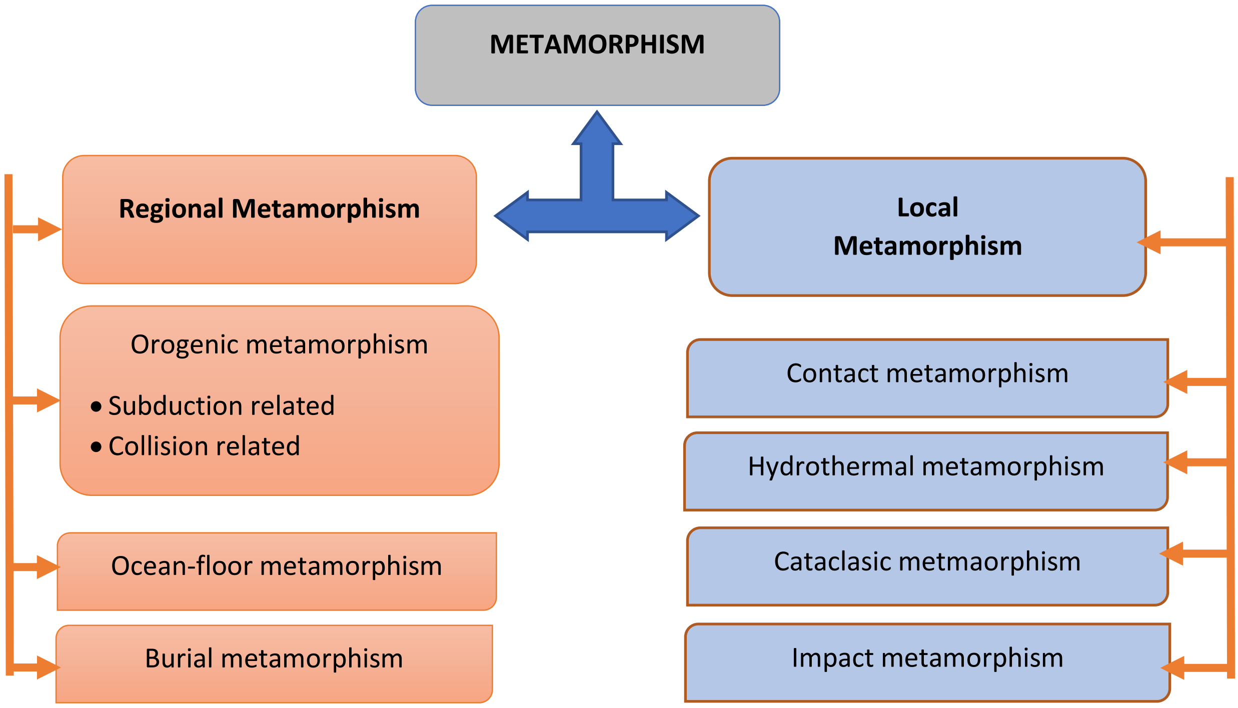


Figure IV.1 *Types of metamorphism*

IV.1 REGIONAL METAMORPHISM

IV.1.1 Orogenic-type metamorphism

Orogenic metamorphism (also called general metamorphism), is related to orogenic processes. It affects large volumes of rock. It is the most significant type of metamorphism extending over large belts (the Alps, the Maghreb, the Himalayas, etc.). Orogenic metamorphism, also known as dynamothermal metamorphism, resulting in three major transformations:

- A deformation of the rock (penetrative texture).
- The development of so-called metamorphic minerals (especially alumina silicates).

 The development of schistosity and metamorphic foliation (see below).

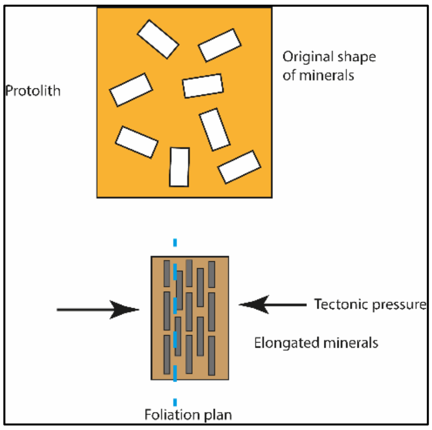


Figure IV.2 *Schematic representation of the application of pressure during metamorphism.*

Orogenic metamorphism is divided into subduction-related and collision related sub-types:

- (1) Early, subduction-related metamorphism, characterized by high pressure and low temperature (HP, LT);
- (2) Late, collision-related metamorphism, characterized by a medium degree (MP, MT).

IV.1.2 Ocean-floor metamorphism

Ocean-floor metamorphism includes transformations of oceanic crust near mid-ocean ridges, where the geothermal gradient is very high, up to several 100°C/km. The metamorphic rocks thus produced are displaced laterally as the ocean floor expands, covering vast areas. Metamorphosed rocks (basalt, gabbro, dolerite and peridotite), show no schistosity. They partially preserve their original magmatic textures.

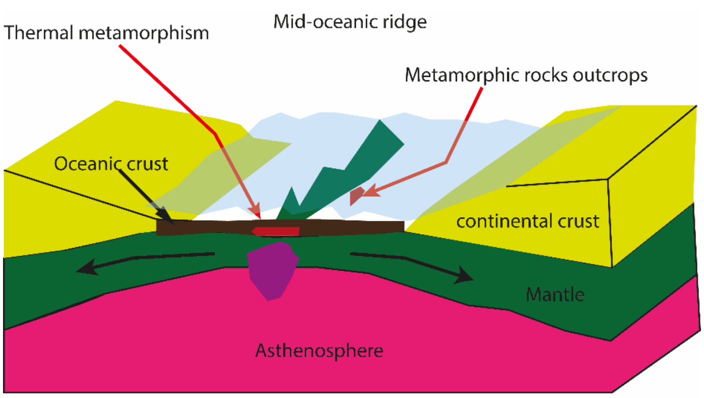


Figure IV.3 *Schematic representation of the ocean-floor metamorphic process.*

IV.1.3 Burial metamorphism

Burial metamorphism occur at low-temperature and affects the sediments and intruded magmatic rocks under lithostatic pressure, which explains the absence of schistosity in the resulting metamorphic rocks. Their mineralogy includes the coexistence of relics of old protolith and new metamorphic minerals due to incomplete mineralogical reactions.

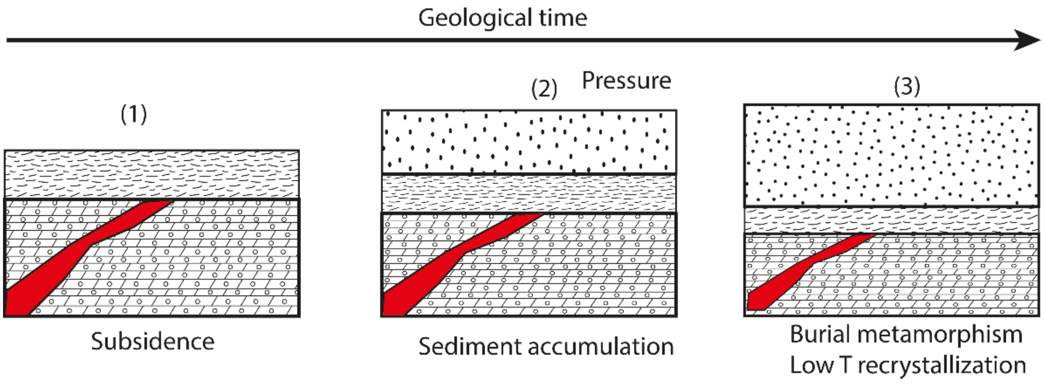


Figure IV.4 *Schematic representation of the burial metamorphism process.*

IV.2 LOCAL METAMORPHISM

IV.2.1 Contact metamorphism

Contact metamorphism takes place when hot magmatic rocks intrude sedimentary host rocks by the increasing temperature. The zone of metamorphic contact is called the "metamorphic halo" or aureoles.

Temperature decreases with distance from the pluton. Contact metamorphism, is characterized by its very limited extent, generally ranging from several meters to a few kilometers.

Although pressure is not involved in this metamorphism (thermal metamorphism) (P= negligible!!!), local deformations associated with the emplacement of the igneous mass can be observed in certain aureoles.

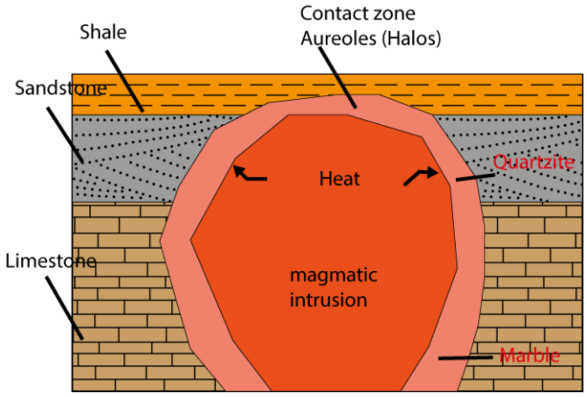


Figure IV.5 *Schematic representation of the contact metamorphism process.*

IV.2.2 Hydrothermal metamorphism

Hydrothermal metamorphism emcompasses recrystallization during percolation of very hot hydrothermal solution within a rock. the transformation of large volumes of peridotites into serpentinites under the influence of hot water is a good example. Figure II-6 illustrates hydrothermal metamorphism.

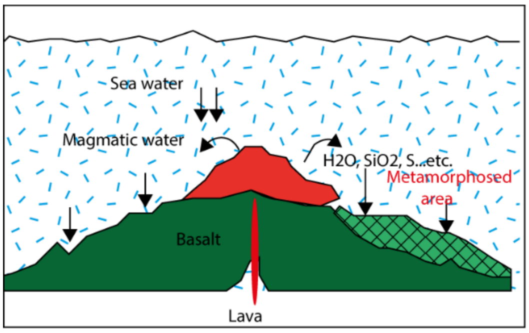


Figure IV.6 *Hydrothermal metamorphism process.*

IV.2.3 Cataclasic metamorphism

Cataclastic metamorphism refers to the crushing and grinding of rocks as a result of very intense tectonics (fault movement) generating ultrahigh pressure (UHP), producing "mylonite". Cataclastic metamorphism occurs at low temperatures in the absence of substantial recrystallization.

Cataclastic rocks can extend for several kilometers along deep faults or sometimes strike-slip faults (Ex. the mega-shear zones in the Hoggar, southern Algeria).

IV.2.4 Impact metamorphism (Shock)

When an extraterrestrial body such as a meteorite or comet fall down with the Earth, it generates enormously high temperatures and pressures, far beyond those reached in regional metamorphism. Mineralogical characteristics include coesite (twined quartz) and stishovite at very high pressures, as well as tiny diamonds. The brecciated and partially molten rock produced by the impact is known as suevite (Figure II-7).

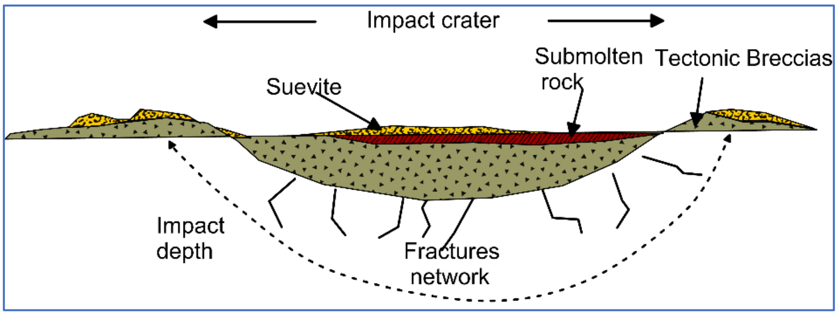


Figure IV.7 *Schematic representation of the impact metamorphism process.*

formed in the presence of $Al2O3$, resulting in the formation of a rock type mineralogically comparable to metamorphic derivatives of mafic igneous rocks.