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Faculty of Natural and Life Sciences and Earth and Universe Sciences **Department of Natural and Life Sciences**		كلية علوم الطبيعة و الحياة و علوم الارض و الكون قسم علوم الطبيعة و الحياة

<u>Course handout</u>

PETROLOGY OF IGNEOUS ROCKS

Destined for the Second year Geology (L2) Bachelor's degree

Presented by: ***Dr. Boulemia Salim***

Academic Year: 2024/2025

FUNDAMENTAL TEACHING UNIT I (**UEF 411**)

(Credits: 5; Coefficients: 3)

Subject 1: **PETROLOGY OF IGNEOUS ROCKS**, Semester: 4

Course : 01H30 TP : 03h00

TEACHING OBJECTIVE:

The teaching of this discipline of petrology aims to acquire the skills to master the minerals composing igneous rocks and the different classifications of magmatic rocks in order to be able to dissect the major groups of these rocks as well as the phenomena at the origin of their formation.

COURSE STRUCTURE AND CONTENT

COURS

1- Introduction, rappels du L1
2- Méthodes d'étude des roches magmatiques
3- Les minéraux des roches magmatiques et leur ordre d'apparition
4- Origine des roches magmatiques et leur mode de gisements
5- Cristallisation et évolution des magmas
6- Classification des roches magmatiques
   Classification minéralogique
   Classification chimique
7- Les grands groupes de roches magmatiques
   Les roches plutoniques
   Les roches intermédiaires
   Les roches volcaniques
8- Les altérations des minéraux des roches magmatiques

TP (12 séances)

Ière partie
- -Présentation du microscope
- -Notions d'indices cristallographiques
- -Etude en lumière naturelle et polarisée
- -Etude en lumière polarisée-analysée

IIème partie : les minéraux
- -Les minéraux cardinaux : Quartz ; feldspaths ; feldspathoïdes
- -Les minéraux essentiels : péridots ; pyroxènes ; amphiboles ; micas ; chlorites.
- -Les minéraux accessoires : zircon, apatite, sphène, grenats ; épidotes; tourmaline ; spinelles ; calcite.

-Textures des roches magmatiques

-Nomenclature des roches magmatiques à partir de leur minéralogie.

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1. INTRODUCTION, L1 REMINDER

I.1. **Definitions**

The Earth is made up of rock. Rocks are aggregates of minerals (R. mono-mineral ex: calcaire or R. hetero-mineral ex: granite). The minerals are formed of atoms.

Petrography (from the Greek Petra, stone, and graphein, to write) is one of the Earth Sciences which is interested in the description and classification of rocks. Petrogenesis aims to understand the mechanisms of rock formation. Petrography + petrogenesis = Petrology.

Petrology (from the Greek logos, discourse, and word) is therefore the science which is interested in the description, classification and interpretation of the *genesis* of rocks.

Rock is a natural aggregate (assemblage) of minerals belonging to different species. There, the oldest rock on our planet ever discovered is the Acasta Gneiss (Northwest Territories, Canada) which is 3.95 billion years old. . "*Igneous, or magmatic rocks,* originate from the cooling and solidification of magma, either at depth (*plutonic rocks* as granite) or at the surface (*volcanic rocks as* basalt)."

Mineral is a solid (it is not a liquid or a gas), natural (it forms without human intervention), having a defined chemical composition (expressed by its chemical formula) and an ordered atomic structure (crystal). Minerals are often visible to the naked eye, as in granite or they can only be seen by looking serving as a microscope; basalt case.

The *rock cycle* is a basic concept in geology that describes transitions through geologic time among the three main types of rock make up the Earth's crust: igneous, sedimentary, and metamorphic. The rock cycle explains how the three rock types are related to each other, and how processes change from one type to another over time. This cyclical aspect makes rock change a geologic cycle and, on planets containing life, a biogeochemical cycle. The following diagram provides an overview of these three main types, along with the processes that lead to their formation.

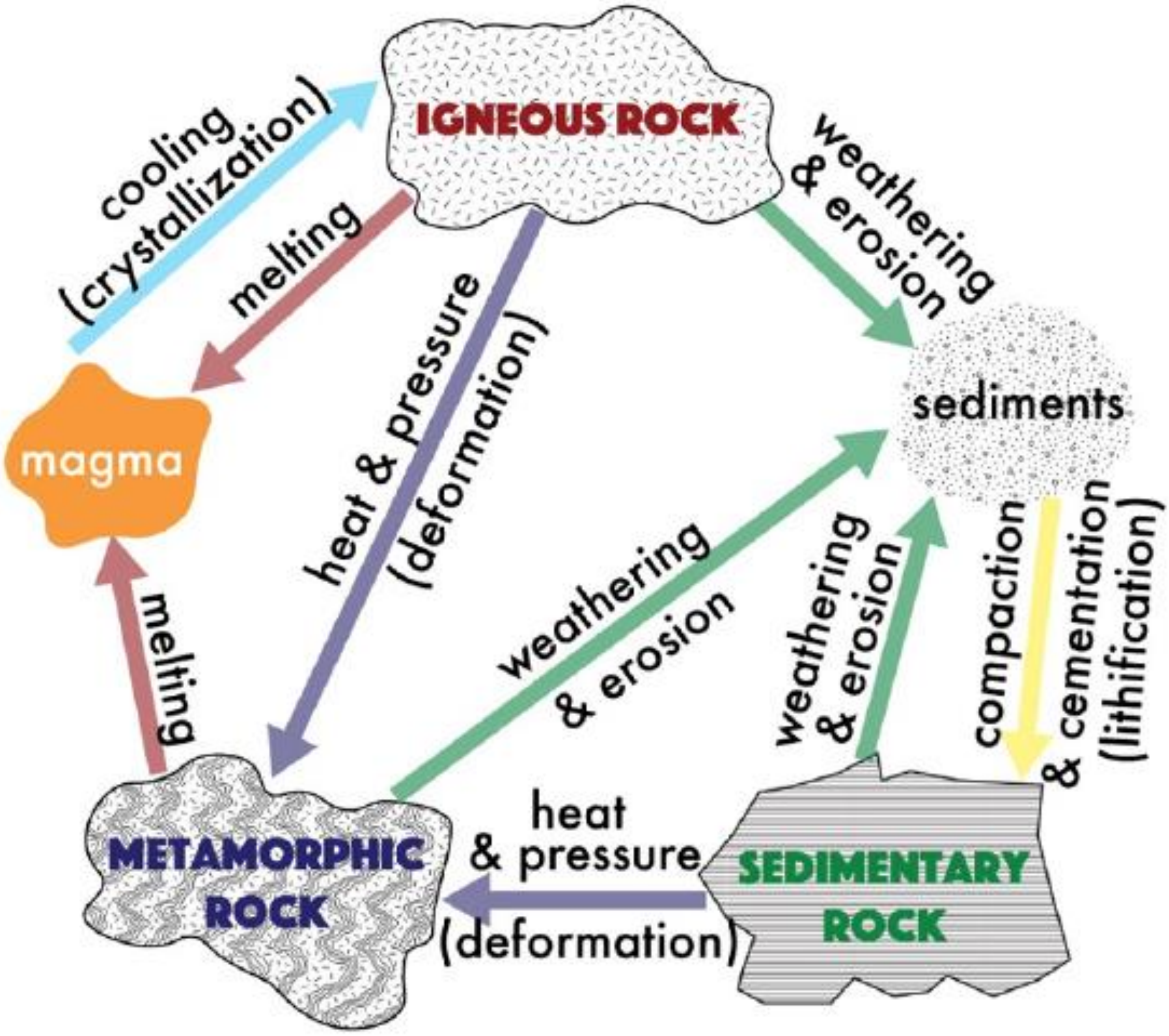


Figure 1. Rock formation cycle (from www.usgs.gov, modified).

I.2. **Interest in petrography**

Scientist: rocks are to geologists what archives are to historians. They allow us to reconstruct the history of the last 4 billion years of the Earth.

Economical: mineral raw materials are all extracted from rock. Building materials are mostly rock-based.

Technological: the construction of engineering structures cannot be carried out without a geological study of the land which is based on the physical and mechanical properties of the rocks. These properties are intimately linked to rock petrography.

2. METHODS OF STUDYING MAGMATIC ROCKS

"Two primary approaches are used to study igneous rocks: the descriptive method (based on petrography observation) and the chemical method.

2.1. Descriptive methods

Descriptive methods are based on:

-Identification of minerals in rocks;

- Determining the proportion of minerals in rocks;

- Determination of the structure and texture of rocks.

Structure *of a rock designates the appearance or shape that the rock takes as it can be observed with the naked eye on a rock outcrop (macroscopic scale). Example: layered, massive, banded structure.*

Texture *of a rock refers to the arrangement, grain size and geometric shape of the minerals as they can be observed under a polarizing microscope (microscopic scale).*

Petrography is based on the examination of thin sections of rocks under the polarizing microscope to precisely determine the minerals and their proportions in the rocks.

The polarizing microscope (also called a *microscopic petrography*) is the basic tool of petrography. It is a specialized microscope designed to determine the optical properties of minerals. Its magnification can reach 1000x and makes it possible to identify the grains of very small minerals.

2.2. **Geochemical methods**

Geochemical methods consist of determining the chemical composition of the rock using different analytical instruments. This chemical composition will be used to classify rocks according to international criteria. Geochemical methods are more reliable than descriptive methods. On the other hand, they are more expensive and do not allow instant identification of rocks in the field, samples must be brought back to the laboratory. Example of measurement equipment used by geochemical methods: X-ray fluorescence spectrometer, plasma emission spectrometer, electron microprobe.

3. Minerals in magmatic rocks and their order of appearance

3.1. Minerals that make up igneous rocks:

A half-dozen mineral families alone make up all igneous rocks. Among these families, we distinguish, on the one hand, quartz, feldspars, and feldspathoids, which are light-colored minerals, and on the other hand, ferromagnesian minerals (micas, pyroxenes, amphiboles, and peridots), which, as their name suggests, are iron and magnesium silicates and whose dark colors range from dark green to black. All these minerals are silicates.

Table 1. Main minerals of igneous rock

Family	Mineral	Chemical formula
silice	quartz	SiO_2
feldspaths	orthose albite anorthite	$KAlSi_3O_8$ $NaAl\ Si_3O_8$ $CaAl_2\ Si_2O_8$
feldspathoïdes	leucite néphéline	$KAl\ Si_2O_6$ $(Na,K)AlSiO_4$
micas	muscovite biotite	$KAl_2\ (Al\ Si_3O_{10})(OH)_2$ $K(Fe,Mg)_3\ (AlSi_3O_{10})\ (OH)_2$
amphiboles	actinote hornblende	$Ca_2(Mg,Fe)_5(Si_4O_{11})_2\ (OH)_2$ $(Ca,Na)_2(Mg,Fe,Al)_5(AlSi_3O_{11})_2\ (OH)_2$
pyroxènes	bronzite augite	$(Mg,Fe)_2Si_2O_6$ $Ca(Fe,Mg,Al)(Si,Al)_2O_6$
péridots	olivine	$(Mg,Fe)_2SiO_4$

The silica content is 100% for quartz. It then gradually decreases as it moves down the table. The color also becomes increasingly darker.

3.2. Crystallization process

The transition between a silicate materials in the amorphous liquid state (***magma***) to that of a material in the crystallized solid state (**mineral**) occurs in 2 stages:

- ***Nucleation***: crystals gradually appear from small molecular clusters,
- ***Growth***: the nuclei grow at the expense of the liquid, which decreases in volume.

Each mineral has a domain of existence and stability.

- **Bowen reaction series**

Reminders on phase diagrams

Phase diagram: graphic representation of phase stability fields as a function of the evolution of 2 or more parameters (generally T° and chemical composition).

Liquidus: curve separating the "liquid phase" domain from the "liquid phase + solid phase" domain.

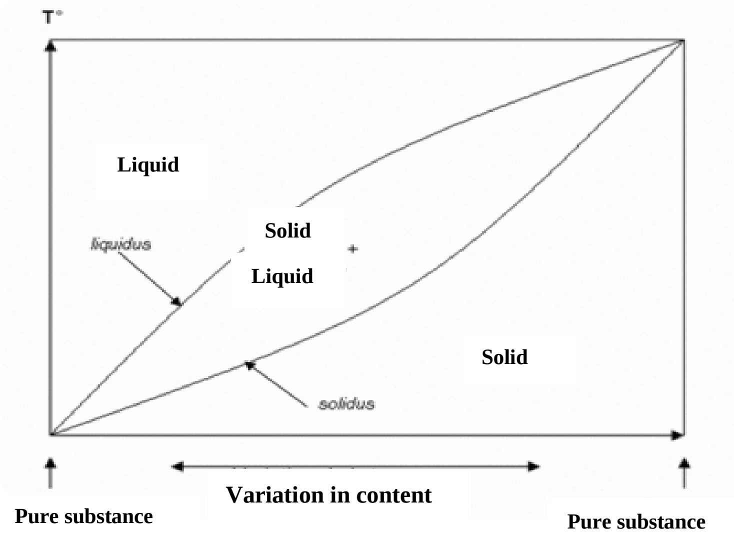


Figure 2. Graphic representation of phase stability fields

Solidus: curve which separates the "liquid phase + solid phase" domain from the "solid phase" domain.

C**<u>ontinuous sequence of plagioclase</u>**

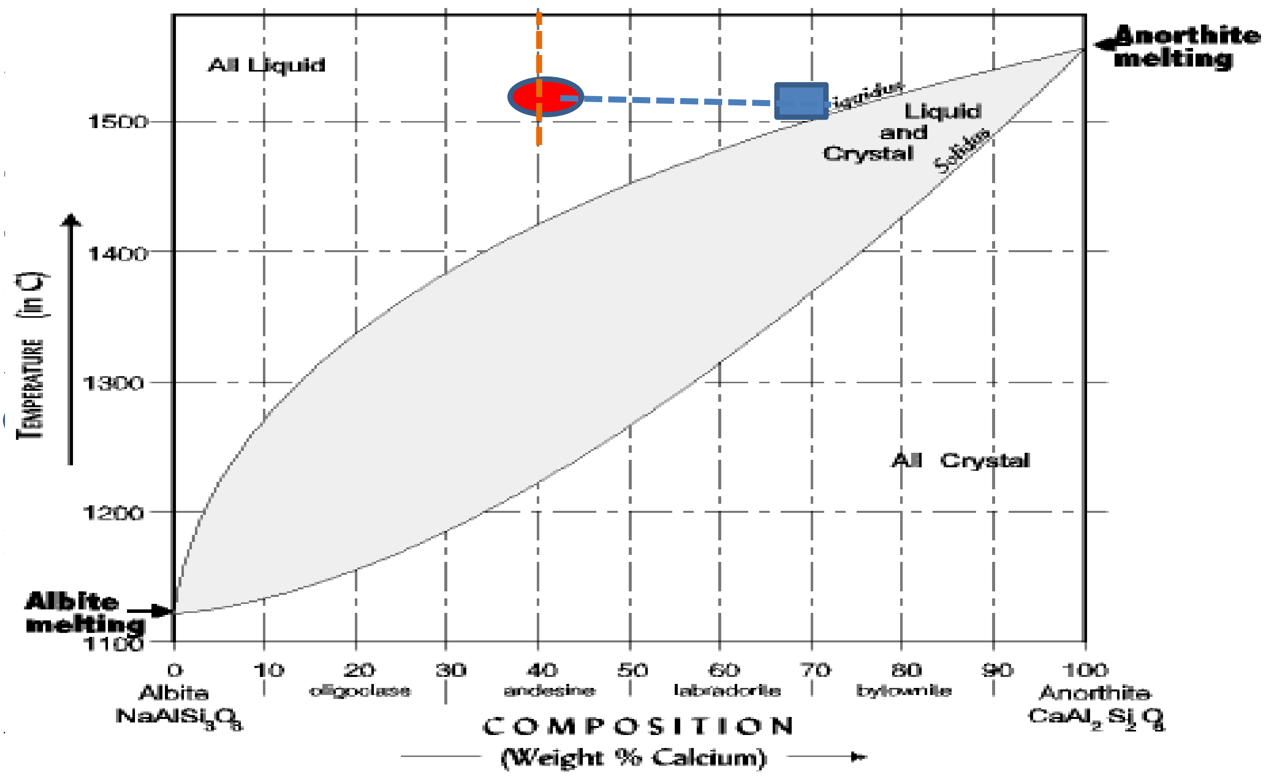
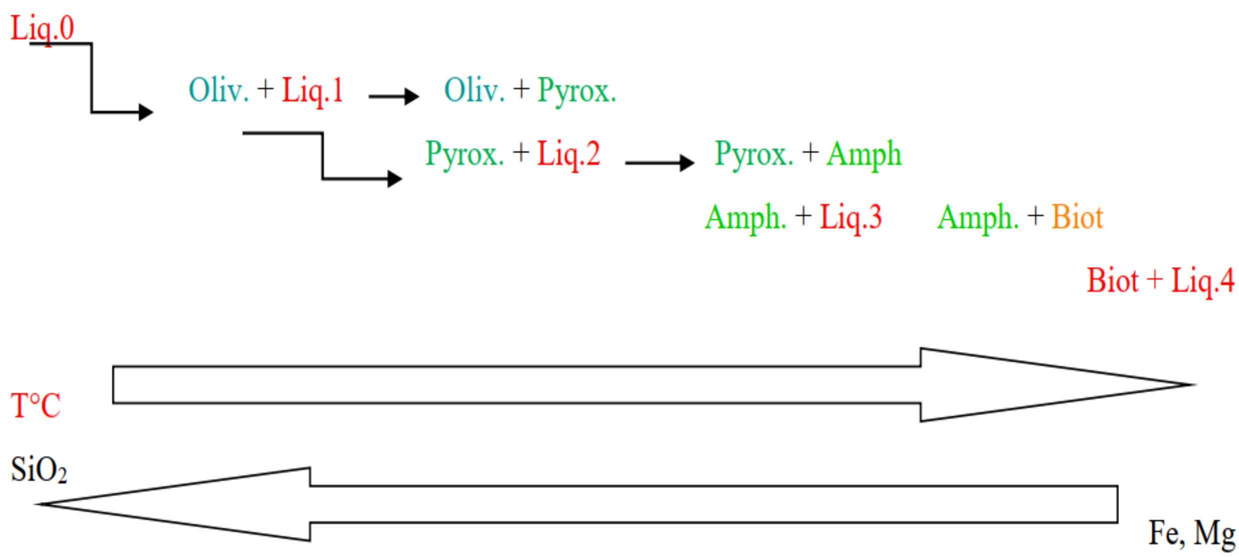


Figure 3. Continuous sequence of plagioclase of 2 poles pure and intermediate minerals

Isomorphic series: series made up of 2 poles pure and intermediate minerals obtained by substitution of ions (charges and/or rays identical or very close).

During crystallization, previously formed minerals can react with the residual liquid to form a new mineral.

Primary magma   Intermediate magma   Differentiated magma



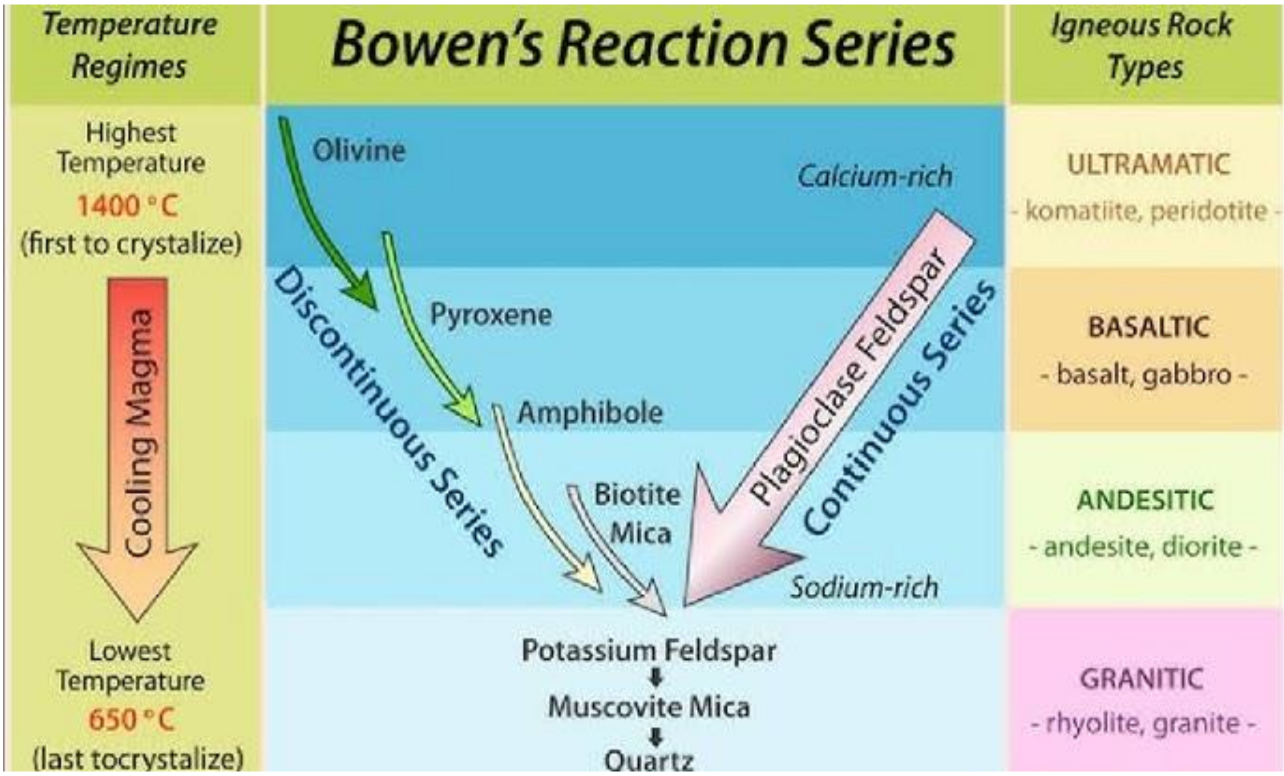
Bowen reaction series

The order of mineral crystallization is defined by the SiO_2 content of the initial magma, by the temperature and by the pressure.

Fractional crystallization

- The 2 series function concomitantly: Ca and Al, released by calcium-plagioclase in the liquid, are incorporated into amphiboles.
- Minerals crystallize successively by taking turns within a temperature range: this is *fractional crystallization*.
- During cooling, the residual liquid becomes depleted in Fe-Mg elements and enriched in Si: we speak of evolution and *magmatic differentiation*.

Tabe 2: Bowen's reaction series, showing the sequences **(Continuous and Discontinuous)** of mineral crystallization during magma cooling."



4. ORIGIN OF IGNEOUS ROCKS AND THEIR MODE OF DEPOSITS

4.1.Origin of magmas

Basaltic magmas; they would have their origins in the mantle from an initial peridotite, pyrolite, rich in feldspar. We could find a rock of similar composition at the base of the oceanic crust.

We distinguish between (tholeitic) basalts emitted from hot spots or OIB (Hawaii type), which take their origin in a deep mantle, from basalts emitted at the level of MORB (Mid-Oceanic Ridge Basalts) which come from a deeper mantle. Impoverished following numerous previous partial mergers. We also find tholeitic basaltic magmas at the level of island arcs.

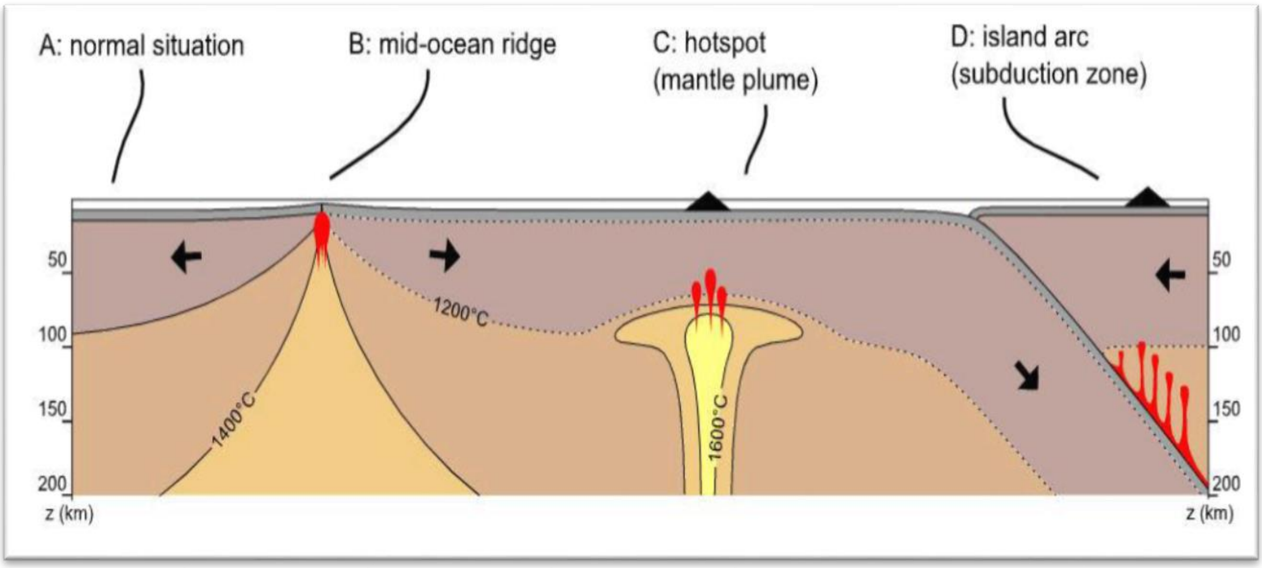


Figure 4. Diferent Origins of Basaltic magmas in the mantle

- **Mechanism of birth of magmas**

Magmatic manifestations show that magmas come from inside the earth. However, seismic studies of the internal structure of the globe show that it is solid except for the outer core which is not in direct relationship with the surface and which only counts for heat transfer. The mechanism of magma formation necessarily involves one or more processes of fusion of the internal parts of the earth.

The temperature increases with depth (geothermal gradient 1° to 10° per 100 m) and melting is expected from a certain depth but the pressure being high, it has the opposite effect by increasing the temperature merger. We obtain a sort of balance between the two parameters and only a disruption of this balance can cause the merger.

This fusion can be obtained in three different ways:

1- Adiabatic decompression, (rising of material without heat exchange with the surrounding environment) Example: dorsal

2- An increase in temperature (isobaric warming)

3- A lowering of the melting point (solidus) by the addition of water.

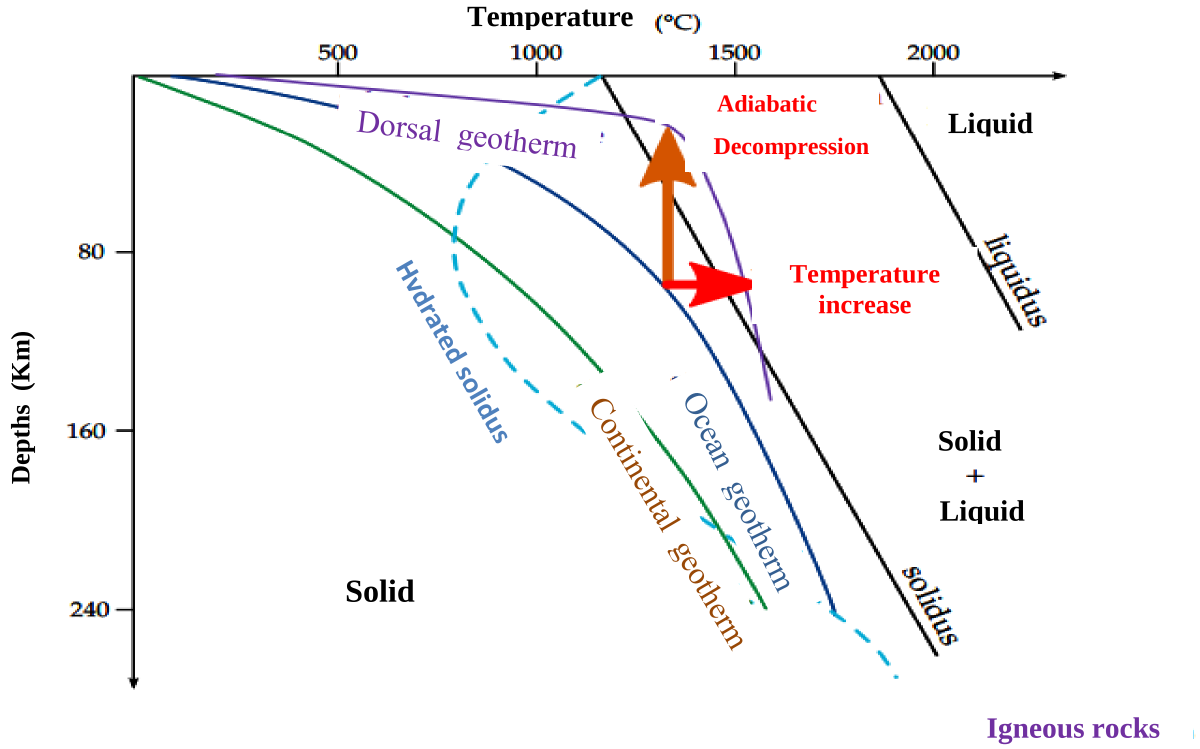


Figure 5. Diferent Mechanisms of magma formation

- **Partial fusion:**

The first drops of magma appear at the junctions between minerals (vertices of the polyhedra then extend to the edges).because only a fraction of the starting rock undergoes fusion. The melted portion is preferentially enriched in **hygromagmatophilic** elements (which have an attraction to the fluid). These elements are alkaline (K, Rb, Cs) Lanthanum (La), Lanthanides, and Zr, Hf, Nb, Ta, U, Th. We say that the fusion is **incongruent** to express the fact that the liquid obtained n It does not have the same chemical composition as the starting solid. The melting rate rarely exceeds 30% (liquid quantity produced / initial solid quantity). So from the same solid and at different fusion rates we can obtain several types of magma. We speak of alkaline magma = low fusion rate (5%) = high concentration of hygromagmatophilic elements, or tholeiitic = rate of high fusion (30%) = dilution of these elements.

Chemical fractionation during partial melting

Compatible element: element that tends to melt last and crystallize first

Incompatible element: element that tends to melt first and crystallize last (high ionic radius → does not fit into the crystal lattice)

Degree of incompatibility d = concentration in the liquid / concentration in the solid

- **Magmatic series**

These different phenomena during crystallization can thus explain the evolution of magmas. During its ascent and its storage in magma chambers, the magma can undergo, in addition to *fractional crystallization*, *contamination* by the surrounding rock during its ascent. So over time the magma will gradually evolve. The succession of *rocks derived from the same magma* constitutes *magmatic series*. This explains how it is possible to go from a basaltic magma to a magma rich in silica.

“Magmatic differentiation follows distinct evolutionary trends, leading to the formation of tholeiitic, calc-alkaline, or alkaline series, each associated with specific tectonic settings such as mid-ocean ridges, subduction zones, or continental rifts.

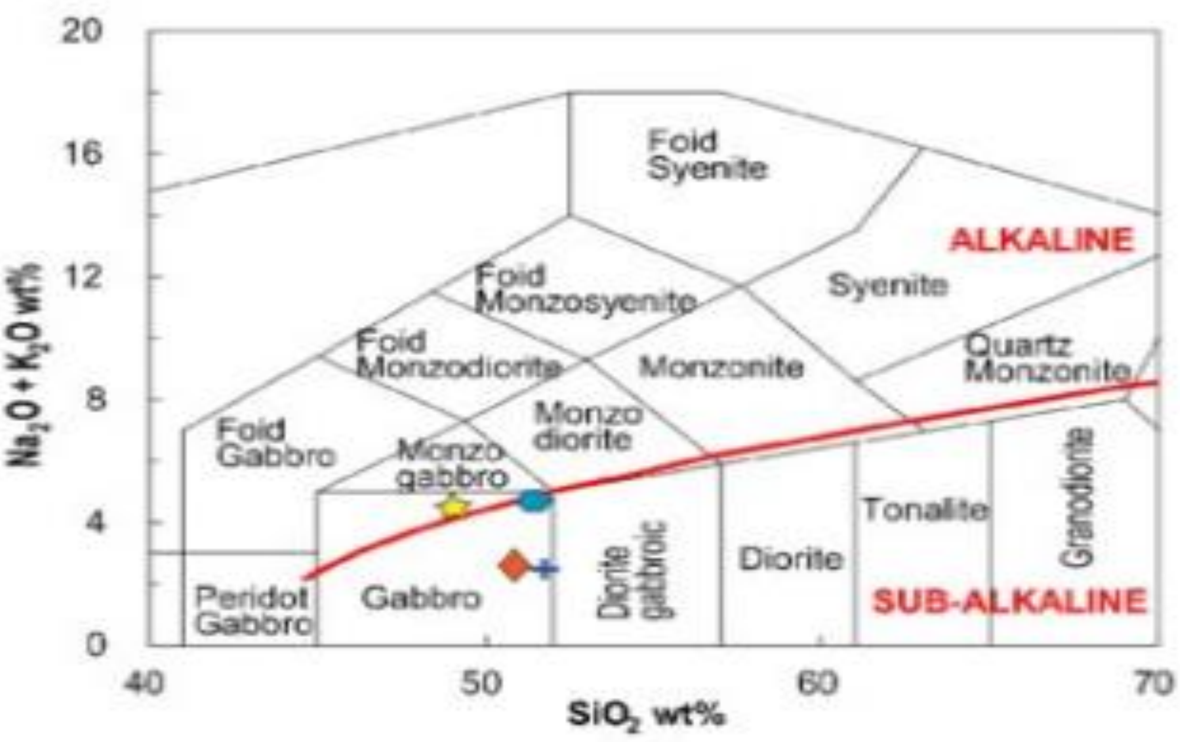


Figure 6. Mafic Rocks and magmatic series

Rocks In The **Alkaline** Magma Series Are Distinguished From Rocks In The **Subalkaline** Tholeiitic And Calc-Alkaline Magma Series By Their High Content Of Alkali Metal Oxides (K_2O Plus Na_2O) Relative To Silica (SiO_2). They Are Distinct From The Rare Peralkaline Magmas, Which Have Excess Alkali Oxides Relative To Alumina ($Na_2O + K_2O > Al_2O_3$).We Distinguish :

a. The **alkaline series**: the Na_2O+K_2O/SiO_2 ratio is strong. The characteristic minerals are olivine and feldspathoids, so it is an undersaturated magma. This series is found in the volcanism of stable continental domains. It ranges from basalts to trachytes. The basalt stage is dominant. Magma only forms at high pressure. **Shoshonitique** series is strong alkaline. Alkaline magmas tend to show high titanium oxide (TiO_2) content, typically in excess of 3% by weight. Other incompatible elements, such as phosphorus and light rare earth elements, are also elevated. This is attributed to a very *low degree of partial melting* of the source rock, with only 5% or less of the source rock going into the magma melt

Alkaline magmas are characteristic of continental rifting, areas overlying deeply subducted plates, or at intraplate hotspots.[2]:Ch6 They are more likely to be generated at greater depths in the mantle than subalkaline magmas.

b. Subalkaline series:

b.1. T**holeitic series**: the Na+K/SiO_2 ratio is low and the magma is saturated (there are no feldspathoids). The starting magma is a tholeitic basalt (very poor in silica) which is generally encountered at oceanic ridges, island arcs and in continental volcanism (trapps). Tholeitic basalt forms at low pressure (therefore at shallow depth) from the mantle. Then by progressive enrichment (contamination, fractional crystallization) of the magma, there is formation of andesites (islandites) then rhyolites. The basalt stage is the most common

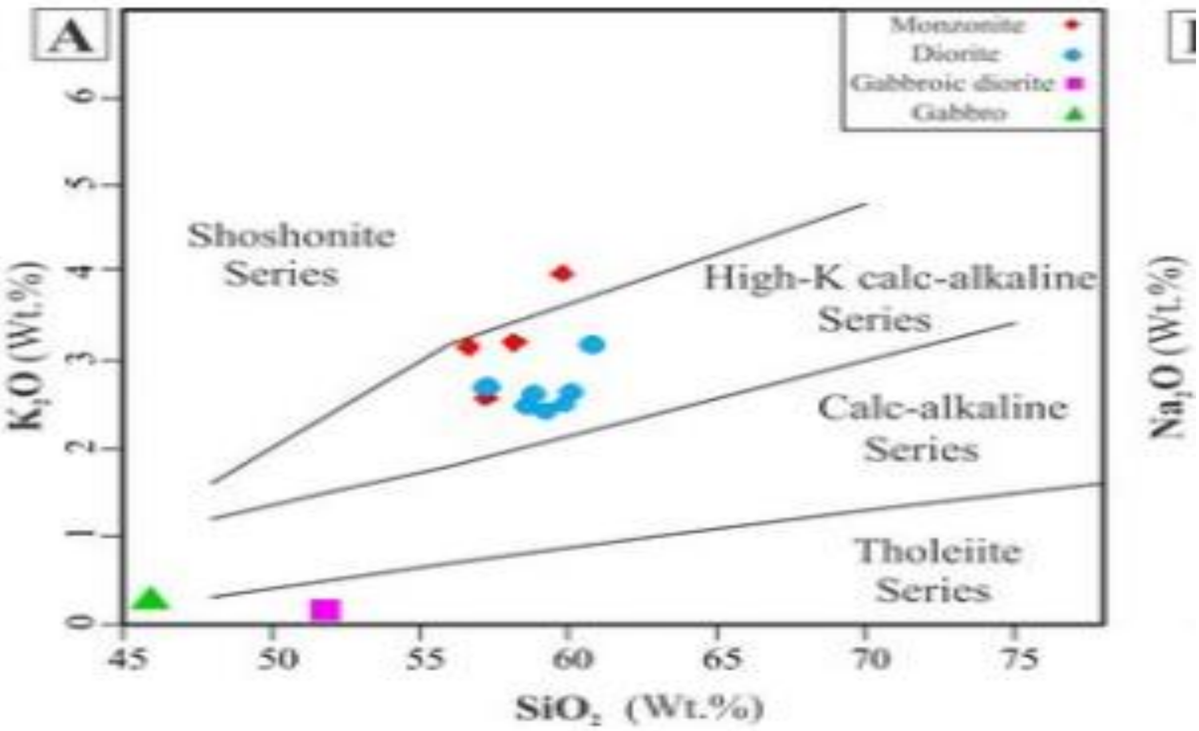


Figure 7. Separation of magmatic series for intrusuve rocks according to K_2O vs SiO_2

b.2. C**alc-alkaline series**: the Na+K/SiO_2 ratio is stronger. Na is dominant compared to K. This series is found in subduction zones (Cordilleras) and evolved island arcs. It begins with basalts and goes to rhyolites. The intermediate andesitic stage is the most common.

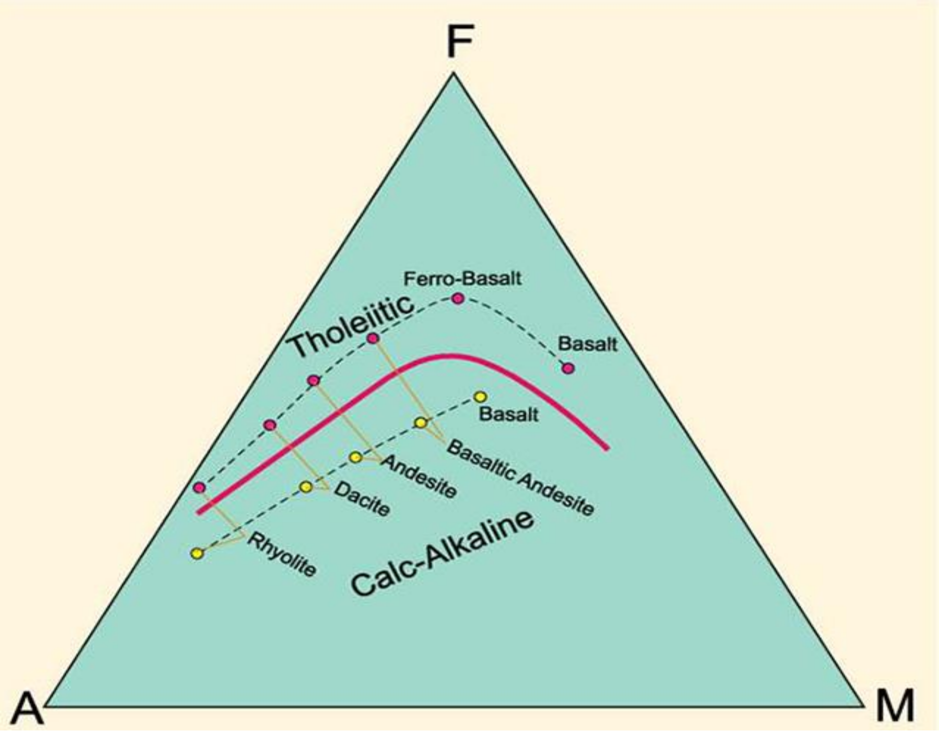


Figure 8. AFM diagram, a ternary diagram showing the relative proportions of the oxides $Na_2O + K_2O$ (A), $FeO + Fe_2O_3$ (F), and MgO (M).

4.2. The types of deposits

Plutonic rocks can occur in two forms: veins and massifs.

The crystallization of magma inside or on the surface of the Earth's crust produces magma bodies. The three block diagrams (fig.8) which follow illustrate the main magmatic bodies inherited from magmatic activity in a region, and their exposure over the course of erosion.

Various intrusive bodies (also called plutonic; from the god of the underworld, Pluto) may have been exposed by erosion: laccoliths, dykes, volcanic necks. Since igneous rocks are more resistant to erosion than surrounding sedimentary rocks, magmatic bodies will tend to form positive reliefs

1**. The veins**

We generally encounter smaller clusters which are grouped under the name of veins when they are small enough. In this case, the rocks occupy the cracks in the earth's crust where the magma was able to inject and recrystallize (fig.9).

a. Veins or dykes

The establishment of the veins is not done by surface effusions. They freeze in open fractures. Their size varies greatly but their thickness is always small in relation to their extension. The latter ranges from a few meters to several tens of km. Many vein fillings are formed from deposits left by solutions: this is how veins of pegmatite, quartz and carbonates are formed where many useful elements are concentrated.

b. Annular veins or ring-dykes

Some veins are annular and result from the placement of magma along large cylindrical or slightly conical fractures.

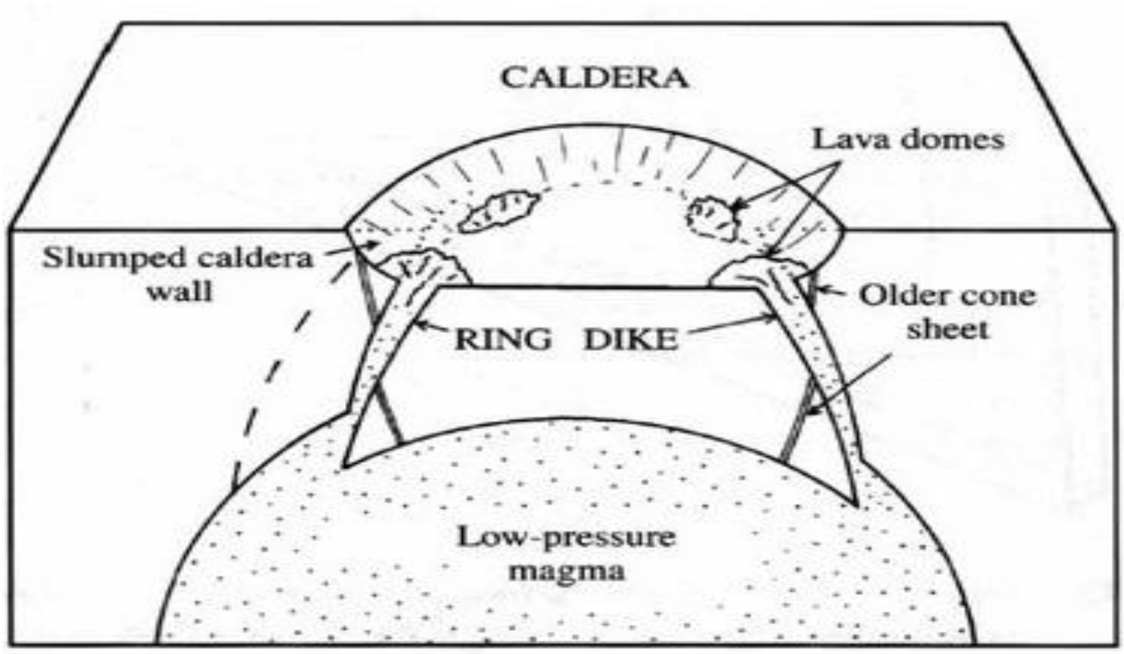


Figure 10. Bloc-diagram for ring-dykes and Caldera

c. Layer veins or sills

The sills have very variable dimensions, but always have a low thickness compared to their extension. They are distinguished from veins by their concordant character with the surrounding layers (fig.10) and by their metamorphism which they develop in the levels sedimentary at its base and roof. These veins are somewhat similar to laccoliths.

d. The necks

A neck is an English word, meaning neck. Unlike the sill, the neck intersects the structures of the surrounding area. Often left in relief by erosion, the neck, whose diameter ranges from around ten to a few hundred meters, corresponds to the filling of an ancient

volcanic chimney (hence its cylindrical, conical piston shape) by a mass of magmatic rock, generally brecciated.

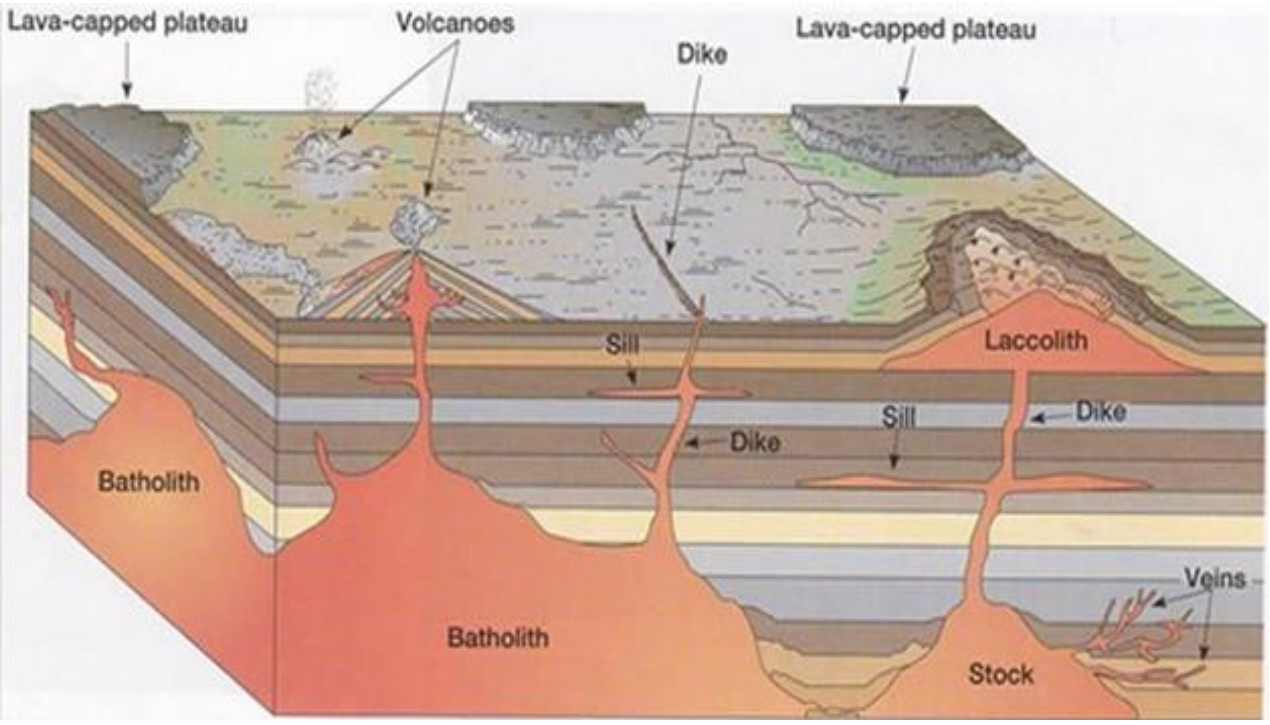


Figure 9 . The main magmatic bodies

2. The massifs

We call massifs plutonic bodies whatever their shape and size, different or not and which do not present the enormous gap between thickness and extension which characterizes the veins.

They are usually discordant (fig.11) on the terrain which contains or supports them. It is this discordant character which justifies the use of the qualifier “eruptive”.

There are mainly three types of massifs:

a. **Batholiths :** Batholite (E. Suess, 1892, from the Greek bathus, deep, and lithos, stone): Very large massif, whose surface area is greater than 100 km2 and can reach several hundred thousand km2. The batholiths are discordant massifs”.and have any shape. Their base is rarely visible (figure 5). They are composed mainly of granites and acidic plutonic rocks. Batholiths often feed intrusive masses of small dimensions in the shape of chimneys called stocks (also called apophysis, injection masses or plugs) (figure 5). “They are frequently bordered by a zone of contact metamorphism.

b. Laccoliths

. Laccolite (G.K. Gilbert, 1877. From the Greek lakkos, cistern, and lithos, stone): Mass of plutonic rocks in the shape of a large lens of several km, with a horizontal lower surface and upper surface convex upwards (vault in the form of a dome). The whole is parallel to the surrounding rocks (figure 3). The laccoliths are very thick and their length is around a hundred meters. They deform the surrounding sedimentary rocks. They are generally formed by the intrusion of acid magma which, due to its high viscosity, penetrates with difficulty between the stratifications, accumulates in an area and lifts the roof rocks.

c. **Lopolite** (F.F. Grout, 1918. From the Greek lopas, a sort of hollow dish, and lithos, stone): Mass of plutonic rocks in the shape of a flat bowl (figure 4), the dimensions of which can be large and extend over tens of thousands of square kilometers. The shape of lopolites is due to the collapse of the underlying layers under the weight of the magma. Lopolites are generally composed of basic and ultrabasic rocks. Concordant like the sills, they have a squat, lenticular shape with a flat floor and a roof convex upwards. Of varying dimensions, they can reach a thickness of several tens of km.

d. **Phacolites:** these are lens-shaped bodies which lie in the core of an anticline or syncline. They are small, rare and form at the same time as the folding.

3. **Mode of deposit of volcanic rocks; volcanoes.**

3.1. Volcanic eruptions

In general, magmas produced inside the Earth tend to rise to the surface because the density of the magma is lower than the density of the surrounding solid medium (around 10% less dense).

On the other hand, magma contains dissolved gas. At a certain depth, the pressure is such that the dissolved gas separates from the magma and forms bubbles. These bubbles tend to expand when the pressure decreases. If the liquid part of the magma has a low viscosity, the gas can expand easily, and on the surface a non-explosive eruption occurs, in the form of a ***lava*** flow (name given to the magma that spills out on the surface. Lava distinguished from magma by the absence of gases which, with the decrease in pressure, separate magma and escape into the atmosphere). If the liquid part of the magma has a ***high viscosity***, the gas encounters strong resistance from the liquid and cannot expand easily. Arriving at the surface, an ***explosive eruption*** occurs. So, depending on the quantity of gas dissolved in a magma and its viscosity, we distinguish eruptions: explosive and non-explosive.

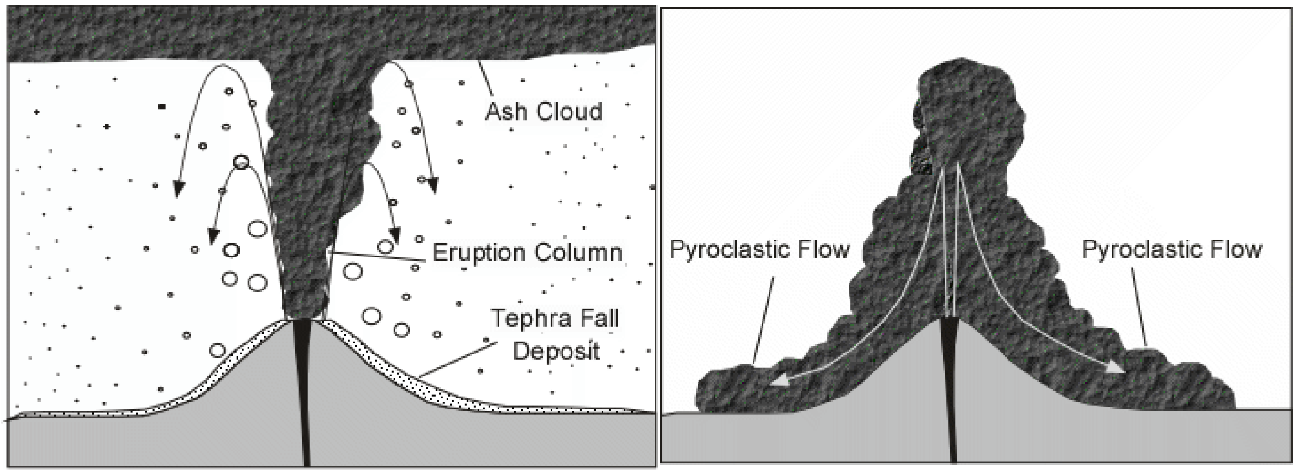


Figure 11: Formation of volcanic rock

3.1.a. Non-explosive eruptions

Non-explosive eruptions are characteristic of magmas of low viscosity and low dissolved gas content. These are basaltic magmas. Lava flows are produced by these eruptions and gradually move away from their eruptive vent across slopes. Sometimes lavas flow from long cracks (***fissural eruption***). Underwater lava flows form: ***pillow lavas***: these are balls measuring 0.6 to 2 m by 0.3 to 1 m which stack on top of each other. Sometimes non-explosive eruptions occur when the magma's viscosity is high but its gas content is very low. In this case, the lava piles up on the ***chimney*** and forms a ***volcanic dome*** (figure 13).

3. .1.b. **Explosive eruptions**

Explosive eruptions are characteristic of magmas of high viscosity and high dissolved gas content. These are andesitic and rhyolitic magmas. The explosion caused by the dissolved gas will break the magma into fragments. These liquid fragments will solidify when thrown into the air and form pyroclastic fragments.

We call ***Téphras*** (Greek word meaning ash, term used for the first time by S. Thorarinsson, Icelandic volcanologist, in 1954) or ***Pyroclastites*** (from the Greek puros, fire, and klastos, broken, “fire debris”), the solid *products projected* by volcanoes. Volcanic projections are classified according to the grain size of their constituent elements, a classification proposed by R. Fisher in 1961 (table 1). The rocks formed by accumulation and cementation of tephras are called: **pyroclastic rocks.**

Table 3.Téphras **and pyroclastic rocks.**

Diameters (mm)	Unconsolidated deposits (Tephra)	Consolidated deposits (Pyroclastic rock)
> 64	Volcanic bombs or blocks	Volcanic breccias
2-64	Lapillis (from the Latin lapillis, small stone)	Tuffs (from the Greek tophos, a type of crumbly stone)
< 2	Volcanic ash	Cinerites (from the Latin cineris, ash)

3.3.a. **Craters and Calderas**: The summit of volcanoes is generally occupied by a small circular or elliptical depression (diameter < 1 km) called: **Crater** (from the Greek krater, mud) formed by volcanic explosions. **Calderas** (Portuguese word meaning cauldron) are large circular or elliptical volcanic depressions whose diameter varies from 1 to 50 km. They are produced by collapse of the volcanic cone in response to the void left by volcanic eruptions in the underlying magma chambers (figure 15). Calderas are often occupied by lakes.

VII.3.3.b. **Maars**: Maars are craters caused by a phreatomagmatic eruption. The meeting of lava and a water table, at shallow depth, induces the vaporization of the water and an overpressure which will cause explosive cycles then generate a “maar crater”. This crater is often bordered by a ring of explosion residue (pyroclastic deposits). The depressions thus shaped are sometimes occupied by a lake (especially when the crater is deeper than the phreatic level).

VII.3.3.c. **Hot springs, geysers and fumaroles**: Fumaroles (from the Italian fumaruolo) are gas emanations coming from cracks or holes (vents) and coming from a magmatic body at depth or from steam produced by hot underground water. They contain water vapor (H_2O), carbon dioxide (CO_2), nitrogen (N_2), sulfurous gas, hydrogen, carbon monoxide (CO), chlorine (Cl)... The composition of fumarole gases depends on their temperature. Depending on the temperature, we distinguish between dry, acidic and alkaline fumaroles.

5. CRYSTALLIZATION AND EVOLUTION OF MAGMAS

5.1. Introduction and general characteristics of magmas

Magmatic rock result from the solidification (crystallization, cooling) of magma. As **magma** is generally at a relatively high temperature (650 to 1250° C), these rocks are also called **igneous rocks** (or fire rock). Magma is a molten silicate bath, consisting of a liquid phase, a solid phase (crystals) and a gas phase.

The solidification of magma can take place inside the lithosphere where cooling is slow, and the rocks formed are then called **plutonic rocks**. They therefore do not appear at the surface than through the play of deformations of the earth's crust and erosion.

Magma can also undergo rapid cooling if it is emitted on the surface of the Earth, in the open air or underwater: the rocks thus formed are called **volcanic rocks** (also known as extrusive or effusive).

Between the two extremes, there are intermediates, and the rocks formed are named according to the context, **semi-depth rock**, **periplutonic rocks**, **hypovolcanic** rocks.

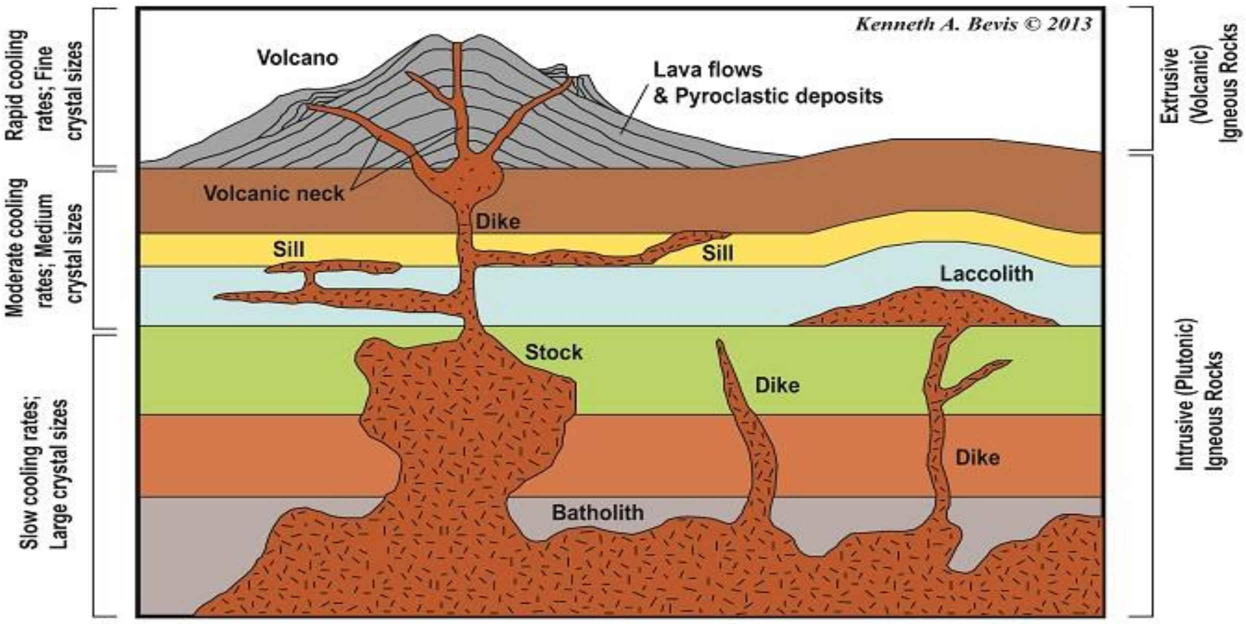


Figure 12. Magma and different igneous rocks

II.2. **General Characteristics of magmas**

II.2.1. **Types of magma**

The types of magmas are determined by their chemical compositions, and more especially by their silica content. Thus, we distinguish three main types of magmas:

1. Basaltic or gabbroic magmas (basic): 45-55% SiO2, rich in Fe, Mg, Ca, poor in K, Na.
2. . Andesitic or dioritic magmas (intermediate): 55-65% SiO2, intermediate in Fe, Mg, Ca, K, Na.

3 . Rhyolitic or granitic magmas (acids): 65-75% SiO2, poor in Fe, Mg, Ca, rich in K, Na.

About 80% of magmas emitted by volcanoes are basaltic, and andesitic and rhyolitic magmas represent ~10% each of the total.

- Gases: Most magmas contain gases (0.2 to 4% by weight) dissolved in the liquid. Although present in small quantities, gases have a huge effect on physical properties magma (the presence of gases gives magma their explosive character). The composition of gases in magmas is as follows:

Mainly H_2O (water vapor) with a little CO_2 (carbon dioxide). Had two, they account for more than 98% of all gases emitted by volcanoes. Other gases include N, Cl, S and Ar are rarely present at more than 1%.

- The presence of gases in magmas is linked to their chemical compositions. Thus, rhyolitic magmas have a higher dissolved gas content than basaltic magmas.
- Magma Temperature: The temperature of a magma is difficult to measure because active volcanoes are obviously dangerous places. Geologists therefore use devices optics to measure the temperature of magma far from an eruption or they carry out laboratory experiments to determine the temperatures of molten rocks.

  Basaltic magma: 1000 – 1200°C.

  Andesitic magma: 800-1000°C.

  Rhyolitic magma: 650-800°C

Table 4. Summary table of general characteristics of magmas

Magma Type	Solidified Rock	Chemical Composition	Temperature	Viscosity	Gas Content
Basaltic	Basalt	45-55 SiO_2 %, high in Fe, Mg, Ca, low in K, Na	1000 - 1200 °C	Low	Low
Andesitic	Andesite	55-65 SiO_2 %, intermediate in Fe, Mg, Ca, Na, K	800 - 1000 °C	Intermediate	Intermediate
Rhyolitic	Rhyolite	65-75 SiO_2 %, low in Fe, Mg, Ca, high in K, Na.	650 - 800 °C	High	High

Note: In the Archaean, hotter magmas existed which gave rise to rocks called Komatiites (named after the Komati River in South Africa, where these rocks were discovered in 1969 by Richard and Morris Viljoen). The temperature of these magmas is estimated between 1400 and 1600°C. The existence of these hot magmas at these ancient times shows that the Earth's geothermal gradient was higher than today. These magmas contained less than 45% SiO2 and are called: ultrabasic magmas. Ultra basic magmas no longer exist on the Earth's surface today.

Let us also point out the existence of a very rare low temperature lava (lava which has the lowest known temperature): carbonatite (alkaline lava very rich in calcium). Only one active volcano currently emits carbonatites: Lengaï, in Tanzania.

II.2.4. Viscosity of magmas: Viscosity is the resistance of magma to flow (the more viscous a magma is, the less it behaves like a fluid). The viscosity of magma depends on its composition (silica content and dissolved gas content) and temperature. Magmas rich in SiO_2 (silica) have a higher viscosity than those poor in SiO_2 (viscosity increases with increasing SiO_2 content of the magma)

Low temperature magmas have a higher viscosity than high temperature magmas (the viscosity of a magma decreases rapidly as the temperature increases). So basaltic magmas tend to be **very fluid** (**low viscosity**), but their viscosity is still 10,000 to 100,000 times higher than that of water. Rhyolitic magmas tend to have a very high viscosity, which is on the order of 1 million to 100 million higher than that of water. Viscosity is a very important property which determines the eruptive character of the magmas.

General remark:

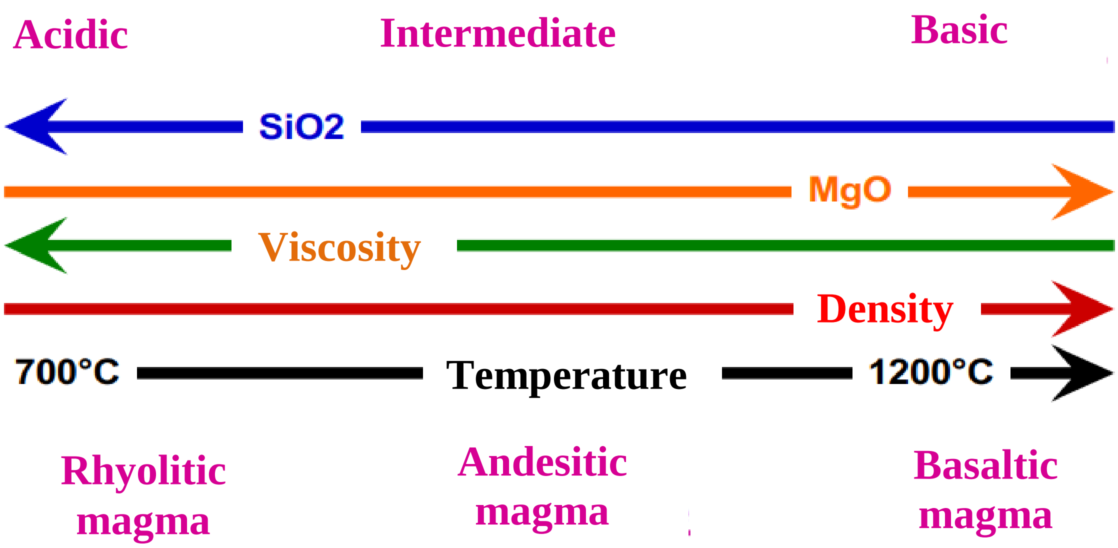
The physical properties of magma determine its rise and crystallization.

- Density: the denser magma is, the more its ascent is slow.
- Viscosity: the more a magma is viscous, the more its rise will be slow.

The 3 parameters influence the properties of the magma:

- T°C: + a magma is hot, – it is less viscous.
- Fluid content (water): the more fluids there are in the magma, – it is less viscous.
- SiO_2 content: + a magma is poor in SiO_2, – it is less viscous.

During crystallization (T [SiO_2]), the magma will become increasingly viscous.



6. CLASSIFICATION OF MAGMATIC ROCKS

There are several types of classification based on different criteria depending on the objective set. Two main approaches to classifying igneous rocks can be distinguished: one based on the so-called descriptive mineralogical composition (size or nature) and the other based on the so-called analytical chemical composition.

6.1. Mineralogical classification (Descriptive classification)

a. Classification based on texture

The texture of igneous rocks is the arrangement of the constituents of the rock (minerals and glass). It is controlled by the cooling rate of the magma. Observation can be done with the naked eye, with a magnifying glass or with a polarizing microscope.

We distinguish :

- **Holocrystalline textures**

The rock is entirely crystallized. Depending on the size of the minerals, we distinguish several varieties:

a- **Grainy texture**: it results from very slow cooling (typical of plutonic rocks). The rock is completely crystallized and made up of well-individualized minerals visible to the naked eye (macro-crystalline rock). The average size of minerals is between 3 and 5 mm (variations from 0.5mm to 1m). we can distinguish :

- Normal or equal grained texture: average minerals of the same dimensions

- Aplitic or micrograined texture: small minerals barely visible to the naked eye

- Pegmatitic texture: all the crystals are enormous

- Porphyroid texture: heterogeneous appearance with large crystals (phenocrysts) next to other smaller ones.

b- Micrograined texture: the rock is entirely crystallized but made up of minerals invisible to the naked eye (micro-crystalline) (typical of veins and edges of plutons). There may be phenocrysts, and the texture is said to be microporphyritic.

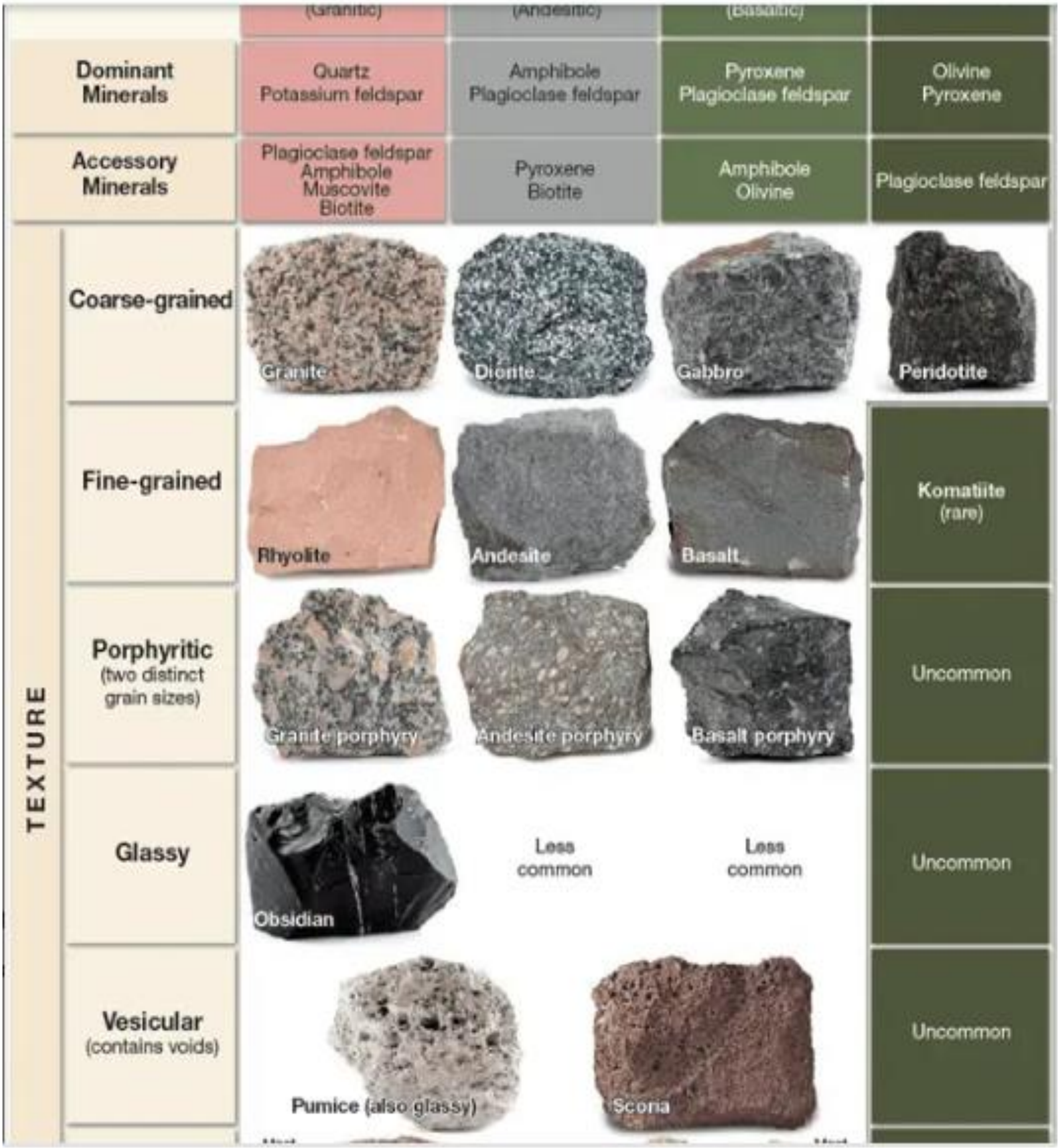


Figure 13: Principals texture of igneous rock

- **HYPOCRYSTALLINE TEXTURES**

The rock is partially crystallized. It is made up of minerals and glass (non-crystallized paste) and results from very rapid cooling (typical of volcanic rock). We distinguish:

a- *Microlithic texture*: the rock is partially crystallized and made up of fine, small crystals in the shape of rods called microliths dispersed in a glassy background. If the rock presents some phenocrysts we speak of microlithic texture porphyritic.

In the particular case of Dolerites, most of the microliths are visible to the naked eye and we speak of a dolerite texture.

b- *Vitreous texture*: glass is dominant with rare microliths. The Glass being unstable, it tends to crystallize very slowly (devitrification) to give rise to crystallites arranged in a fibroradiated manner (spherulites) and the texture is spherolitic.

The study of textures therefore provides no information on the origin and genesis of the rocks and only allows us to know the methods of cooling and installation. Texture variations, in addition to the cooling speed, can also be linked to a increase in pressure which can cause crystallization at elevated temperatures. loss of water can have the same consequences.

- **Classification based on mineralogical composition**

Rock minerals are divided into three groups:

<u>The cardinal minerals</u>: quartz, potassium feldspars (orthose, microcline and sanidine), calc-sodium feldspars (plagioclase) and feldspathoids (leucite, nephiline, melilite)

• <u>Essential minerals</u>: or colored micas, amphiboles, pyroxenes and olivine

• <u>Accessory minerals</u>: zircon, apatite, sphene etc…

The effective mineralogical composition of the rock as observed under the microscope is called mode or modal composition used in the Streckeisen classification and valid only for completely crystallized rocks. In the case of hypocrystalline rocks, glass must be taken into account because it is a part of the uncrystallized magma. For this, we use chemical analysis and, knowing the theoretical composition of the cardinal minerals, we can calculate from this analysis the minerals which should have appeared if all the liquid had been crystallized. We thus determine a virtual mineralogical composition from the chemical composition. This composition is called the CIPW (Cross, iddiings, Pirson and Washington) standard or normative composition.

On the basis of the composition of these minerals we can classify the rocks according to their saturation or their coloring.

b.1. Saturation

Silica being present in all silicates, the notion of saturation takes into account the mineralogical expression, in the form of quartz, of the silica richness. It is based on the presence of quartz or feldspathoids. We then distinguish:

• Supersaturated rocks with the presence of quartz and feldspars

• Saturated rocks with the presence of feldspars

• Undersaturated rocks with feldspars and feldspathoids

• Extremely undersaturated rocks with feldspathoids only

This notion of saturation can be expressed by the ratio below which can vary from 0 to 100: (quartz / (quartz + feldspars)) x 100 In the presence of feldspathoids we define an under-saturation index (or feldspathoid index) which varies also from 0 to 100%:

(feldspathoids / (feldspathoids + feldspars))x 100

b.2- **Coloring :** the coloring is based on the percentage of chemically colored or ferromagnesian minerals (olivine, pyroxene, amphiboles and black micas). We distinguish :

• hololeucocratic rocks (white) almost without ferromagnesians (<10%)

• leucocratic rocks poor in ferromagnesians (between 10 and 35%)

• mesocratic rocks moderately rich in ferromagnesians (between 35 and 65%)

• melanocard rocks richer in ferromagnesians between 65 and 90%)

• Holomelanocratic rocks almost exclusively made up of ferromagnesians (> 90%).

The concept of coloring can be expressed by the terms below and which vary from 0 (very light rocks) to 100 (very dark rocks)

100- (Quartz + feldspars) if the rock contains quartz

100- (feldspathoids + feldspars) if the rock contains feldspathoids

Note: when the rock is poor in colored minerals we speak of felsic rock (quartz rocks and feldsapths), when the content is more or less high we speak of mafic rocks (Mg + Fe), if it is very high we speak of ultramafic rocks or ultramafites

b.3. Nomenclature of igneous rocks

To give a name to igneous rocks we base our mineralogical composition and texture.

1- Double-entry painting by Lacroix from the 1930s

The first rapid and very simplified determination of the names of igneous rocks is given by Lacroix's table (see plate). This table is based on the combination of the saturation and the dominant feldspar type. For each rock with a grainy texture (plutonic) we match its equivalent with a hypocrystalline texture (volcanic).

Tabe 5. Casification of nomenclature of igneous rocks

Glassy	Obsidian Pitchstone Perlite						
Fine-grained aphanitic	Felsite					Trap	
	Rhyolite	Trachyte	Latite (Trachyandesite)	Dacite	Andesite	Basalt	
Medium-grained phaneritic	Aplite					Dolerite Diabase	
Coarse-grained, phaneritic	Granite	Syenite	Monzonite	Quartz diorite	Diorite	Gabbro	Peridotite Dunite Pyroxenite Hornblendite
	0–10 C.I.		10–40 C.I.			40–70 C.I.	70–100 C.I.
	Qz	No Qz		Qz	No Qz		
				Na Pl		Ca Pl	
	Kf > Pl		Kf = Pl	Pl > Kf			No feldspar

Note: in practice, naming a rock involves assigning it a box in the table, but the surface area of the boxes does not give any idea of the relative importance of the rocks; for example, granite is the most dominant rock of rocks with grainy textures (95%) while basalt is the most dominant rock of rocks with hypocrystalline textures. Syenites and trachytes are very rare. Rocks can be classified according to their mineralogical composition

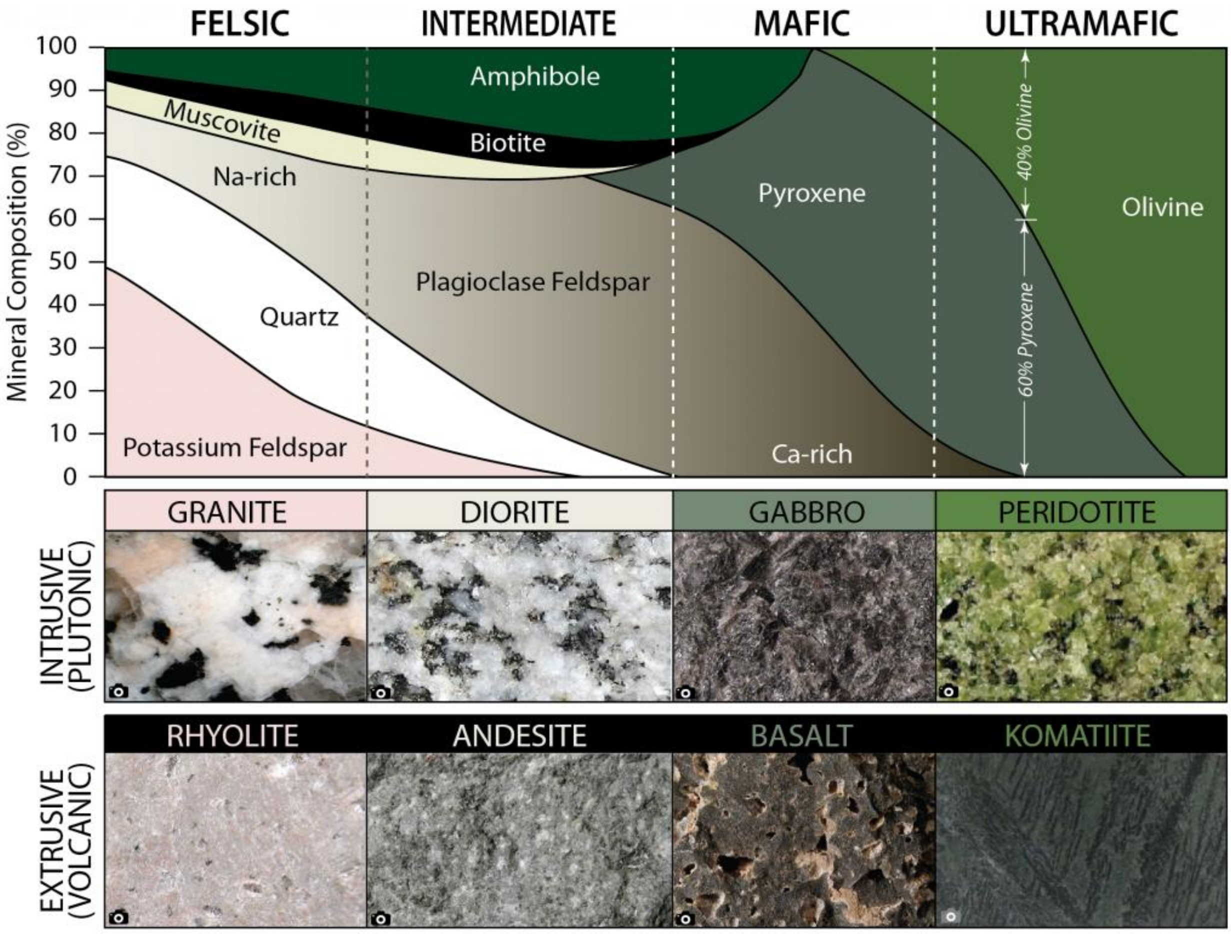


Figure 14: Schematic position of the main igneous rocks according to their mineralogical composition

2- ***Double Streckeisen triangle***

To take into account the relative proportions of different minerals and to unify the terminology of igneous rocks, the International Union of Geological Sciences (UISG) recommended the use of the double triangle of Streckeisen (1974). It is based on the proportions of minerals present in holocrystalline rocks (modal composition) or on the normative composition of hypocrystalline rocks. The 4 vertices of the double triangle corresponding to the cardinal minerals (quartz, alkali feldspars, plagioclase and feldspathoids).

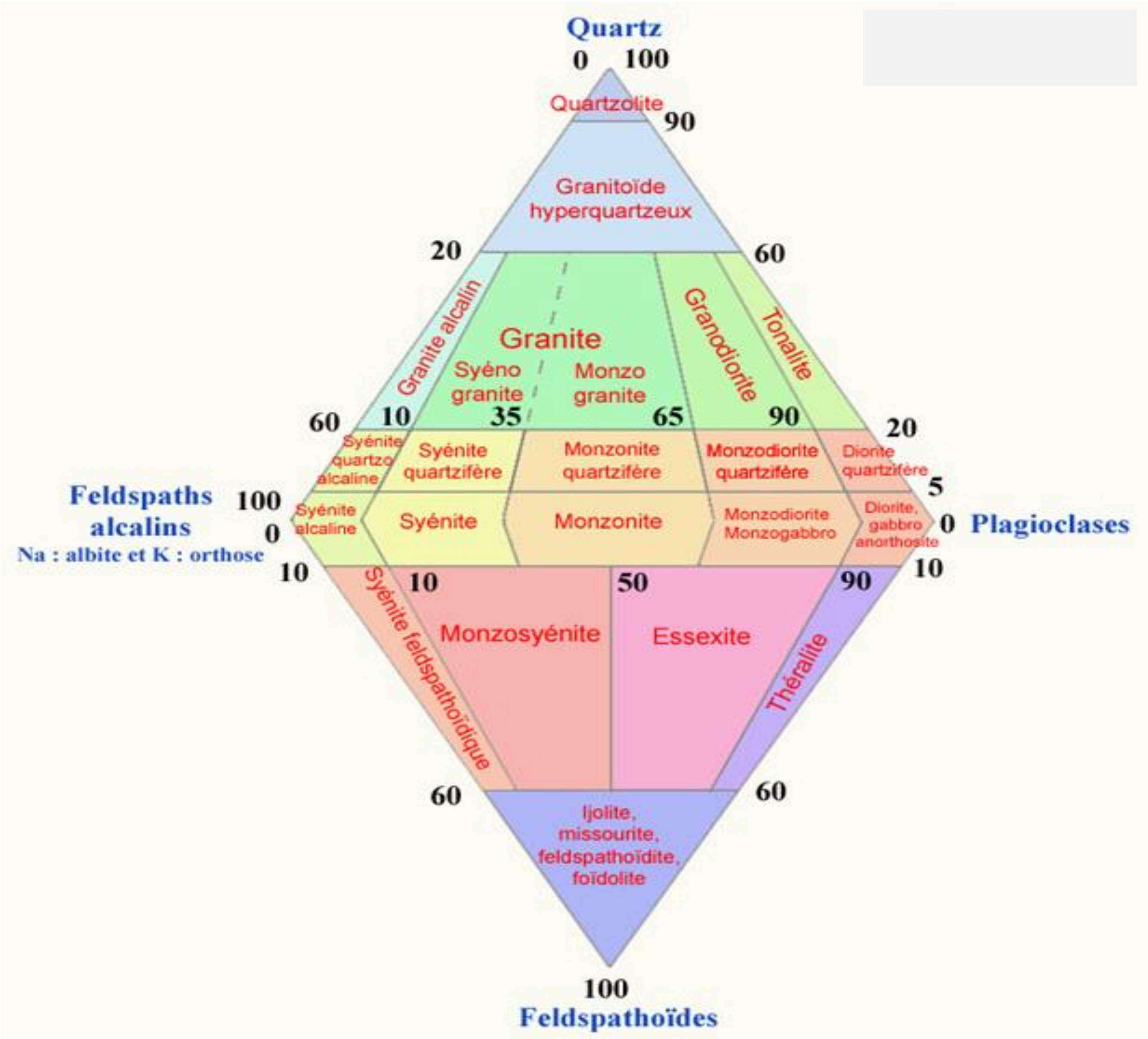


Figure 15. Streckeisen diagram for plutonic rocks

For rocks containing more than 90% ferromagnesian minerals (ultramafites), the classification is done on another triangular diagram whose vertices are occupied by olivine, orthopyroxene and clinopyroxene

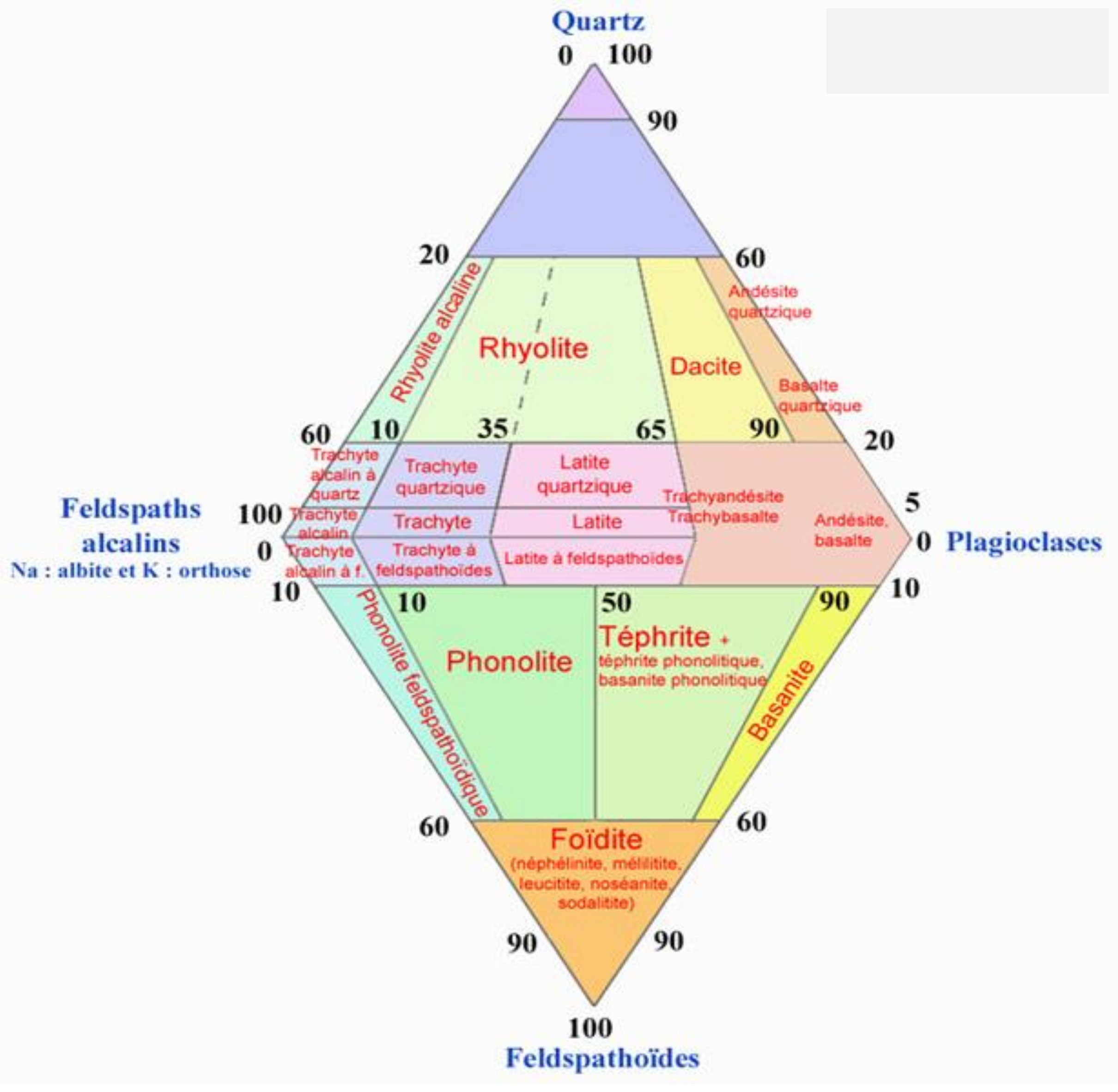


Figure 16 Streckeisen diagram for effusive rocks

Classification of ultrabasic rock: A plutonic rock comprising less than 45% SiO_2 is called an ultrabasic rock. From a mineralogical point of view, ultrabasic rocks do not contain tectosilicates in significant quantities, which makes the Streckeisen classification inappropriate. We then use a classification based on the proportions of ferromagnesian minerals which are the majority (hence the name ultramafic rocks which we also give them): olivine, orhtopyrxene and clinopyroxene.

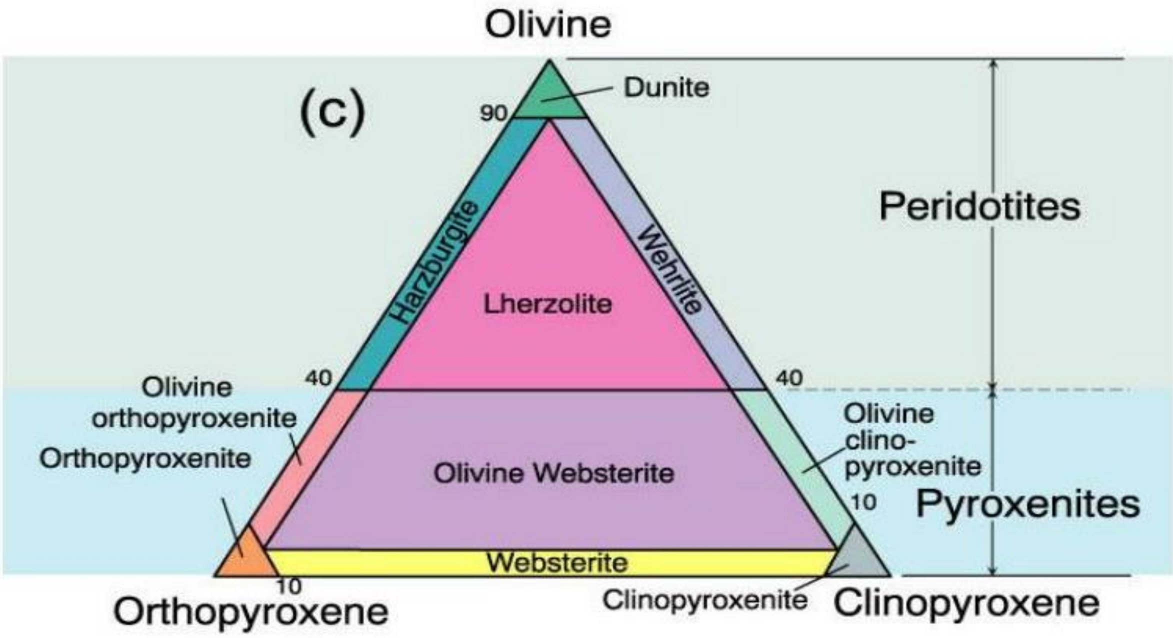


Figure 17. A classification of the phaneritic igneous rocks: Ultramafic rocks. After IUGS.

6.2. CHEMICAL CLASSIFICATION (based on chemical composition)

6.2.1. Classification parameters

- **Acidity and Basicity** : The concept of acidity is introduced for rocks according to the SiO2 content to distinguish:

  • Acidic rocks SiO2 > 65%

  • Intermediate rocks 52% < SiO2 < 65%

  • Basic rocks 45% < SiO2 < 50%

• Ultrabasic rocks SiO2 <45%

- **Basicity** : Σ bas: Fe2O3 + FeO + MnO + MgO + CaO

  Σ Bas < 10 Acidic rock %

  10 % < Σ Bas < 25 Intermediate rock %

  25 % < Σ Bas < 40 Basic rock %

  Σ Bas > 40 % Ultra-basic rock

- **Alkalinity :** On the basis of the richness of alkaline elements we can distinguish:

  • Hyperalkaline rocks (Na + K >> Ca)

  • Alkaline rocks (Na + K > Ca)

  • Calco-alkaline rocks (Na + K close to Ca)

  • Sub-calcic and calcic rocks (Na + K < Ca).

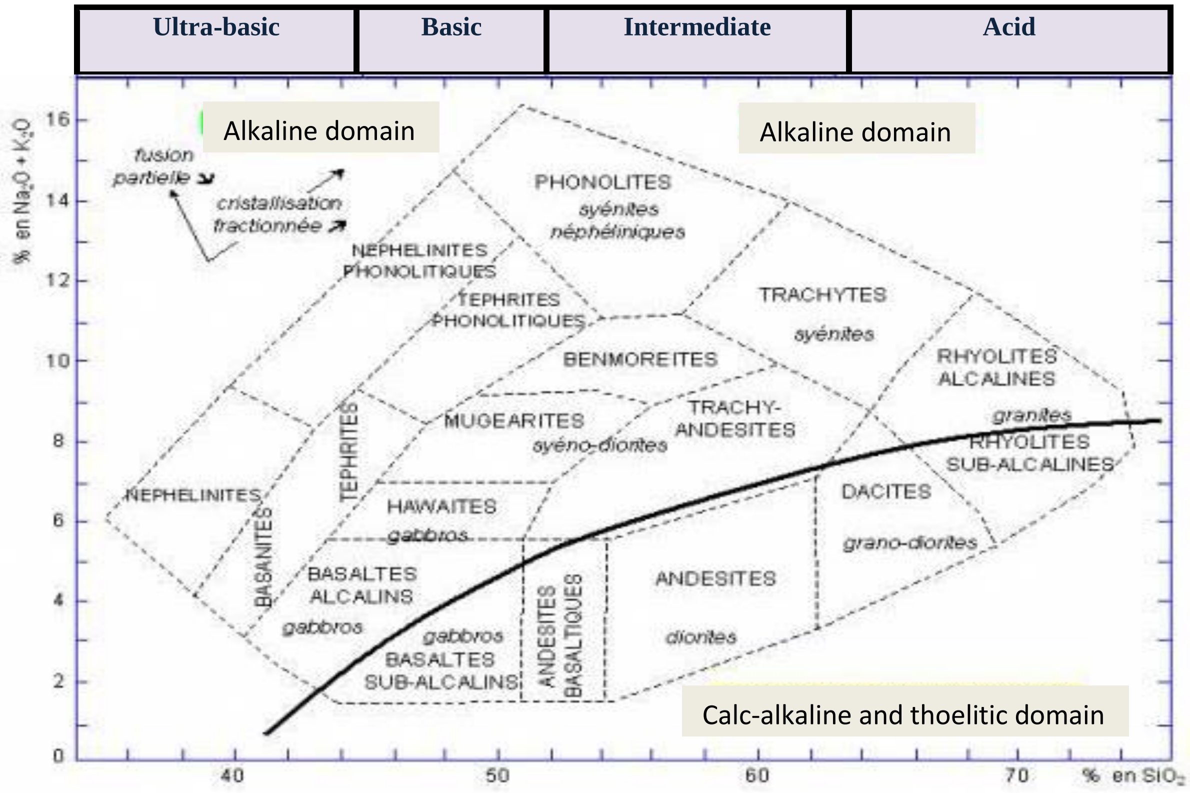


Figure 18. Classification of Cox (1979) % SiO_2 vs. (% Na_2O + % K_2O)

Table 6. Analyzes of plutonic and volcanic rocks

oxides	Acid (Granite)	Intermediate (Andesite)	Basic (Basalt)	Ultra-basic (Peridotite)
SiO2	71.3	57.94	49.2	42.26
TiO2	0.31	0.87	1.84	0.63
Al2O3	14.32	17.02	15.74	4.23
Fe2O3	1.21	3.27	3.79	3.61
FeO	1.64	4.04	7.13	6.58
MnO	0.05	0.14	0.2	0.41
MgO	0.71	3.33	6.73	31.24
CaO	1.84	6.79	9.47	5.05
Na2O	3.68	3.48	2.91	0.49
K2O	4.07	1.62	1.1	0.34
H2O	0.77	1.17	0.95	3.91
CO2	0.05	0.05	0.11	0.30
P2O5	0.12	0.21	0.35	0.10

- **Frequencies of igneous rock in relation to their chemical composition**

The global frequency curve of rocks, calculated on thousands of analyzes of plutonic and volcanic rocks, indicates two maximums, one corresponding to rocks which contain 73% silica (granites and rhyolites), the other to rocks which contain 52% silica (basalts and gabbros).The main chemical characteristics of these two major types of rock are as follows: the Al2O3 content is approximately the same regardless of the silica content;

- *Granitic rocks* have a high content of SiO2 and alkalis but a low content of total iron, CaO, MgO and TiO2;
- *Basaltic rocks* have a low content of SiO2 and alkalis but a high content of total iron, CaO, MgO and TiO2.

Thus, the Al2O3 content practically does not vary from basic rocks to acidic rocks; Total Fe, CaO and MgO vary in the same direction decreasing from basalts to granites while Na_2O and K_2O vary in the opposite direction

- **The norm (normative composition)**
  "Normative analysis involves calculating the idealized mineral composition of a rock based on its chemical analysis. By grouping the major elements to construct theoretical minerals, with a fixed formula, a normative composition, or standard, is calculated, which allows comparisons. The standard therefore expresses the theoretical (virtual) mineralogical composition of an igneous rock.

To establish the standard of a rock, we must first determine its chemical composition, which is given as a percentage of the oxide weight. The basic principle is to distribute the chemical elements: Si, Al, Mg, Fe2+, Fe3+, Ca, Na, K, Ti, P between standard mineral molecules (quartz, orthoclase, albite, anorthite, nepheline, leucite, orthopyroxene, clinopyroxene, olivine, apatite, ilmenite, magnetite), following a calculation procedure according to strict rules: either those of Cross, Iddings, Pirsson and Washington (called CIPW standard), or those of Niggli (Niggli molecular standard). This calculation is a complex operation which involves at least 25 steps in order to best express the mineralogical composition of the rock. The standard is therefore a calculated mineralogical composition which helps to compare uncrystallized volcanic rocks with crystallized plutonic rocks and to establish whether or not there are petrogenetic links between the two. Table 5 is an example of the results of chemical analysis and the corresponding standard of a rhyolite. Minerals whose presence is theoretically only highlighted in the standard calculation are called **normative minerals.**

The best known and most used standard in modern petrology is the CIPW standard which gives the normative minerals in weight percentages. Established by W. Cross, J.P. Iddings, L.V.Pirsson and H.S. Washington (hence its name) in 1903, modified in 1912, this anhydrous standard does not take into account H_2O present in the rock. The calculation method defines more than 16 different normative minerals, no mineral being able to have negative contents (see TP).

Table 7. Chemical and normative composition of a rhyolite

Weight oxides	Percentages	Normative calculation	
		Mineral	Weight percentages
SiO_2	73,3	Quartz (Qz)	33,2
TiO_2	0,2	Orthose (Or)	31,7
Al_2O_3	13,4	Albite (Ab)	25,1
Fe_2O_3	1,2	Anorthite (An)	5,0
FeO	0,7	Nepheline (Ne)	-
MnO	0,1	Diopside (Di)	0,8
MgO	0,3	Hypersthène (Hy)	
CaO	1,1	Olivine (Ol)	-
Na_2O	3,0	Magnétite (Mt)	1,9
K_2O	5,3	Ilménite (Il)	0,5
H_2O+	0,8	Apatite (Ap)	0,2
CO_2	-		
P_2O_5	0,1		

7. THE MAJOR GROUPS OF MAGMATIC ROCKS

Generally, igneous rocks are the primary rocks from which others evolve. They constitute the mass of the terrestrial (rocky) planets, not just Earth, formed by the cooling and crystallization, after fusion, of the silicate materials from which the planets are composed during their accretion. They are also present, for identical causes and mechanisms, in the cores of gigantic planets, in many of their satellites, and in the largest solid asteroids.

Volcanic rocks constitute a small portion of the rocks that originate from magma. It is estimated that during the Cenozoic, an annual average of 3.7 to 4.1 km3 of volcanic rocks was generated on Earth, a much smaller amount than the 22.1 to 29.5 km3 of plutonic rocks that would have formed on average each year during the same period.

7.1. Plutonic rocks

Plutonic rock is a rock formed by the slow crystallization of magma at a certain depth. Plutonic rock is an igneous rock that is generally grainy, with a homogeneous texture over large volumes. It is a crystalline rock, most often holocrystalline. Plutonic, or intrusive, rocks are formed from magma solidified in large masses within the Earth's crust.

The magma, surrounded by pre-existing rocks (called rectangular rocks), cools slowly, allowing the minerals to form large crystals of pure minerals and giving them a heterogeneous and granular texture to the naked eye, making them "coarse-grained" rocks. This is the case with granite and porphyry.

The magmatic intrusions from which plutonic rocks are formed are called plutons, like batholiths and laccoliths. Plutonic rocks are only visible when the crust rises and erosion removes the rocks covering the intrusion. When the rock mass is exposed, it is called an outcrop. The heart of the main mountain ranges is formed by plutonic rocks which, when they emerge, can cover vast areas of the Earth's surface.

In quantitative terms, plutonic rocks are the most abundant. They overwhelmingly dominate the Earth's composition, comprising the entire Earth's mantle and most of the crust.

Granite, gabbro, syenite, diorite, peridotite, and tonalite are examples of plutonic rocks.

GRANITE:

The words granite is transcribed from the Italian granito (same meanings) , built on the Latin granum ("grain") in reference to the granular texture.

“Granite is a light-colored, coarse-grained felsic plutonic igneous rock primarily composed of quartz, K-feldspar (orthoclase), plagioclase, and micas (biotite or muscovite).”

Granite and its associated rocks form the bulk of the planet's continental crust. Granite is the result of the slow cooling, at depth, of large masses of intrusive magma which will most often form plutons, the latter finally outcropping through erosion which strips the overlying rocks. These acidic magmas (i.e. relatively rich in silica) are essentially the result of the partial melting of the continental Earth's crust.

Some granites (plagiogranites) encountered as small plutons in the oceanic crust are, for their part, the result of the ultimate differentiation of basic magmas. Its constituent minerals are mainly quartz, micas (biotite or muscovite), potassium feldspars (orthoclases) and plagioclases. They can also contain hornblende, magnetite, garnet, zircon and apatite. There are more than 500 different colors of granite2. The corresponding volcanic rocks are rhyolites.

The average chemical composition of granite is: 74.5% SiO_2, 14% Al_2O_3, 9.5% (Na_2O, K_2O), 2% other oxides (Fe, Mn, Mg, Ca). Granite is an acidic (silica-rich) and dense rock (average specific gravity: 2.7)3 and has a hardness of approximately 6 Mohs. The largest granite monoliths in the world are found in Yosemite National Park, California.

In reality, the term granite is often used in the broader sense of granitoids, plutonic rocks with more than 20% quartz, regardless of the nature of the feldspar(s) found there. Granitization thus refers to all the geological phenomena leading to the formation of a granitoid.

• **<u>Genesis of granites</u>**

Granites are of plutonic origin (as opposed to effusive rocks, which are of volcanic origin, such as basalt). They form at depth by the very slow cooling of magma, mixed with other rocks. The minerals then crystallize in a specific order: first micas, then feldspars, and finally quartz. Some granites are formed from the melting of the continental crust during a collision between two tectonic plates. Two main models of the petrogenetic process responsible for the formation of granites are proposed:

- crustal melting of rocks at different levels of variable composition (these rocks of the continental or oceanic crust directly melt to form a granitic liquid);
- Mantle melting of ultramafic rocks, which forms basalts or andesites/diorites, then evolve through the process of differentiation into a more or less complete magmatic series, which extends from primary basic magma to granite.

These models (mantle and crustal origin) are insufficient to explain the variety of granites whose formation most often results from contamination and enrichment of basic magma by silica and alkalis (Na and K) which diffuse from the continental crust, or from a mixture between basic magmas of mantle origin and granitic magmas of crustal origin (mixed granite). If the vast majority of granites can have two different origins (mantle and crustal), but not incompatible, all possible intermediates exist.

The formation of granites results from mechanisms that differ depending on the geodynamic environment at the time of their formation. Geologists distinguish between anorogenic granites (in a region not subject to an orogenic cycle) and orogenic granites whose formation is linked to orogeny and can occur during it (more or less orthogneissified syntectonic granites forming circumscribed granites with clear edges, anatectic granites with diffuse edges, or mixed granites) or at the end (syn- to post-tectonic granites forming small circumscribed massifs or large late batholiths).

Typology

Calc-alkaline granites: are of mixed origin (mantle and crustal) and are predominant in subduction zones where they participate in the formation and recycling of the continental crust. These are Type I granites. Calc-alkaline granites are present in the continental crust near the Moho (Mohorovicic discontinuity). They are distinguished by their graininess, but more importantly, the presence of microlites (rare) demonstrates the activity of the Earth's internal envelopes.

Tholeiitic granites: Associated with the oceanic crust, they result from extensive differentiation of basaltic magma origin. Plagiogranites are very rich in plagioclase feldspars, hence their light color. Plagiogranites can be observed in the Chenaillet ophiolites...

Alkali granites: These are the result of alkaline magmatism typical of a distensive context. Of mantle origin, the 86Sr/87Sr ratio of these rocks is high. These are M-type granites, and they play a key role in the formation of the protocrust (thickening and enrichment in certain minerals). They are mainly composed of minerals called alkali feldspars. They are recognizable by their pale color. They contain little pyroxene, but more quartz. They are rare and require near-rival drilling.

Leucogranites (from the Greek leucos, meaning white) are relatively rich in alumina and are characterized by the presence of muscovite (white mica) alongside biotite. The Locronan mountain was formed on a leucogranite pluton.

Anatexis granite (from the Greek ana, up, and texis, birth, fusion) has a different appearance from other granites. It often has heterogeneities, with oriented minerals. It is the result of the melting of the continental crust in two different geodynamic contexts. In subduction zones, this melting occurs following the hydration of the rocks of the continental crust by water from the dehydration of the subducted oceanic crust.

In post-collision zones, melting is made possible by the increase in temperature thanks to the radioactive disintegration of the elements of the continental crust. In both cases, the continental crust undergoes partial melting. The liquid can then remain in place and form batholiths or migrate via tectonic accidents. In both cases, it is said to be concordant and does not digest the host rock. The resulting granite can form milonites or gneisses exposed by erosion. These granites are of type S (origin from a sedimentary continental crust rich in aluminum).

• Uses:

o construction materials

o paving, curbstones, etc.

o noble material used for sculpture and funerary monuments, etc.

o kitchen and bathroom decoration, etc.

o see also: Uses of subsoil resources

• Granite weathering generally begins along joints, leading to the formation of granite balls, then a granite chaos at the foot of which a granite arena is observed. The arena is formed mainly of quartz grains, but also of altered feldspars and altered micas.

Granite weathering can give rise to deposits from which various minerals can be extracted (including clay, e.g., the kaolin mining in Ploémeur, Morbihan; or sand).

Algeria hosts numerous granitic massifs .These Algeria's granite resources are found in North-Eastern regions and the Hoggar Mountains, with different suites like the Filfila and Collo granites containing rare metals. Although Algeria exports some granite.

- **Kabylie and Filfila:**The Miocene granites in these northeastern regions are known for potential metal content, including rare metals and elements like lithium, tantalum, and niobium, especially in the Filfila suite.
- **Hoggar Region:**The Djilouet granite suite and Ebelekan granite in the Hoggar Mountains are also notable for their specific mineral compositions, including rare metals like tantalum.

GABBRO:

Rock that is entirely crystallized; it is a plutonic igneous rock. - We note that the rock is formed half by light minerals, and half by dark ferromagnesian minerals. It is a mesocratic rock rich in pyroxenes and calcic plagioclase, with/without a small amount of olivine or amphiboles. A gabbro is a rock with a coarse-grained structure, with crystals 1 mm or larger in size; predominantly green to black in color. It is composed of ferromagnesian minerals pyroxene, amphibole and olivine, giving it this dark color, and plagioclase, which are light whitish minerals. Gabbros form the < part of the oceanic crust. They are formed by deep cooling of part of the magma at the axis of the ridge

• Composition: Gabbro is composed primarily of calcium-rich plagioclase feldspar, usually labradorite or bytownite, and pyroxene, usually clinopyroxene (such as augite) or orthopyroxene (such as hypersthene). It may also contain small amounts of olivine, amphibole, and other minerals.

• Texture: Gabbro has a coarse-grained texture, with individual mineral grains visible to the naked eye. The grains are usually interlocking, giving the rock its characteristic appearance.

• Color: Gabbro is typically dark gray to black in color, due to the presence of dark-colored minerals such as pyroxene and olivine.

• Occurrence: Gabbro is commonly found in large plutonic bodies, such as batholiths, which are large intrusive rock formations, and dykes, which are tabular intrusions that cut through other rocks. It can also be found in layered intrusions, such as in the Bushveld Complex in South Africa.

• Petrogenesis: Gabbro typically forms through the slow cooling and crystallization of mafic magma beneath the Earth's surface. As the magma cools and solidifies, mineral crystals begin to form, resulting in the coarse-grained texture of gabbro.

• Uses: Gabbro is used as a dimension stone for construction and architectural purposes because it is durable and can be polished to a high luster. It is also used as crushed stone for road construction and as an aggregate in concrete. In some cases, gabbro may contain valuable minerals such as nickel, copper caps and platinum group elements (PGE) and can be mined for these resources.

Gabbroic rocks within the Algerian landscape, such as in the *Narm area* of western Algeria and the *Tirek area* in the Hoggar, where gold is found within shear veins which are intrusive igneous formations relevant to geological studies and mineral resources.

PERIDOTITES:

These are particular and very rare rocks on the Earth's surface, which mainly constitute the mantle. They include the most basic and densest rocks. Their mineralogical composition is made up of more than 90% ferromagnesian rocks, composed exclusively of olivines, with a few pyroxenes. The peridotite family is the essential constituent of the mantle. It includes several types based on their mineralogical composition:

• - Peridotite itself, composed of olivine and pyroxene,

• - Pyroxenite, mainly composed of pyroxenes,

• - Hornblendite, composed of hornblende-type amphiboles,

• - Dunite, mainly composed of olivine

• Peridotites are often the site of economically important minerals such as Cr, Ni, Co, and platinum.

Peridotites in Algeria are found primarily in the ultramafic massifs of the Maghrebide range, particularly in the northeastern regions of Edough Massif and Collo. These ultramafic rocks, which are predominantly lherzolites and harzburgites, are believed to originate from the Earth's upper mantle and became incorporated into the continental crust during the Cenozoic rifting and opening of the Western Mediterranean basin. They are associated with other metamorphic formations and mafic rocks, providing insights into the geodynamic evolution of the region.

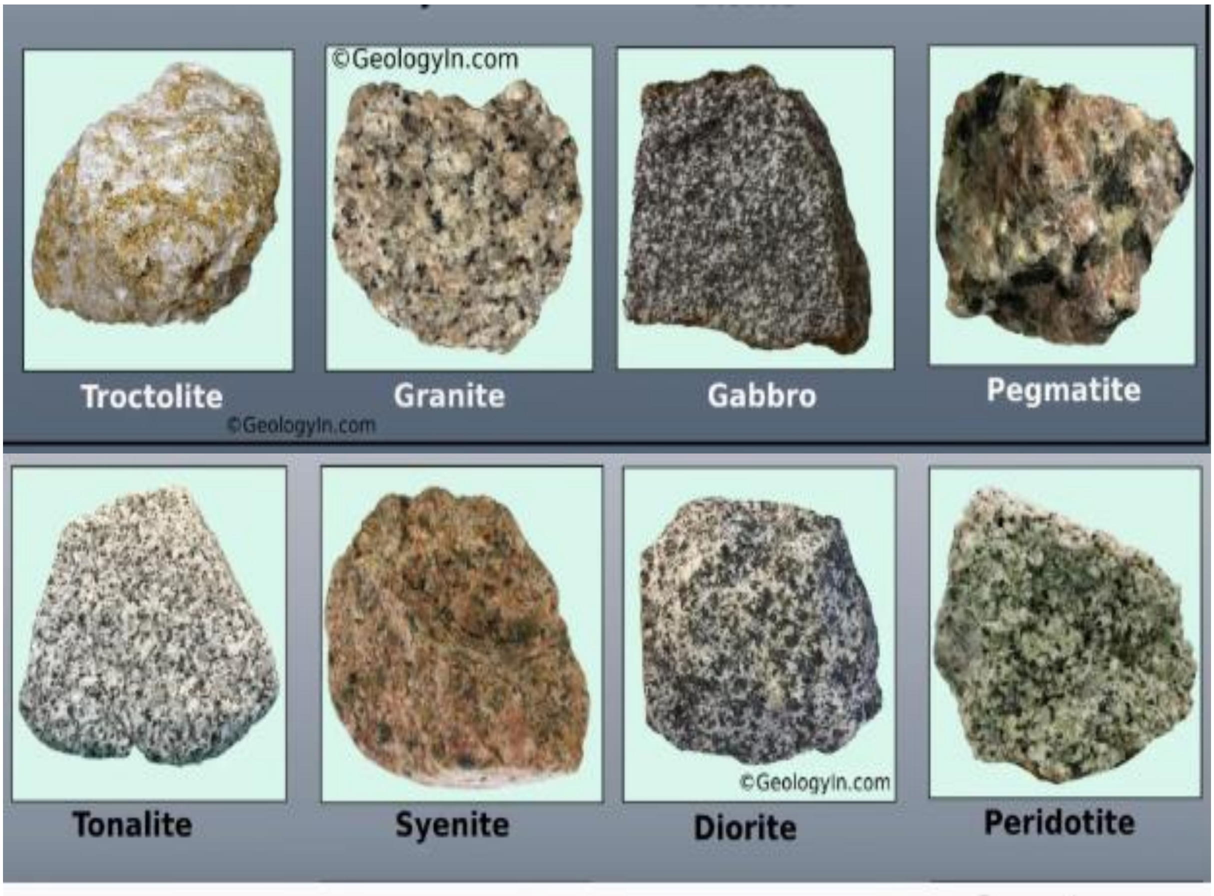


Figure 19. Photos of the main plutonic rocks.

7.1. VOLCANIC ROCKS

Volcanic or extrusive rocks are formed by the solidification of magma (lava) at the surface of the Earth's crust, usually after a volcanic eruption, which suddenly comes into contact with the atmosphere or bodies of water. Since cooling is much faster than in the case of intrusive rocks, the minerals cannot organize into large crystals. Therefore, volcanic rocks are either fine-grained (crystals invisible to the naked eye), such as basalt, or completely amorphous (a glass-like texture), such as obsidian. In many volcanic rocks, you can see the holes left by gas bubbles escaping as the magma solidifies.

The volume of extrusive rocks ejected by volcanoes each year depends on the type of tectonic activity:

• Divergent edges: 73%, such as oceanic ridges, Iceland, and the East African Rift.

• Convergent edges (subduction zones): 15%.

• Such as the Andes Mountains or the Pacific island arcs with hotspots (intra-plate volcanism): 12%, as in Hawaii.

The most common volcanic rocks on Earth are basalt followed by andesite. Other volcanic rocks include rhyolite, dacite, and trachyte, to name a few.

Volcanic rocks can be divided into those that do not have crystals visible to the naked eye, i.e., they have an aphanitic texture, and those that have crystals visible to the naked eye, i.e., a phaneritic texture. When large crystals (phenocrysts) are present that break away from the matrix, it is called a porphyritic or porphyritic texture.

The basalt

The word basalt is borrowed from the Latin basaltes, a term often said to be derived from an Ethiopian term meaning "black rock."

- Basalt is a volcanic igneous rock formed from rapidly cooled magma and characterized by its mineralogical composition: plagioclase (50%), pyroxenes (25 to 40%), olivine (10 to 25%), and 2 to 3% magnetite. On Earth, it is of volcanic origin and is one of the main constituents of the oceanic crust. On the Moon, it forms the surface of the lunar maria. It is believed to be an important constituent of the crusts of Mars, Venus, and Mercury.
- Basalt is a melanocratic to holomelanocratic rock (dark to very dark) with a microlitic structure, which is derived from the partial melting of the Earth's peridotite mantle (lherzolite). The largest known basalt outpourings are the Siberian Traps in Russia, the Deccan Traps in India, the Columbia Plateau in the United States, the Tassili des Ajjers in Algeria, and the Triassic lavas of North America. The most famous basalt structure is undoubtedly the Giant's Causeway in Ireland, where columnar basalt columns (columnar-shaped formations, generally hexagonal in cross-section) can be admired. In France, they are mainly found in the Massif Central. The dark regions of the Moon (the "seas") are formed of basalts. 4
- Basalt is a basic rock. Plutonic rocks with the same mineralogical composition are gabbros.

- Basalts are classified by their silica saturation level.
- When the basalt does not reach the silica saturation plane, nepheline [$SiAlO_4$]Na is expressed. This is the basanite domain, and, as it approaches the saturation plane, that of alkali olivine basalt. Beyond the saturation plane, it is the tholeiitic domain, with tholeiitic basalt if quartz is not expressed, and otherwise tholeiite quartz.
- Alkali olivine basalt: Alkali olivine basalt is a ubiquitous rock. It is found in oceanic and continental intraplate volcanism when the volume is small.

Figure 21. Cooled basaltic lava flow

Tholeiitic basalt

Tholeiitic basalt (or olivine tholeite, or olivine tholeite) forms the ocean floor. MORB (MORB = Mid Ocean Ridge Basalt) – K_2O less than 0.2% and TiO_2 less than 2.0% – are the essential constituents of the oceanic crust. It is also found in oceanic and continental intraplate volcanism. It contains a normative orthopyroxene (not expressed).

Origin of basalts

The magma that gives rise to basalts comes from the partial melting of rocks in the Earth's mantle (peridotite).

Depending on the pressure at which partial melting occurs, the minerals affected by the melting vary. At low melting rates, the liquid is rich in water and alkali:basanites or alkaline olivine basalts are obtained. At high melting rates, the liquid is richer in calcium, iron, and magnesium, and olivine tholeiites are obtained.

At hot spots, the pyrolite melting rate ranges from 5% at the periphery, with the formation of basanite, to 30% in the center, with the formation of olivine tholeiite. When the melting rate is 10%, olivine alkali basalt is formed.

At mid-ocean ridges, the melting rate is 30%, and olivine tholeiite is obtained.

Uses ;

Basalts are used in construction and statuary. Due to their fine, isotropic texture, basalts are also valued as highly compact and highly resistant aggregates. Some can be used to make railway ballast.

Rock wool is obtained from basalt or basalt-like diabase rock through a melting process (in a cupola furnace to which fluxes and coke are added to heat it to 1,500°C) and extrusion.One geoengineering method, forced weathering, and involves spreading finely ground basalt to fix atmospheric CO_2 in agricultural soils.

Basalt in Algeria is found in several volcanic regions, notably the Atakor and Tahalra volcanic fields in the Hoggar Mountains, the coastal region of Western Oran, and the Tindouf and Reggane basins in the southwest

Rhyolite: is a volcanic rock of a fairly light color: pink or gray. It is a rock with a microlitic structure presenting minerals visible to the naked eye: quartz, feldspars and amphibole. Rhyo /$^*lite is the volcanic equivalent of granite.

Trachyte: are volcanic rocks rich in alkali feldspars and with a fairly high silica content. Their structure is mainly microlithic but the presence of phenocrysts is usual. The structure is also fluid because the microcrystals present fields of common orientation along fluid lines. When broken, the appearance is rough. The color is quite light: trachytes are leucocratic rocks, generally whitish to greenish gray. The equivalent plutonic magmatic rock is syenite (fig.20). Trachytes are associated with explosive type volcanism**.**

Phonolite is a volcanic rock with a fluid microlithic structure, gray to greenish in color, it is composed of feldspar, feldspathoid and a scant glass paste. The phonolite is cut into slabs. This rock is characterized by a clear sound when hitting a slab. It is this property which gave its name to the rock.

Andesite (Fig. 17) is a volcanic rock of intermediate composition, *with Na/Ca amphiboles and plagioclase with/without little biotite or quartz* with a texture ranging from aphanitic to porphyritic. It is generally composed of plagioclase (oligoclase and andesine), and more rarely biotite, amphibole (hornblende), and pyroxene. Potassium feldspars are completely absent. Since they are often associated with basalts, it is sometimes difficult to differentiate them (the two rocks contain plagioclase and ferromagnesian minerals). However, andesite can be characterized according to the following criteria:

- the type of plagioclase;
- the ferromagnesian mineral is an amphibole;
- the volume percentage of ferromagnesians is less than 35-40%.

Andesite is the volcanic equivalent of plutonic diorite. Like diorites, andesites are characteristic of subduction zones and tectonic environments.

Dacite is a microlithic volcanic rock composed of quartz, plagioclase, glass, and ferromagnesian minerals: biotite, hornblende, or pyroxene.

Obsidian

Obsidian is a volcanic rock of Glassy texture and viscous acid lavas (rhyolitic magma, 70-75% SiO2).

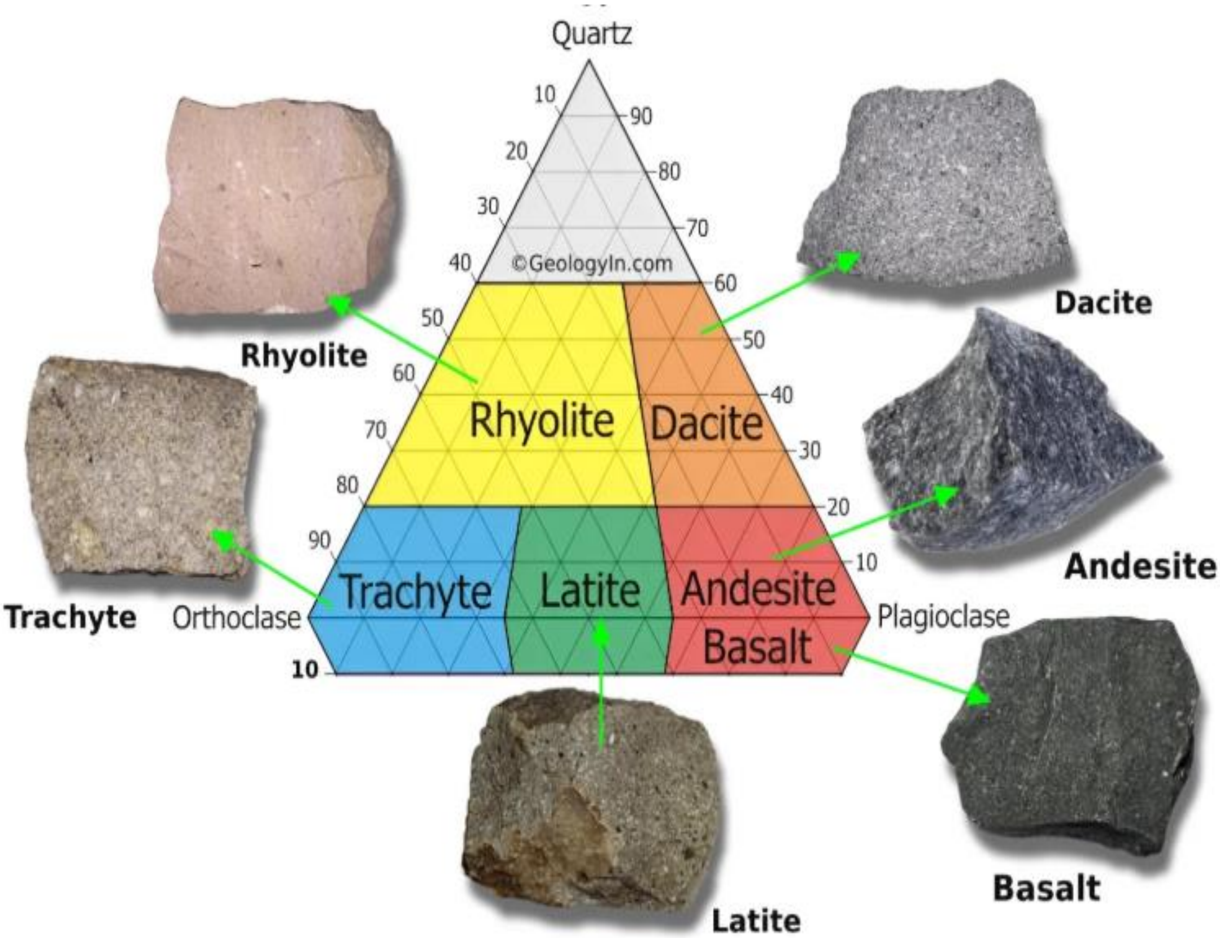


Figure 21. Photos of the main volcanic rocks.

7.1. Intermediate Rocks

A dolerite (from the Greek doleros, "deceptive") is a microgabbro, a dense, hard, and massive, fine-grained igneous rock, corresponding to basaltic magma that solidified (relatively) slowly in a vein, then underwent light metamorphism. It is composed of grains visible under a magnifying glass. Greenish to bluish in color, it is composed of rectangular rods of intersecting plagioclase feldspar, between which dark minerals (pyroxenes, olivine, etc.) are found. This compact rock originates from the conduits connecting the magma chamber to the surface volcanic apparatus. In terms of texture, it is an intermediate rock between gabbros (grainy, with all crystals visible to the naked eye) and basalts (microlithic, with some of the rock uncrystallized). The term dolerite is also used, in a broader sense, to refer to microdiorites and microgabbros.

Today, it is tending to replace the term diabase, which refers to the same type of rock but modified by low-grade metamorphism.

Geological Formation

Dolerite is a dense, hard, and massive, fine-grained igneous rock (blackish-green, brownish through alteration), which formed at depth, in a sill (a horizontal inclusion, due to the rise of magma in a fault between two pre-existing layers) or in a dyke (for example, in the upper part of an oceanic ridge). Erosion, which breaks the dolerite into balls, then brought it to the surface due to its stronger nature than the surrounding rock.

Dolerite is a rock formed from albite (altered plagioclase), epidote, augite (pyroxene partially transformed into fibrous amphibole), chlorite, and also quartz microcrystals. It is particularly resistant and also appears to continue to harden after extraction.

Two types of dolerite are distinguished:

• Olivine dolerite; • Olivine-free dolerite.

Varieties

• Ophite is a Pyrenean dolerite dating from the Upper Triassic.

• Diabase, or epimetamorphic dolerite, or metadolerite, is an altered dolerite with a green tint.

The doleritic structure is composed of rod-shaped crystals visible to the eye embedded in a mass of smaller crystals.

Aplite

The name aplite is derived from the ancient Greek ἁπλόος (haplóos), meaning simple. An aplite is a very fine-grained, leucocratic vein rock. Aplites are associated with either igneous or metasomatic rocks.

Aplites are characterized by their small crystal size (less than 1 mm), with a very low mafic mineral content (generally below 5%).

Aplites are light-colored vein rocks; they are compact and fine to very fine-grained, sometimes even aphanitic. Their color can vary from whitish to reddish, through grayish. Aplitic veins can be zoned. The veins are centimeter thick, more rarely decimeter thick. The texture of aplites is equidimensional and non-porphyritic. The grain size is submillimeter.

Figure 22.Pink Aplitic Vein

A magnifying glass is therefore needed to identify them. Because of this fine and equidimensional grain size, rapid and simultaneous crystallization can be expected in magmatic aplites. The crystal habit is predominantly subhedral and the texture takes on a mosaic appearance. Sometimes aplites can form small granitic bodies or irregular masses within or around the perimeter of plutons. Pegmatites often show aplitic edges.

Aplites consist mainly of quartz, alkali feldspar (orthoclase or microperthite), and plagioclase. They are very poor in mafic minerals (usually biotite), which is why their color index is below; they are therefore hololeucocratic. The color index of aplites associated with more basic intrusions is slightly higher, but always remains below.

Their chemical composition is very similar to the interstitial material of porphyry rocks, remarkably similar to the eutectic composition of granitoids. Alkali feldspar can exhibit porphyritic tendencies, but quartz never does.

This fact underlines the association of aplites with granophyres, rhyolites, and felsites. Aplites related to diorites and quartz diorites have a slightly different mineralogy; they are dominated by plagioclase, with additional muscovite, apatite, and zircon. Syenitic aplites consist mainly of alkali feldspar, with occasional nepheline occurrences (previously, nephelinitic aplites were called aploids). As the silica content increases, aplites can transition to quartz veins.

Biotite and other ferromagnesian minerals are very rare or nonexistent. Tourmaline can also occur alongside pneumatolytic minerals such as topaz and fluorite. Aplites often have high levels of the elements beryllium and lithium.

Aplitic granites are light-colored rocks with the same composition as granites, but they contain no (or very little) biotite. There are also aplosyenites, aplodiorites and even aplogabbros.

7. ALTERATIONS OF MINERALS IN MAGMATIC ROCKS

7.1. PHYSICAL WEATHERING

The processes involved in physical weathering are as follows:

• Freeze-thaw cycles, in a sufficiently humid climate, fragment rocks (cryoclasty). Water, when freezing, increases its volume by 9-10% and acts as a wedge, gradually widening fractures;

• Repeated temperature variations (40-50°C daily range in the Sahara) also have the same effect as frost: differences in thermal expansion between the minerals of a rock cause fractures to appear;

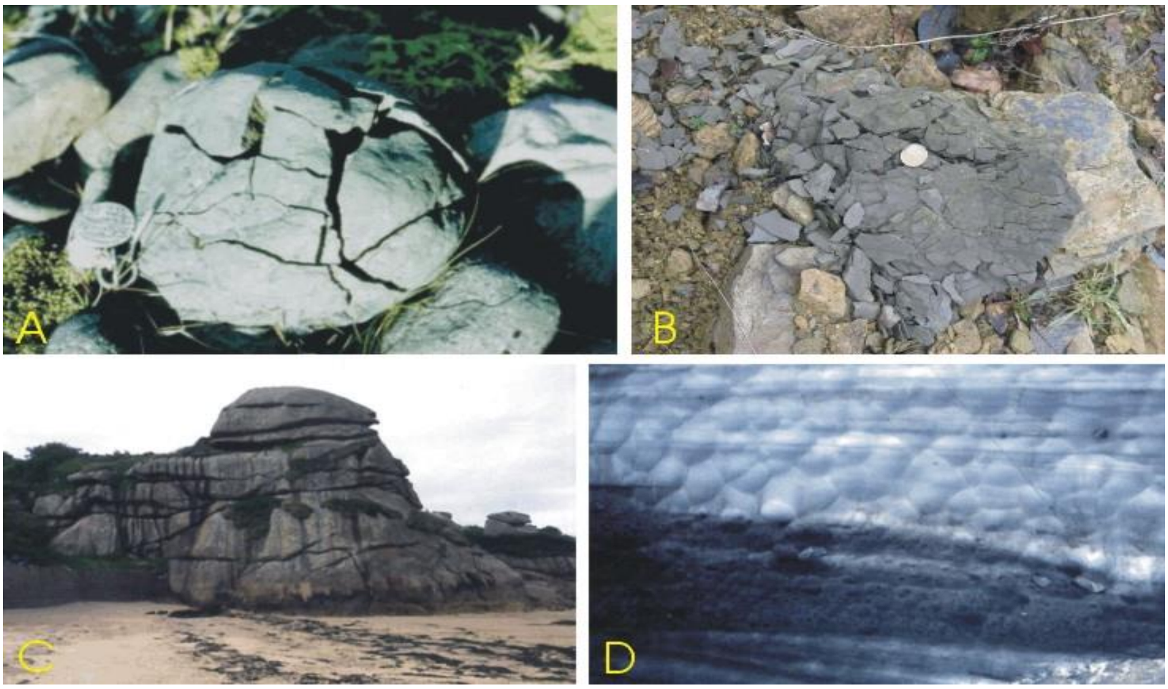


Figure 23. Physical alteration. A: cryoclasty of a basalt (macrofrost rock), Iceland; B: cryoclasty of a schist (microfrost rock), Belgium; C: decompression joints in a granite massif, Ploumanach; D: ice loaded with sand and gravel, Pyrenees

• Crystallization of salt or other evaporite minerals can also widen cracks in rocks (haloclasty);

• Decompression occurs when buried rocks are released from lithostatic pressure by removing overlying formations. Decompression joints, practically parallel to the ground surface, gradually develop.

• Mechanical wear by detrital grains carried by wind, water, ice.

Figure 24. *Great Salt Lake, Utah, USA (A). Haloclasty (salt crystallization) of a limestone crust in an evaporitic environment (B):*

8.2. BIOLOGICAL ALTERATION

We distinguish between the alteration caused by the chemical action of compounds produced by organisms (plants, microbes, etc.) and the purely mechanical action of plants or animals (for example: progressive expansion of roots acting as a wedge in rock fractures). The ingestion of materials by animals living in soils is a process involving both types of mechanisms mentioned at the same time. A first important process is the oxidation of organic matter (by fermentation or respiration), producing water and CO2, itself involved in dissolution reactions:

$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$

The combination of CO_2 and water gives rise to carbonic acid (H_2CO_3), a weak acid that can nevertheless solubilize calcite (or another carbonate):

H_2CO_3+ $CaCO_3$ -> Ca^{++} + 2 HCO_3-

It has indeed been observed that for a CO_2 concentration equivalent to the atmospheric concentration (~3.10-4 atm), the concentration of Ca^{++} and HCO_3^- was respectively 20 mg/l and 60 mg/l. In a soil where the CO_2 concentration can reach 3.10-2 atm, the respective concentrations of Ca^{++} and HCO_3^- can increase to 90 mg/l and 260 mg/l.

The action of microorganisms is important and is not limited to the production of CO_2. As soon as they arrive in the subsurface, the minerals of the rocks are subjected to their metabolism. Microbial colonies grow on their surface, infiltrating into the fractures in search of elements essential to life. Microbial alteration is mainly manifested in the form of dissolution by organic acids, the most common of which is oxalic acid.

The attack of minerals by these acids releases metal cations which, combined with organic anions, will give rise to organometallic complexes (in the case of oxalates, combined with calcium from the dissolution of carbonates, this will give rise to CaC_2O_4, common in soils). Many microbes have the ability to produce specific molecules depending on the type of mineral to be degraded. The example in Fig. shows the dissolution of iron from hornblende by bacteria. In addition to the action of organic acids, the formation of EPS biofilms ("exopolymeric substances" or extracellular polymers) maintains constant hydration around the minerals which promotes solution reactions.

These microbial alteration processes by dissolution of primary minerals and precipitation of new minerals of biogenic origin (such as calcium oxalate) modify the appearance of the rock and deserve the name microbial diagenesis. This particular diagenesis is often marked by the precipitation of microcrystals replacing larger crystals. This is the process of micritization in the case of carbonates, frequent in particular in soils.

8.3. **CHEMICAL ALTERATION**

Chemical alteration acts in two ways: some minerals (halite, calcite) are completely dissolved and their ions are evacuated in solution. Other minerals, such as micas or feldspars are transformed into other mineral species (especially clays), often of finer grain size and more easily mobilized by erosion. Most of the reactions involved in alteration require the presence of water and air. Let us review the most significant reactions.

8.3.1. **Main chemical reactions involved in alteration**

- Dissolution: this is the simplest reaction, involving water or an acid. Let's consider some concrete cases:

• The Solubility of quartz is very low (6 ppm in surface water); the dissolution reaction is as follows: $SiO_2 + 2\ H_2O \rightarrow H_4SiO_4$

• calcite, on the other hand, is much more soluble, because rainwater is charged with CO2 and acts as a weak acid when it comes into contact with calcite (about 2000 ppm). The reaction is as follows: $CaCO_3 + H_2O + CO_2 \rightarrow Ca^{++} + 2\ HCO_3^-$ (bicarbonate in solution).

• Halite and other halides are very soluble (solubilities of the order of a thousand ppm).

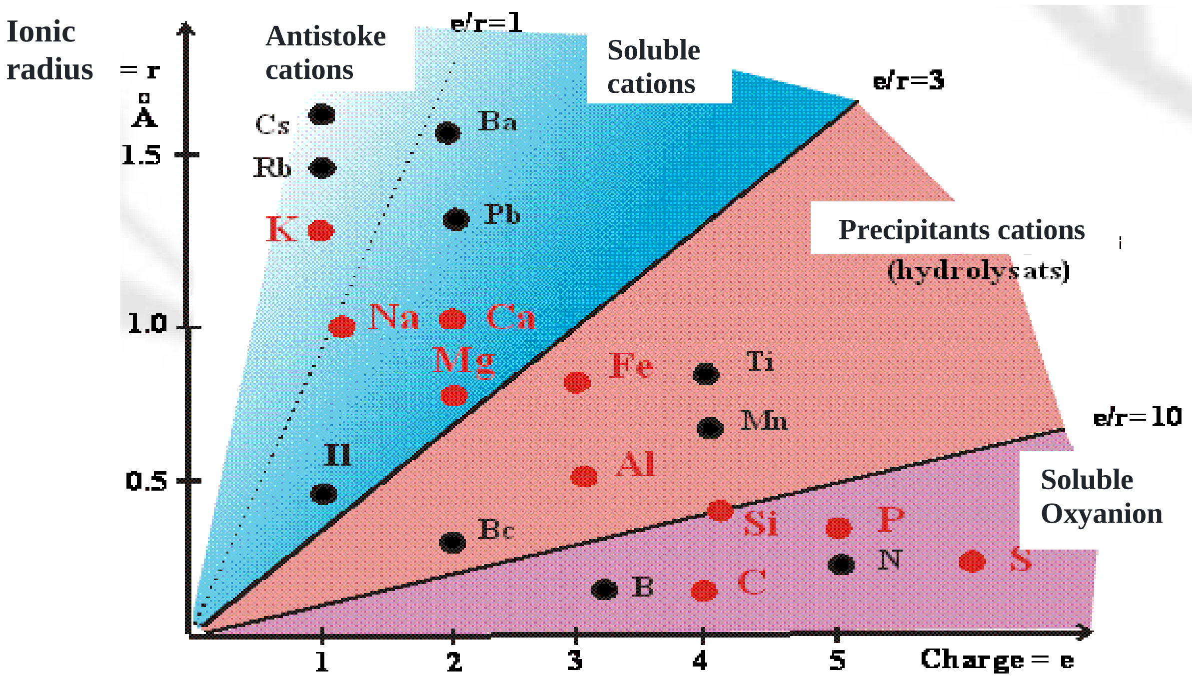


Figure 25. *Goldischmith diagram showing the behavior of ions with respect to the water molecule as a function of their ionic ratio e / r*

Hydration and dehydration, or more concretely: mineral + water = new hydrated mineral; dehydration being the reverse process. The most important reactions are:

• Dehydration of gypsum to produce anhydrite: $CaSO_4.2H_2O$ -> $CaSO_4$+ 2 H_2O;

• Hydration of hematite to produce limonite: Fe_2O_3+ 3 H_2O -> 2 $Fe(OH)_3$;

Let us take the example of the reactions involved in the alteration of orthoclase:

The first stages of the alteration of orthoclase result in the formation of clay minerals, *illite*, or if drainage is poor, *smectites*:

2.3 Na Al Si_3O_8 + H_2O ------> $Si_{3.7}$ $Al_{0.3}$ O_{10} Al_2 $(OH)_2$ $Na_{0.3}$ +3.2 H_4SiO_4 + 2 (Na+, OH-)

Smectite

• orthoclase + water -> illite + silica + potassium (entrained in solution)

This process is called bisiallitization because the Si/Al ratio (equal to 3 in orthoclase) is 2 in illite;

In case of more significant leaching of silica (more advanced alteration), kaolinite is obtained where the Si/Al ratio is 1. This is the process of monosiallitization.

$Na\ Al\ Si_3\ O_8 + 11\ H_2O$ ------> **$Si_2O_5Al_2(OH)_4$** $+ 4\ H_4SiO_4 + 2\ (Na^+, OH^-)$ …….(1)

albite + eau ------> **kaolinite** + silicic.ac. + ions

• Hydration of kaolinite to produce gibbsite.

Finally, in the final stage (humid tropical climate), all the silica is leached and only an aluminium hydroxide remains, gibbsite, in which the Si/Al ratio is zero.

.$Na\ Al\ Si_3\ O_8 + 8\ H_2O$ -------> $Al\ (OH)_3 + 3\ H_4\ SiO_4 + Na^+OH^-$

Albite + water --------> gibbsite + silicic acid + precipitated ions + leaching solution

(*) $Al\ (OH)_3$ or Al_2O_3, $3\ H_2O$

• This process is called allitisation and results in the formation of bauxites but, as the alteration product most often contains iron, it is called ferrallitisation or laterisation.

• **Hydrolysis:** this reaction is the process by which a cation of a mineral is replaced by H+ from an acidic solution. This reaction has the effect of destroying the mineral (complete dissolution) or converting it into a new species. For example, olivine and pyroxene dissolve completely, while feldspars dissolve partially, producing dissolved silica and clay minerals. Since meteoric waters contain dissolved CO_2, the reactions are as follows:

- • Mg_2SiO_4 (forsterite) + $4\ H_2\ CO_3$ -> $2\ Mg^{++} + 4\ HCO_3^- + H_4SiO_4$

• 4 NaAlSi3O8 (albite) + $4\ H_2CO_3$ + 18 H2O -> 4 Na+ + 8 H4SiO4 + $Al_4Si_4O_{10}(OH)_8$ (kaolinite) + 4 HCO_3-

- (Note: these weathering reactions of silicate minerals are therefore "pumps" for atmospheric CO2!)

- **Oxidation-Reduction**. The best-known oxidation process is the transformation of Fe2+ into Fe3+; from the ferrous to the ferric state Mn behaves in the same way as iron, with pyrolusite (MnO2) and manganite (Mn2O3.H2O) as the main oxidation products.

- • $(Fe^{2+})_2SiO_4$+ 1/2 O_2+ 5 H_2O -> 2 $Fe^{3+}(OH)3$ + H4SiO4
- • 4 FeS2+ 15 O2 + 8 H2O -> 2 Fe2O3+ 8 H2SO4

Soluble constituents	Na+, Ca^{2+}, K+, Mg^{2+}, H_4SiO_4, HCO_3-, SO_4^{2-}, Cl^-
Residual minerals	quartz, zircon, magnétite, ilménite, rutile, grenat, sphène, tourmaline, monazite
Neoformed minerals	kaolinite, montmorillonite, illite, chlorite, hématite, goethite, gibbsite, boehmite, diaspore, silice amorphe, pyrolusite
Organic constituents	organic acids, humic acids, kerogen

• **Decarbonation**

It produces the solubilization of limestones and dolomites generally under the action of CO2 dissolved in water:

$Ca CO_3 + CO_2 + H_2O$ -------> $Ca (CO_3 H)_2$ soluble

Example of The alteration of igneous rocks

These rocks are in thermodynamic disequilibrium when they reach the outcrop. They are generally polymineral rocks and their sensitivity to alteration is a function of both the alterability of the different minerals and the structure of the rock. With equal sensitivity of the minerals, coarse-grained rocks (pegmatites) are more vulnerable than fine-grained rocks (aplites).

8.3.3. Resistance of a mineral to alteration

The binding energy varies according to the type of ions concerned. K+ is weakly bound to oxygen, Fe++ and Mg++ are moderately bound; Si 4+ on the contrary establishes very strong bonds. It is thus understood that quartz, a tectosilicate containing only strong bonds between silicon and oxygen, resists alteration better; olivine on the other hand, containing less bound cations (Fe^{++} and Mg^{++}) has a more fragile crystal lattice.

GOLDICH (1938) established the order of resistance of minerals to alteration:

Labile olivine..plagioclases Ca
augite ....plagioclases Ca-Na
hornblende ....plagioclases Na-Ca
biotite ....plagioclases Na
feldspaths K
muscovite
Résistant ....quartz

We note that this order evokes the BOWEN sequences The alterability of the minerals constituting magmatic rocks is inversely related to their order of crystallization in magmas. This is not by chance. In a magma, olivine crystallizes at high temperature, it is therefore particularly unstable in surface conditions; it is the most labile. Quartz, on the other hand, is formed at a lower temperature, it is more stable. Orthoclase is not very alterable, while plagioclases are more so. Within plagioclases, sensitivity to alteration increases from albite to anorthite.

The type of crystal lattice plays a role in the stability of the mineral on the surface. Phyllosilicates, such as muscovite, are more resistant to alteration.

Work has made it possible to evaluate the hydrolysis rate of a silicate mineral by measuring the rate of release of silica from the mineral into the environment. This rate is a function of the mineral's contact surface, the pH and a release rate constant "k" specific to the mineral which is measured in mole/m2/year; here are some values of k:

anorthite : 1,76 10^{-1} Feldspath K : 5,26 10^{-5}

néphéline : 8,83 10-2 olivine : 3,78 10-5

Enstatite : 3,15 10^{-3} muscovite : 8,09 10^{-6}

albite : 3,75 10^{-4} quartz : 1,29 10^{-7}

• We see that we go from a factor of 10-1 (anorthite) to a factor of 10-7 (quartz). We find more or less the order established by GOLDICH.

8.3.4. Minerals formed

Phyllosilicates

The new minerals formed are generally phyllosilicates. These minerals come either from the transformation of a pre-existing phyllosilicate, or from a neoformation from a non-sheet silicate whose structure is completely destroyed. The reactions take place mainly in the soil.

The phyllosilicates formed are clay minerals of two types:

* type 1/1: the sheet has 1 layer with SiO 4 tetrahedra and 1 layer with AlO6 octahedra

* type 2/1: the sheet has 3 layers, namely 1 octahedral layer between 2 tetrahedral layers.

Correlatively, the inter-reticular distance, which separates the clay sheets, changes and goes from 10 A° (muscovite, illite) to 14 A° (smectite) or to 7 A° (kaolinite). The K+ ions ensure the cohesion of the clay sheets. The alteration is manifested by the exfoliation of the sheets, clearly visible under the electron microscope, which produces particles of smaller size, a few 0.1 microns, and increases the contact surface of the mineral and the exchange capacity of the cations with the solutions of the environment.

* **Biotite**

Its resistance to alteration depends on the content of Fe++ in the crystal; its state of alteration is expressed by the quantity of K+ extracted from the network. Little oxidized biotite (especially with Fe++) is very alterable and behaves like other ferro-magnesian minerals (pyroxenes...); it gives in particular vermiculites and smectites and ferric oxide which precipitates. The more oxidized biotite (Fe+++ especially) is more stable.

* **Other ferromagnesians**

Their alteration is similar to that of the little oxidized biotite; they give vermiculites, smectites, chlorites or magnesian clays if the medium is very confined

.4.4. **Complexolysis**

This is a variant of hydrolysis in the presence of organic matter. It occurs in cold (boreal) and temperate climates. The organic compounds of humus extract the metal cations from the crystal lattices. The minerals are destroyed; the cations are fixed on the organic compounds, giving organometallic complexes. The cations binding to the large organic molecules of humus are mainly the ions Al 3+, Fe 2+ and Fe 3+.

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