# 6. Igneous rocks

Igneous rocks form whenever molten rock cools and minerals crystallize to produce a solid rock. Therefore, the prerequisite for the formation of igneous rocks is the melting of rocks. Molten rock is called ***magma*** if it occurs within the lithosphere and is called ***lava*** when the molten rock is extruded on Earth's surface through volcanic activity.

*Where does magma form?*

Magma forms whenever the conditions of pressure and temperature cause a solid rock to start melting. This happens primarily in three major geological settings: (1) mid-ocean ridges, (2) subduction zones, and (3) hotspots. Details about the melting process in these three settings are presented in section 6.2 of this chapter.

## 6.1. Classification of igneous rocks

Igneous rocks are classified according to their texture (coarse-grained vs. fine-grained) and their chemical and mineralogical compositions. The texture and chemical or mineralogical compositions of an igneous rock can give us information on where and how the rock formed.

### *6.1.1. Classification based on rock texture*

***Extrusive igneous rocks***

These rocks derive from the relatively rapid cooling of a magma/lava on or very near the Earth's surface. The rapid cooling is due to the great difference in temperature between the hot molten rock and the relatively cool surrounding environment. These rocks are ***fine-grained*** since minerals crystallize too rapidly to form large crystals. A common example of an extrusive igneous rock is ***basalt***. Basalt is a major component of the oceanic crust and produced in great abundance at mid-ocean ridges.

The extremely fast cooling of a lava extruded on Earth's surface results in the production of ***volcanic glass***, in which atoms do not have time to arrange themselves into a regular crystal lattice (amorphous solid).

When lava is ejected out of a volcano, pieces of lava cool and solidify in the air. The pieces of igneous rocks then fall on the ground by gravity. These pieces of igneous rocks are called ***pyroclasts***. They may have various sizes, from volcanic ***ash*** (<2 mm) to large volcanic ***bombs*** (>6.4 cm). Pieces of intermediate size are called ***pumice***. Explosive volcanic eruptions are sometimes characterized by a sudden and massive release of a dense mixture of extremely hot gas and ash rushing down the volcano's flank at very high speed. This is called a ***pyroclastic flow***. Pyroclastic flows represent a major hazard for anyone being in the vicinity of the volcano when it erupts.

***Intrusive igneous rocks***

These rocks derive from the relatively slow cooling of magma within the Earth's lithosphere. The slow cooling enables minerals to form relatively large crystals. The texture of these rocks is ***coarse-grained***. An example of an intrusive igneous rock is ***granite***. Granite is a major component of the continental crust.

Igneous rocks may sometimes consist of a combination of fine-grained and coarse-grained textures which tells us something interesting about their history. ***Porphyry*** is the name given to an igneous rock composed of large crystals (or phenocrysts) "floating" in a fine-grained matrix. This particular texture indicates that the rock started to cool slowly at some depth beneath the surface, producing large crystals, and then began to cool faster as it approached the surface, forming tiny crystals out of the remaining melt.

*6.1.2. Classification based on chemical and mineralogical compositions*

Igneous rocks enriched in silica ($SiO_2$) and silicates rich in Al, K, and Na (e.g., feldspar) are called ***felsic*** (from feldspar and silica). These rocks are characteristic of the continental crust (e.g. ***granite***, Fig. 1)

Igneous rocks with a high proportion of silicates rich in Mg and Fe (e.g., olivine) are called ***mafic*** (from magnesium and ferric). These rocks are particularly abundant in the oceanic crust (e.g. ***basalt***, Fig. 1).

Igneous rocks composed almost exclusively of silicates of Mg and Fe (e.g., olivine, $(Mg, Fe)_2SiO_4$) are called ***ultramafic***. The ultramafic rock ***Peridotite*** is composed mostly of olivine and pyroxene* and is believed to be a major constituent of the Earth's upper mantle (Fig. 1).

Felsic and ultramafic rocks are the two end-members of a continuum of compositions. Igneous rocks may be more or less felsic, more or less mafic depending on how they formed. Igneous rocks with different chemical and mineralogical compositions have different physical properties. Felsic igneous rocks tend to be lighter than mafic igneous rocks. Felsic rocks have a lower density and start melting at a lower temperature. Magma with a felsic composition is more viscous than magma with a mafic composition (Fig. 1).

Note that the name given to igneous rocks (granite, basalt…) depends on both texture and composition. For instance, the name of a coarse-grained intrusive igneous rock with a felsic composition is ***granite***, whereas the name of the fine-grained extrusive rock with a similar mineralogical composition is ***rhyolite***. Also, ***basalt*** is the name given to a fine-grained extrusive igneous rock with a mafic composition, but the intrusive equivalent is called ***gabbro*** (Fig. 1).

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* Pyroxene is a silicate mineral formed of single chains of silicate tetrahedra. The pyroxene commonly occurring in peridotite is $(Mg, Fe)SiO_3$. The mineral with the formula $MgSiO_3$ is called enstatite. The mineral with the formula $FeSiO_3$ is called ferrosilite.

The figure below summarizes the main characteristics of extrusive and intrusive igneous rocks.

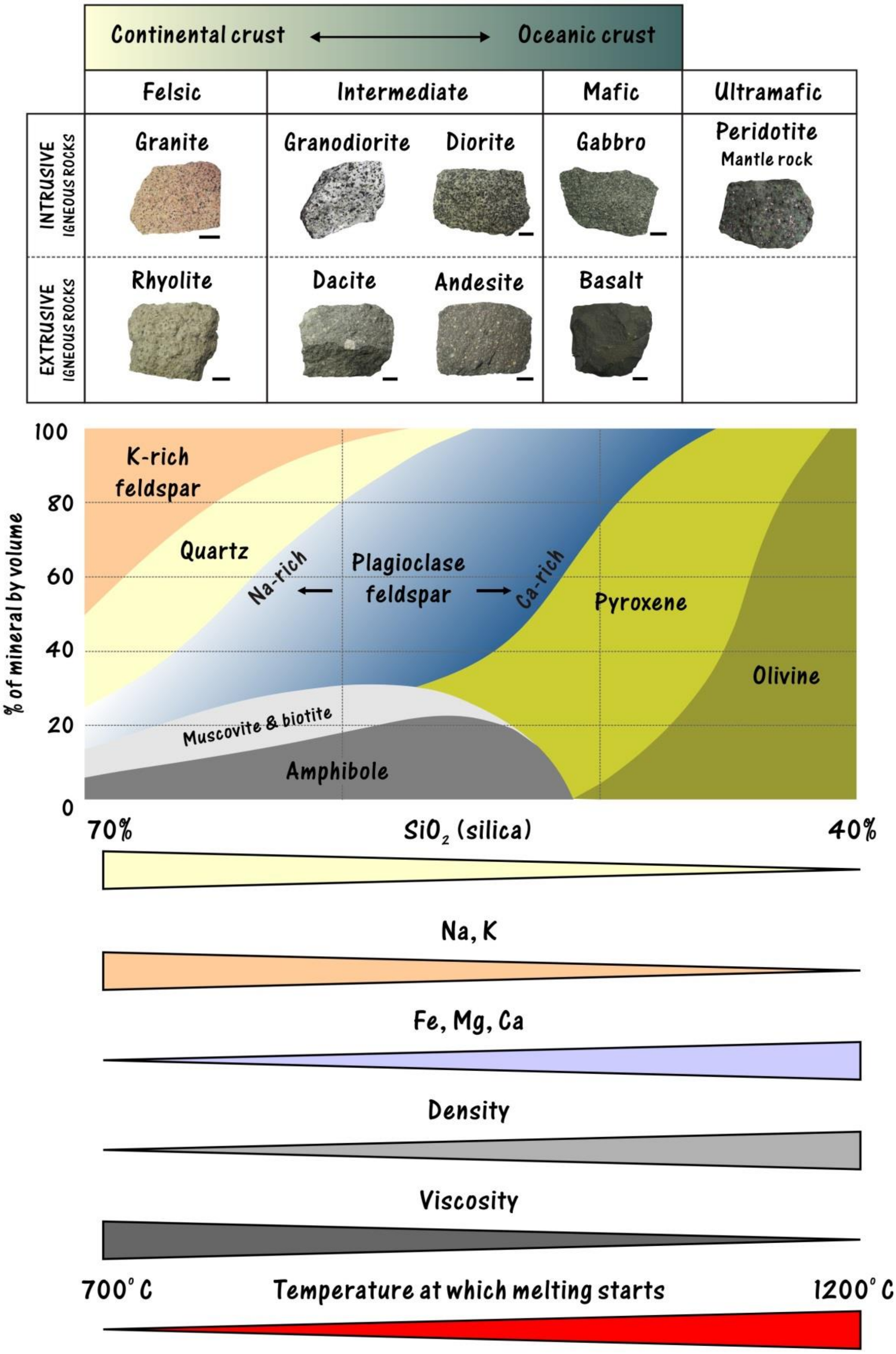


**Figure 1**: Classification model of igneous rocks. Igneous rocks are classified according to their mineralogical and chemical compositions, which is illustrated by the graph showing the proportion of certain minerals in the rocks (expressed as a % of rock volume) as a function of the silica content (expressed as a % of rock weight). The upper part of the figure shows images of rocks samples. Note the difference of color between felsic (lighter) and mafic (darker) rocks. Source: modified from Understanding Earth 6th edition, Boston, Bedford, (rock images: Imperial College Rock Library, except granodiorite: US National Park Service website, and peridotite: Wikipedia).

## 6.2. Processes of magma formation

### *6.2.1 Heat and pressure*

Temperature increases with depth. This is called the ***geothermal gradient***. On average the geothermal gradient in the Earth's crust is 30°C/km. As depth increases, pressure increases too, which prevents rocks from melting. In "normal" conditions, rocks of the crust and mantle cannot melt extensively*. At ***mid-ocean ridges*** however, where hot mantle rock rises to the surface, the geothermal gradient increases sharply and ***partial melting*** occurs at relatively shallow depth where the pressure becomes too low to maintain the whole rock at the solid state. The resulting melt is the source of the new oceanic crust generated at mid-ocean ridges (see section 6.4). Since pressure drop plays such a crucial role in the melting process, it is called ***decompression melting***. Decompression melting occurs also beneath ***hotspots*** (e.g. Hawaii) where a mantle plume rises toward the surface. In this setting, the source of the plume may be as deep as the boundary between the mantle and the outer core, and therefore the rising mantle rock is even hotter than beneath mid-ocean ridges.

### *6.2.2. Influence of water*

Besides mid-ocean ridges and hotspots, another geological setting where abundant magma is produced is the subduction zone. In subduction zones, an oceanic plate is sliding beneath another plate –oceanic or continental– and plunges into the mantle. The subducting oceanic plate is relatively cold in comparison with the surrounding rocks. What is causing rock melting in this case? The answer is: water. The process of magma formation in subduction zones is called ***water-induced melting***. The subducting oceanic plate carries a lot of sediments and sedimentary rocks with relatively high water content. Water is present in the open space between sediment grains (pore space) and in the crystal lattice of clay minerals. The electric polarity of water molecules disrupt chemical bonds and lower the melting temperature of rocks.

### *6.2.3. Magma composition and style of volcanism*

The composition of the rock from which magma is initially derived (***parent rock***) is important in determining magma composition. The magma may gain new components by melting the surrounding rocks during its ascension toward Earth's surface. Magma composition also depends on temperature because different minerals melt at different temperatures (Fig. 1).

An important property of magma is its ***viscosity***. A magma that is more viscous has more chance to remain stuck in the volcano's vent. The pressure building up under this natural "cork" is particularly dangerous and may result in a violent explosive volcanic eruption.

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* No melt is normally allowed except probably a tiny fraction in the upper asthenosphere (up to 1% of the rock volume only) directly below the moving tectonic plates.

The viscosity of magma is proportional to its silica content* and inversely proportional to its temperature (the cooler, the more viscous). The most violent volcanic eruptions are related to magmas that are both viscous and rich in volatiles (water, $CO_2$…). A volatile-rich, highly viscous magma is much more likely to give rise to an explosive eruption. A magma nearing the surface behaves like a soda drink when you unscrew the bottle cap. The volatiles contained in the magma form gas bubbles which expand due to the pressure drop. Decreasing the amount of volatiles dissolved in the magma make it also more viscous. A volatile-rich, highly viscous magma is likely to give rise to an explosive eruption due to the pressure that progressively builds up in the chimney and is suddenly released in the form of a violent explosion.

Hawaii is an oceanic hotspot where magma is derived from mantle rock. The magma has a mafic composition and therefore contains little silica. Moreover, it is particularly hot because the parent rock originates from very deep in the mantle. As a result, Hawaiian volcanoes are characterized by a low-viscosity lava that can easily flow out and spread over large areas, forming so-called ***shield volcanoes*** (volcanoes with low-angle flanks). The risk of explosive eruptions in Hawaii is relatively low. Conversely, in continental hotspots (e.g. Yellowstone), continental rifts (e.g. East African Rift) and ocean-continent subduction zones (e.g. Japan), the magma may become more felsic as it penetrates the continental crust and melts the surrounding rocks. Felsic magma is highly viscous because it contains a lot more silica. The magma may also become enriched in volatiles derived from the transformation of sedimentary rocks carried by the subducting plate at high pressure and high temperature (e.g. $CaCO_3 + SiO_2$ à $CaSiO_3 + CO_2$). Consequently, the risk of explosive volcanic eruptions in these settings is much greater.

*6.2.4. Magma chambers*

Magma has a lower density than the surrounding solid rock and therefore tends to migrate slowly toward the surface. It rises through cracks and by melting its way up. Magma tends to accumulate in regions of the crust called ***magma chambers***. During its ascent, the magma composition may change by mixing with other magmas or by melting surrounding rocks.

## 6.2. Magma crystallization and the formation of igneous rocks

The process by which magma composition is modified during crystallization is called ***magmatic differentiation***. Magmatic differentiation can lead to the formation of various igneous rocks from a single initial melt through the following processes:

(1) Different minerals crystallize at different temperatures. The order at which minerals crystallize has been determined experimentally (see related slide showing the Bowen's reaction series).
(2) In a cooling magma, minerals crystallizing first tend to settle down first. This is called ***crystal fractionation***. The crystal settling rate does not only depend on the timing of crystallization but

* Silica tetrahedra ($[SiO_4]^{4-}$) tend to form chains which greatly increase the viscosity of the magma. Therefore, more felsic magmas are more viscous.

also on the density and size of crystals and the viscosity of the remaining magma.

The result of magmatic differentiation is that a cooling magma may produce a succession of igneous rocks whose chemical compositions vary from relatively more mafic to relatively more felsic.

Besides magmatic differentiation, other factors should be accounted for in order to explain the diversity and abundance of igneous rocks. Two of these factors are:

*(1) Variability in parent magma composition*

At mid-ocean ridges and oceanic hotspots, the initial parent magma is derived from the melting of mantle rock and its composition is mafic (i.e. basaltic).

In subduction zones, the initial parent magma is derived from the melting of the oceanic crust (including various sedimentary rocks) and mantle rock. Its composition is mafic to intermediate (i.e. andesitic).

In the case of continental rifts, continental hotspots, and ocean-continent subduction zones in which continental crust is involved, magma may become more felsic as it penetrates the continental crust and melt surrounding rocks.

*(2) Mixing of different magmas*

Magmas that can mix with each other are said to be miscible. Crystallization of a magma resulting from the mixing of two miscible magmas produces rocks whose chemical compositions differ from those which would have been produced if each magmas had crystallized separately. Some magmas however cannot mix and are called immiscible.

## 6.3. Forms of igneous intrusions

The path taken by the magma from its source to the surface can result in the formation of different geological structures described in figure 2.

## 6.4. Formation of new oceanic crust at mid-ocean ridges

The asthenosphere is convecting and asthenospheric mantle rocks rise slowly toward the surface beneath mid-ocean ridges. The ascending hot mantle rock is composed of peridotite (olivine and lesser pyroxene and garnet). Decompression melting of the peridotite occurs at shallow depth. Up to 15% of the rock volume can melt. Magma accumulates in a magma chamber beneath the mid-ocean ridge. Since pyroxene and garnet melt first, the composition of the resulting partial melt is not peridotitic but basaltic. The remaining solid, which has not melted, is enriched in olivine and forms a layer of ultramafic peridotite at the base of the oceanic crust. Part of the basaltic magma cools slowly in the magma chamber to form a layer of gabbro overlying the ultramafic peridotite. The remaining basaltic magma rises to the surface and solidifies quickly near or on the seafloor to form a layer of basalt. As the two plates are pulled apart, the oceanic crust grows laterally by successive intrusions of basaltic magma which produce numerous dykes (see related slide for an illustration of the process of oceanic crust formation at mid-ocean ridges).

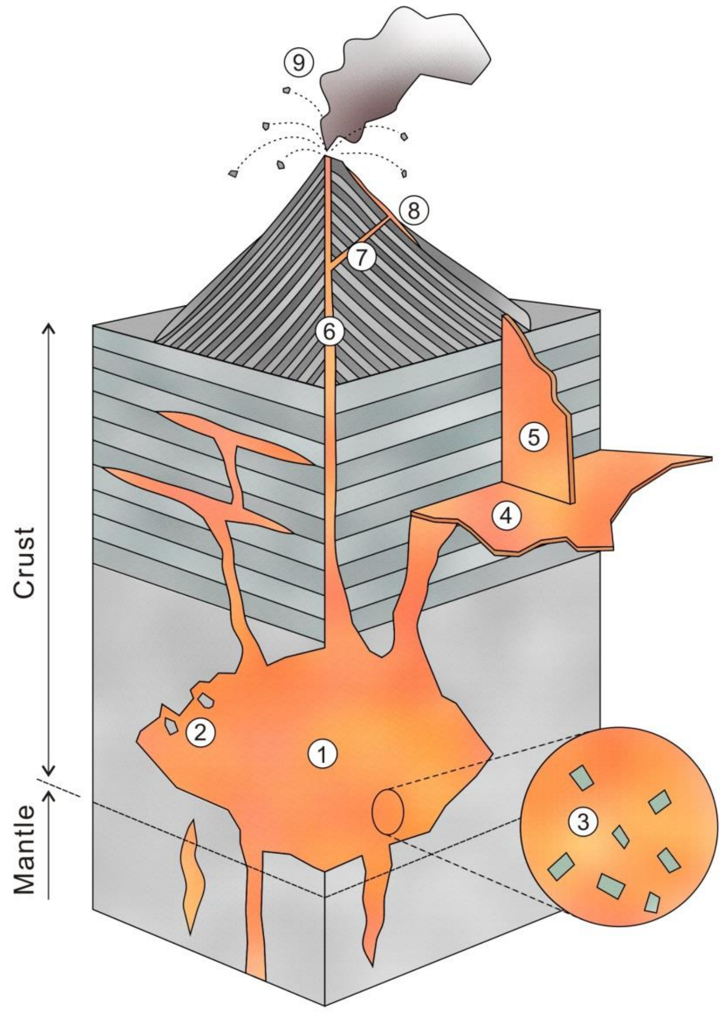


**Figure 2**: Cross section of a portion of the lithosphere through which magma is rising to the surface. Magma typically accumulates in the crust in large ***magma chambers*** (1). Pieces of surrounding rocks can be incorporated in the magma and change its chemical composition (2). The magma may start to crystallize upon cooling which also change the chemical composition of the remaining melt (3). Some of the magma leaves the chamber through fractures and may form large sheets, either parallel to rock layers －***sill***－ (4) or intersecting rock layers －***dyke***－ (5). A volcano is composed of a ***central vent*** (6) which may branch off and form a ***side vent*** (7). Lava is ejected from the vents and form ***lava flows*** (8). Other materials which may be ejected from vents are ***pyroclasts*** (ashes, volcanic bombs…) and gas (9). Source: modified from Understanding Earth 6th edition, Boston, Bedford,