As a *mafic* magma starts to cool, some of the silica combines with iron and magnesium to make olivine. As it cools further, much of the remaining silica goes into calcium-rich plagioclase, and any silica left may be used to convert some of the olivine to pyroxene. Soon after that, all of the magma is used up and no further changes take place. The minerals present will be olivine, pyroxene, and calcium-rich plagioclase. If the magma cools slowly underground, the product will be **gabbro**; if it cools quickly at the surface, the product will be **basalt** (Figure 1).

*Felsic* magmas tend to be cooler than mafic magmas when crystallization begins (because they don't have to be as hot to remain liquid), and so they may start out crystallizing pyroxene (not olivine) and plagioclase. As cooling continues, the various reactions on the discontinuous branch will proceed because silica is abundant, the plagioclase will become increasingly sodium-rich, and eventually potassium feldspar and quartz will form. Commonly even very felsic rocks will not have biotite or muscovite because they may not have enough aluminum or enough hydrogen to make the OH complexes that are necessary for mica minerals. Typical felsic rocks are **granite** and **rhyolite** (Figure 1).

The cooling behaviour of intermediate magmas lie somewhere between those of mafic and felsic magmas. Typical intermediate rocks are **diorite** and **andesite** (Figure 1).

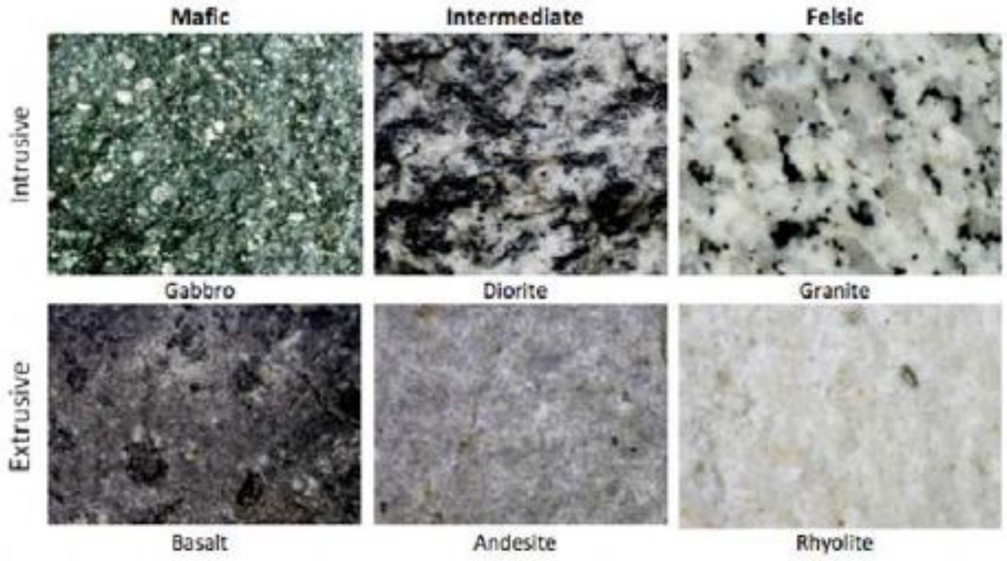


**Figure 1** *Examples of the igneous rocks that form from mafic, intermediate, and felsic* ***magmas***

A number of processes that take place within a magma chamber can affect the types of rocks produced in the end. If the magma has a low viscosity (i.e., it's runny) — which is likely if it is mafic — the crystals that form early, such as olivine (Figure 2a), may slowly settle toward the bottom of the magma chamber (Figure 2b). The means that the overall composition of the magma near the top of the magma chamber will become more felsic, as it is losing some iron- and magnesium-rich components. This process is known as **fractional crystallization**. The crystals that settle might either Form an olivine-rich layer near the bottom of the magma chamber, or they might remelt because the lower part is likely to be hotter than the upper part (remember, from Chapter 1, that temperatures increase steadily with depth in Earth because of the geothermal gradient). If any melting takes place, crystal settling will make the magma at the bottom of the chamber more mafic than it was to begin with (Figure 2c).

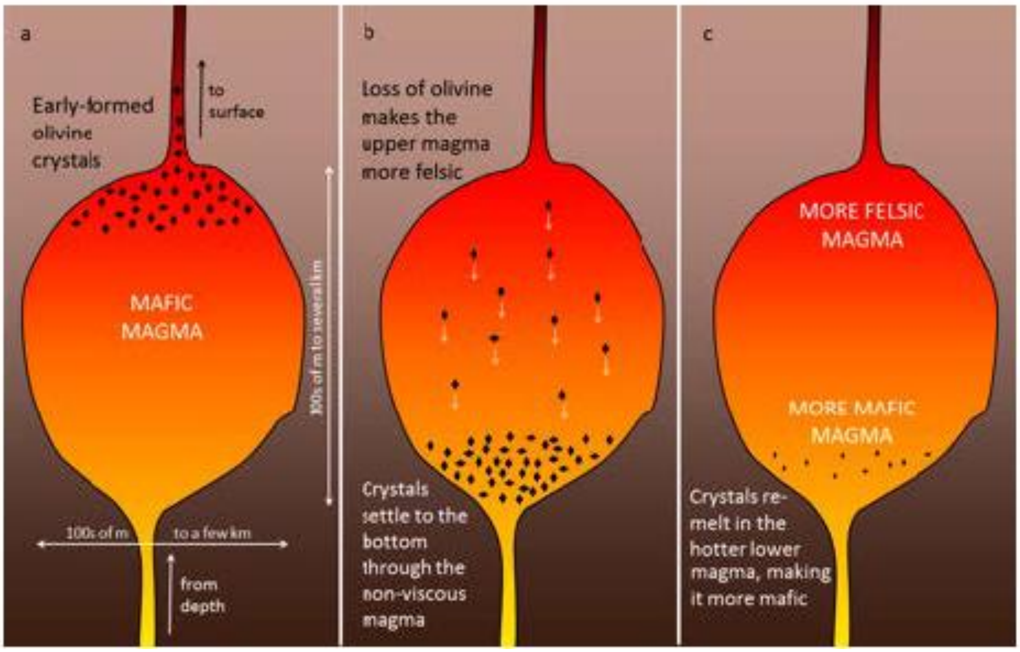


**Figure 2** ***an example of crystal settling and the formation of a zoned magma chamber***

If crystal settling does not take place, because the magma is too viscous, then the process of cooling will continue as predicted by the Bowen reaction series. In some cases, however, partially cooled but still liquid magma, with crystals in it, will either move farther up into a cooler part of the crust, or all the way to the surface during a volcanic eruption. In either of these situations, the magma that has moved toward the surface is likely to cool much faster than it did within the magma chamber, and the rest of the rock will have a finer crystalline texture. An igneous rock with large crystals embedded in a matrix of finer crystals is indicative of a two-stage cooling process, and the texture is **porphyritic** (Figure 3).

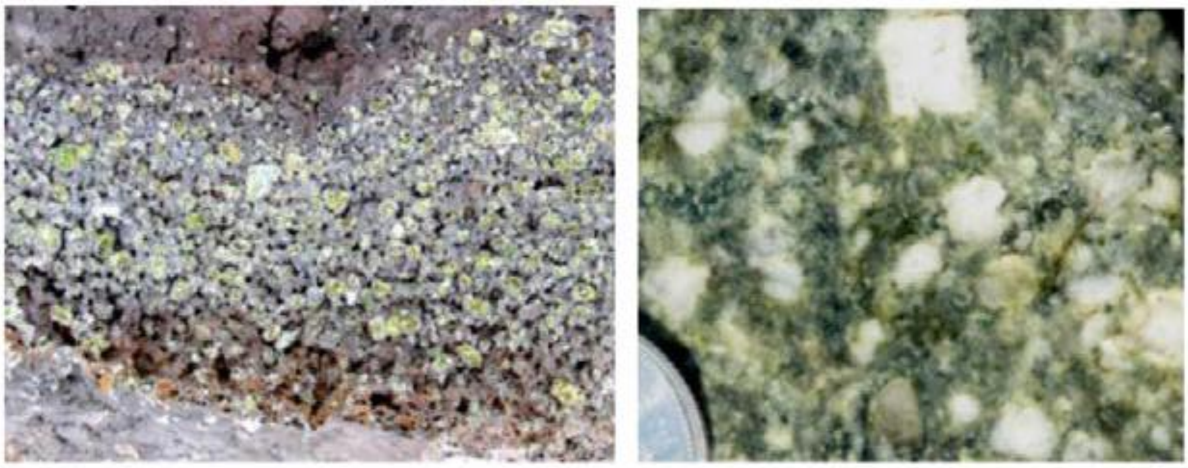

Figure 3 *Porphyritic textures: volcanic porphyry (left – olivine crystals in Hawaiian basalt)* ***and intrusive porphyry (right)***

## Classification of Igneous Rocks

As has already been described, igneous rocks are classified into four categories, based on either their chemistry or their mineral composition: felsic, intermediate, mafic, and ultramafic. The diagram in Figure 4 can be used to help classify

Igneous rocks by their mineral composition. An important feature to note on this diagram is the red line separating the non-ferromagnesian silicates in the lower left (K-feldspar, quartz, and plagioclase feldspar) from the ferromagnesian silicates in the upper right (biotite, amphibole, pyroxene, and olivine). In classifying intrusive igneous rocks, the first thing to consider is the percentage of ferromagnesian silicates. That's relatively easy in most igneous rocks because the ferromagnesian minerals are clearly darker than the others. At the same time, it's quite difficult to estimate the proportions of minerals in a rock.

Based on the position of the red line in Figure 4, it is evident that felsic rocks can have about 1% to 20% ferromagnesian silicates (the red line intersects the left side of the felsic zone 1% of the distance from the top of the diagram, and it intersects the right side of the felsic zone 20% of the distance from the top). Intermediate rocks have between 20% and 50% ferromagnesian silicates, and mafic rocks have 50% to 100% ferromagnesian silicates. To be more specific, felsic rocks typically have biotite and/or amphibole; intermediate rocks have amphibole and, in some cases, pyroxene; and mafic rocks have pyroxene and, in some cases, olivine.

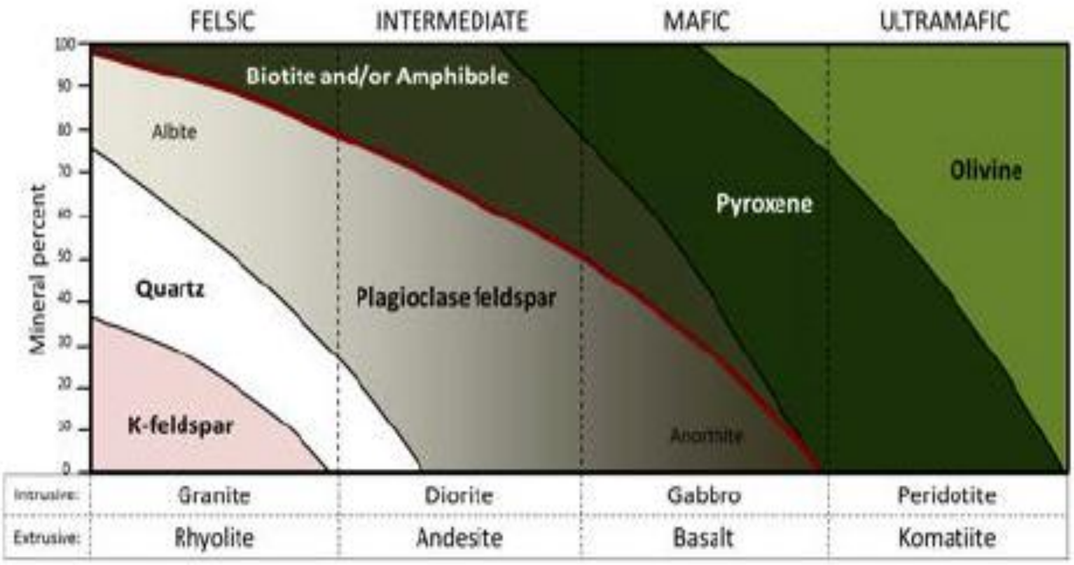


Figure 4 *A simplified classification diagram for igneous rocks based on their mineral* ***compositions***

If we focus on the non-ferromagnesian silicates, it is evident that felsic rocks can have from 0% to 35% K-feldspar, from 25% to 35% quartz (the vertical thickness of the quartz field varies from 25% to 35%), and from 25% to 50% plagioclase (and that plagioclase will be sodium-rich, or albitic). Intermediate rocks can have up to 25% quartz and 50% to 75% plagioclase. Mafic rocks only have plagioclase (up to 50%), and that plagioclase will be calcium-rich, or anorthitic.

Igneous rocks are also classified according to their textures. The textures of volcanic rocks will be discussed in the next chapter, so here we'll only look at the different textures of intrusive igneous rocks. Almost all intrusive igneous rocks have crystals that are large enough to see with the naked eye, and we use the term **phaneritic** (from the Greek word *phaneros* meaning visible) to describe that. Typically that means they are larger than about 0.5 mm — the thickness of a strong line made with a ballpoint pen. (If the crystals are too small to distinguish, which is typical of most volcanic rocks, we use the term **aphanitic**.) The intrusive rocks shown in Figure 1 are all phaneritic.

In general, the size of crystals is proportional to the rate of cooling. The longer it takes for a body of magma to cool, the larger the crystals will be. It is not uncommon to see an intrusive igneous rock with crystals up to a centimeter long. In some situations, especially toward the end of the cooling stage, the magma can become water rich. The presence of liquid water (still liquid at high temperatures because it is under pressure) promotes the relatively easy movement of ions, and this allows crystals to grow large, sometimes to several centimetres (Figure 5). As already described, if an igneous rock goes through a two-stage cooling process, its texture will be porphyritic (Figure 3).


**Figure 5** *A pegmatite with mica, quartz, and tourmaline (black) from the White Elephant* ***mine, South Dakota***