Minerals explained II—More rock forming silicates

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Overview

In part I of the *Minerals Explained* online release we discussed and described, in detail, the most common rock forming silicate minerals (i.e. quartz, plagioclase and alkali-feldspars) as well as an unusual but associated mineraloid (i.e. opal). The silicates are by far the most important minerals in the Earth's crust, accounting for around 90% of the total. However, this should hardly be a surprise when you consider that as much as 85% of the crust is a mixture of the elements silicon and oxygen. While pure SiO_2 (in the form of quartz), is the most common mineral at Earth's surface, it is not the case at depth in the crust and shallow mantle, an honour reserved for olivine (Mg, Fe)SiO_2 (Fig. 1A, B). As indicated in the first release, many individual minerals are often grouped together under a generic name (i.e. plagioclase feldspars, olivines, amphiboles, micas) based upon specific characteristics shared by the mineral grouping. For example the plagioclase feldspars (*Minerals explained I*) all share similar atomic structures, crystal form and basic chemistry but what defines individual minerals within the group is the specific range of sodium and calcium contents of the minerals (ranging from the end members albite to anorthite).

The minerals discussed in this second release are still silicates; however, the minerals discussed are, on the whole, less common (in terms of their *overall* abundance) and show greater complexity in either their chemical compositions or formation conditions. The olivine, garnet and aluminosilicate (kyanite is an Al_2SiO_5 member) groups (Fig. 1A,B; Fig. 2A, B) are all orthosilicate (also known as neosilicate) minerals; the mica group (Fig. 3A), are phyllosilicates (better known as sheet silicates); and the amphibole group (Fig. 3B) are insolicates (also known as chain silicates). These differences (neo-, phyllo- and iso-) relate to the position and relationship of silicate tetrahedra to the surrounding elements forming the mineral. Thus, neosilicates consist of isolated SiO_4 tetrahedra, linked via interstitial cations; phyllosilicates consist of parallel sheets of Si_2O_5 tetrahedra; and inosilicates consist of interlocking chains of silicate tetrahedral (SiO_3 for single chains and Si_4O_{11} for double chains). The mica group of phyllosilicates, including muscovite ($KAl_2(AlSi_3O_{10})(F,OH)_2$ and biotite ($K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$), are probably best known in this selection for their characteristic perfect basal cleavage which give rise to thin-lamellae like mineral sheets.

Ampbiboles, micas and olivines are all primarily associated with igneous rocks (Fig. 4), although they can be found to variable extents in the other rock types. Olivines dominate the ultramafic and mafic end of the igneous scale (i.e. rhyolites, granites) while amphiboles and micas dominate the felsic end of the scale (i.e. gabbros and basalts). In contrast, both kyanite (Al_2SiO_5) and the garnet group are metamorphic minerals, formed at high pressures and temperatures in Earth's crust (Fig. 5). The formation of these minerals, at depth, is restricted to specific ranges of pressure (P) and temperature (T), as well as chemical constraints. For example, a pure sandstone (e.g. pure SiO_2) buried alone without Al, Fe, Mg elements present will not create garnet, even if buried to the correct depth. This is because garnet has the generic formula $X_3Y_2(SiO_4)_3$ meaning that not only is Si and O required for it to form, but also some of either Mg, Fe, Al, Ca or Cr (the exact chemistry available will dictate the type of garnet mineral that grows).

Mineral details

The olivine group has the chemical formula (Mg, Fe)$_2SiO_4$ and contains two end-member minerals, which are a solid solution series between Mg (forsterite) and Fe (fayalite). Olivine, when of gem-quality, may also be referred to as peridot (Fig. 6A), which, while containing both Mg and Fe, is far more magnesium rich. Peridot will only ever be found as a green colour, although the percentage of Fe present in the lattice gives rise to a whole array of greenish tints from yellowish-green at one end of the scale through to brownish-green at the other. Unless you are an expert it is very easy to confuse cut peridot gemstones with emeralds (the gem variety of the mineral beryl), which are very similar to be almost indistinguishable (Fig. 6B). Forsterite is the most stable variety of the olivines and can be found at depths of over 400 km within the Earth, below the crust and into the mantle. At these conditions the dominant mineralogy of the mantle is olivine, pyroxene, spinel and garnet. At deeper levels, between ~400–650 km within Earth, these minerals all start to become unstable such that by 650 km none are present and the dominant mineral (in the simplest terms) is perovskite. Olivine, while stable to considerable depths within Earth, is generally unstable at Earth's surface and readily breaks down to a mixture of clay minerals, Fe oxides and oxyhdroxides with water.

Did you know olivine is so common on Hawaii, due to the volcanic nature of the islands, that a number of the beaches consist entirely of rich-green olivine sands?

The amphibole group of minerals consists of a number of distinct series that can either be separated out due to differing crystal structures (i.e. orthorhombic and monoclinic series) or by differing chemical compositions (i.e. cummingtonite, tremolite, sodium-amphibole series). Suffice to say the amphibole group contains a large number of individual minerals with a wide range in chemical composition and a tremendous range of properties.

One of the most well know amphibole varieties, especially to students of geology, is hornblende ($Ca_2(Mg, Fe, Al)_5$ $(Al, Si)_8O_{22}(OH)_2$) a mineral common both in igneous rocks and also as the primary constituent of the metamorphic rock amphibolite (Fig. 7A). The tremolite series consists primarily of tremolite ($Ca_2Mg_5Si_8O_{22}(OH)_2$) and actinolite ($Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$); though a number of other varieties exist including nephrite, one of the two minerals of the gemstone jade (Fig. 7B). Where tremolite occurs in a fibrous form, it is considered to be one of the six asbestos minerals and is regulated in most countries in the world. As well as tremolite another four amphibole minerals are considered to be asbestos minerals: amosite (brown asbestos), crocidolite (blue asbestos), actinolite and anthophyllite (Fig. 8A, B). Glaucophane is an unusually Na-rich amphibole mineral that is noted for its rich blue colour and also its origin in suduction zones (relatively low temperature but high pressures) in Earth's crust.

Did you know that the semi-precious stone known as jade can in-fact be used to describe two different minerals: Nephrite, a Mg-Fe-rich tremolite and jadeite a Na-Fe-rich pyroxene? The fact that two minerals were being classed as jade was not discovered until the nineteenth century!

The mica minerals are all phyllosilicates, which are renowned for their perfect basal cleavage, a very distinctive property. The micas include the well known: muscovite ($KAl_2(AlSi_3)O_{10}(OH)_2$), biotite ($K(Mg,Fe)_3(AlSi_3)O_{10}(OH)_2$) and phlogopite ($KMg_3(AlSi_3)O_{10}(OH)_2$) as well as perhaps less well known glauconite, lepidolite, and a number of others. All of the mica group minerals are monoclinic and can be found in all three major rock groups (igneous, metamorphic, sedimentary) but are most prominent when generated in granite pegmatites. Muscovite, also known as white mica, tends to be colourless, though tinted varieties in a range of hues are possible. It is by far the most common mica mineral (Fig. 9A), often found in granitic igneous rocks and also metamorphic schists and gneisses. Biotite (Fig. 9B), also known as black mica, is Fe-rich and tends to appear greenish to brown/black in colour—though where heavily weathered it can appear much lighter.

As with muscovite, biotite is a common constituent of both igneous and metamorphic rocks and the two minerals will often occur together. They can easily be distinguished from one another under the microscope due to biotite's pleochroic nature in plane polarized light, and quite often the presence of radiation haloes. Biotite is an important mineral for isotopic dating, specifically via K-Ar and Ar-Ar radiometric procedures. Phlogopite ($KMg_3(AlSi_3)O_{10}(OH)_2$) is a common mica and shares a solid-solution series with biotite, phlogopite being the magnesium end-member. This mica mineral is commonly found in both igneous and contact metamorphic rocks (including the contact metamorphic marbles of Iona, Scotland). Glauconite ($(K,Na)(Fe^{3+},Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$) is an Fe-K mica which is best known for its characteristic green colour and very low resistance to weathering. Glauconite is generally found in sedimentary rock types and is most well known for its occurrence in 'greensands'.

Did you know the largest documented single crystal of mica was found at the Lacey mine, Ontario, Canada? It measured 10 m × 4.3 m × 4.3 m and weighed ~330 tonnes!

The garnet group is probably one of the best-known mineral groupings, certainly to those who have at one point been students of geology, due to its distinctive characteristics and related assemblages. The garnet group contains six common series, as well as few rarer varieties with pyrope, almandine and spessarite forming one solid-solution (Mg, Fe and Mn varieties of $Al_2(SiO_4)_3$ respectively) and grossular, andradite and uvarovite forming a second solid solution (Al, Fe and Cr varieties of $Ca_3(SiO_4)_3$ respectively). All garnets are neosilicates and they can occur in virtually any colour, with exceptions within specific varieties. For example, the mineral pyrope ($Mg_3Al_2(SiO_4)_3$) is the only member of the group that has only one colour, red. Ironically, though pyrope (Fig. 10A), is probably one of the best known garnets, due to its distinctive red colour, and the fact that most gemstone-quality red garnets are pyrope, it is the least common. Pyrope is commonly found in ultra high-pressure metamorphic rocks as well as within the Earth's mantle, as the rock peridotite.

Almandine ($Fe_3Al_2(SiO_4)_3$) (Fig. 10B) is the Fe-rich end member of the first solid-solution series, and as greater proportions of Mg are substituted into the almandine lattice it tends towards pyrope. Almandine can occur in a variety of reds, oranges and purples, and like Pyrope can be of gemstone quality. Grossular ($Ca_3Al_2(SiO_4)_3$) (Fig. 11A) is an end-member of the second solid-solution of garnet varieties and can occur in a range of colour shades from red and yellow to brown and green, the latter being highly sought after as a gemstone. This type of garnet is most commonly found in contact metamorphic settings, predominantly marbles. Uravorite ($Ca_3Cr_2(SiO_4)_3$) (Fig. 11B) is the only chromium-rich garnet and as with pyrope is found only in one particular colour, in this case a range of greens. Uravorite is by far the rarest garnet mineral but is highly sought after as a gemstone. Unsurprisingly this garnet is commonly found associated with metamorphosed chromium ores metamorphism is essential to generate garnet and the ore is needed as a source of Cr!

Did you know garnets were used as bullets to fight the British in Kashmir in 1892 in the belief that garnets, due to their believed mystical nature, were deadlier than lead?

Kyanite is not a group of minerals but, rather an individual mineral that is a member of the aluminosilicates (Al_2SiO_5). The aluminosilicates are made up, in the simplest terms, of three minerals: kyanite, andalusite and sillimanite all of which are polymorphs that are stable at a specific range of conditions in Earth's crust (Fig. 5). All are metamorphic in origin, with kyanite the high pressure polymorph, sillimanite the high temperature polymorph, and andalusite falling between both. Kyanite generally indicates pressures greater than 4 kilobars in the formation of metamorphic rocks and although it can retain stability at pressures lower than this, it more commonly either transforms to andalusite or breaks down to minerals such as muscovite or kaolinite. Kyanite can occur in a range of colours but is probably best known for its characteristic, elongate, blue crystals commonly found in museums and mineral shops (Fig. 2B). Kyanite is of primary interest to geologists as a metamorphic index mineral, used (along with the total mineral assemblage of the rock) to define pressures and temperatures of metamorphism.

Did you know, that unlike most other minerals, kyanite has two hardnesses on Mohs scale, depending upon the direction of measurement? When tested lengthwise the hardness is 5–5.5 and when tested crosswise it is 7!

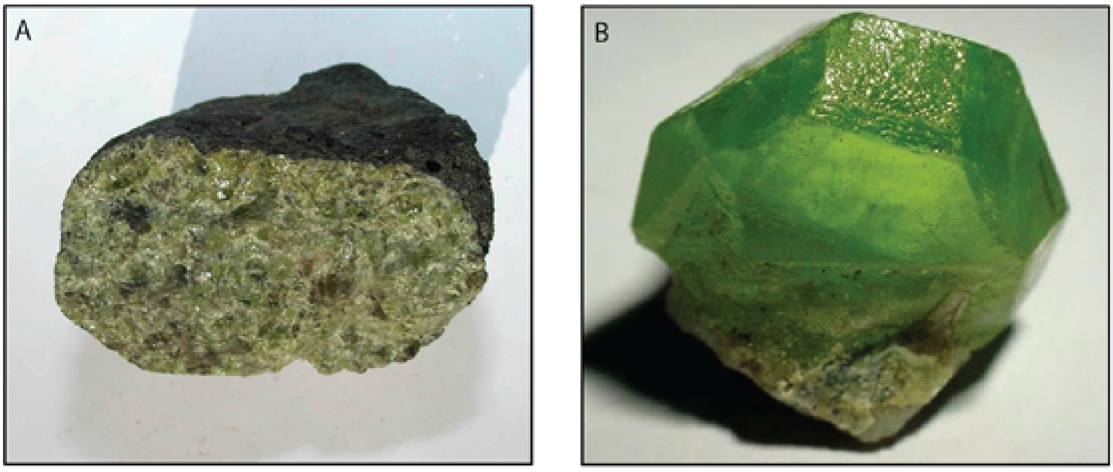

Fig. 1. A. Olivine rich gabbro showing coarse, interlocking crystals. **B.** Forsterite variety of olivine of gemstone quality, size 2.3 × 1.9 × 1.3 cm; locality: Northwest frontier province, Pakistan.

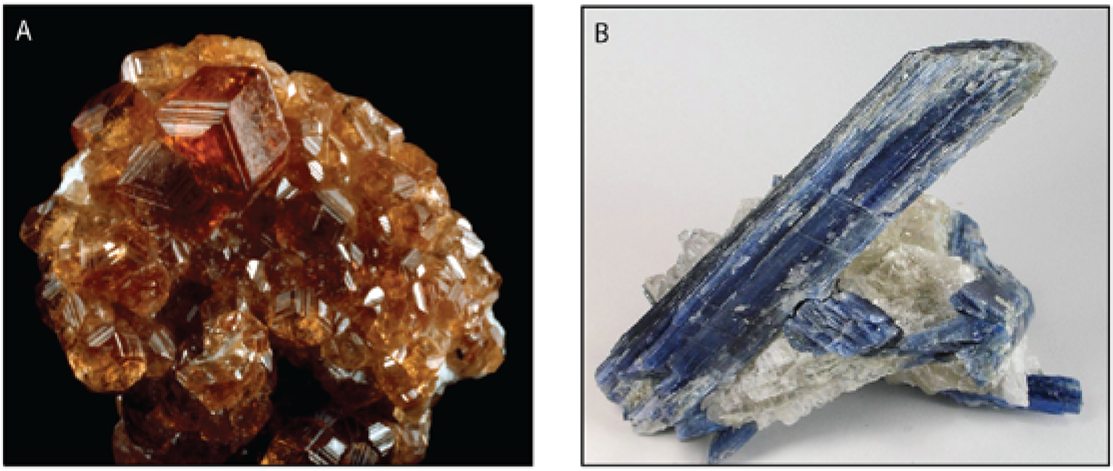

Fig. 2. A. A large cluster of garnets from the Jeffery Mine, Quebec, Canada. **B.** Kyanite crystal sitting in a matrix of quartz, the crystal measures 19 × 3 cm; locality: Minas Gerais, Southeast Region, Brazil.

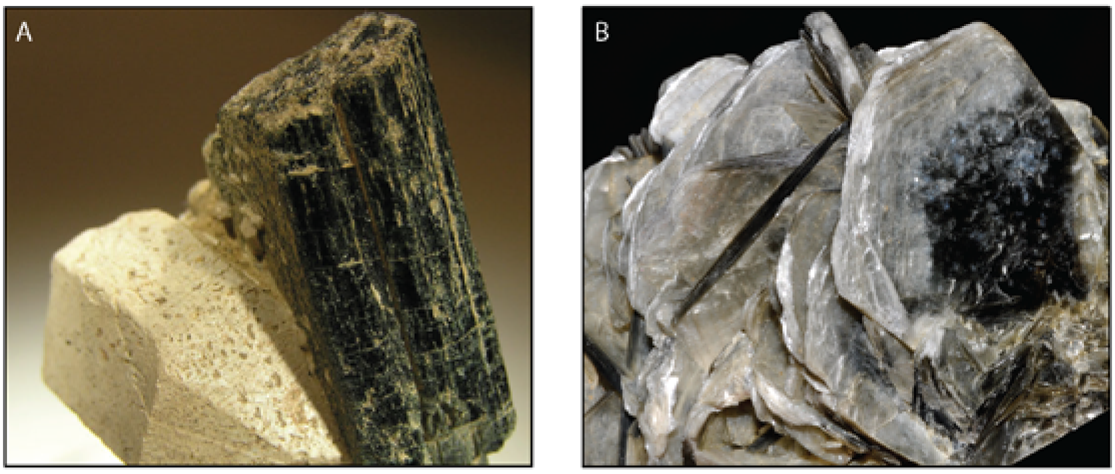

Fig. 3. A. An example of a large hornblende amphibole crystal on a matrix of apatite; locality Buskerud, Norway. **B.** A package of muscovite mica crystals from Pakistan.

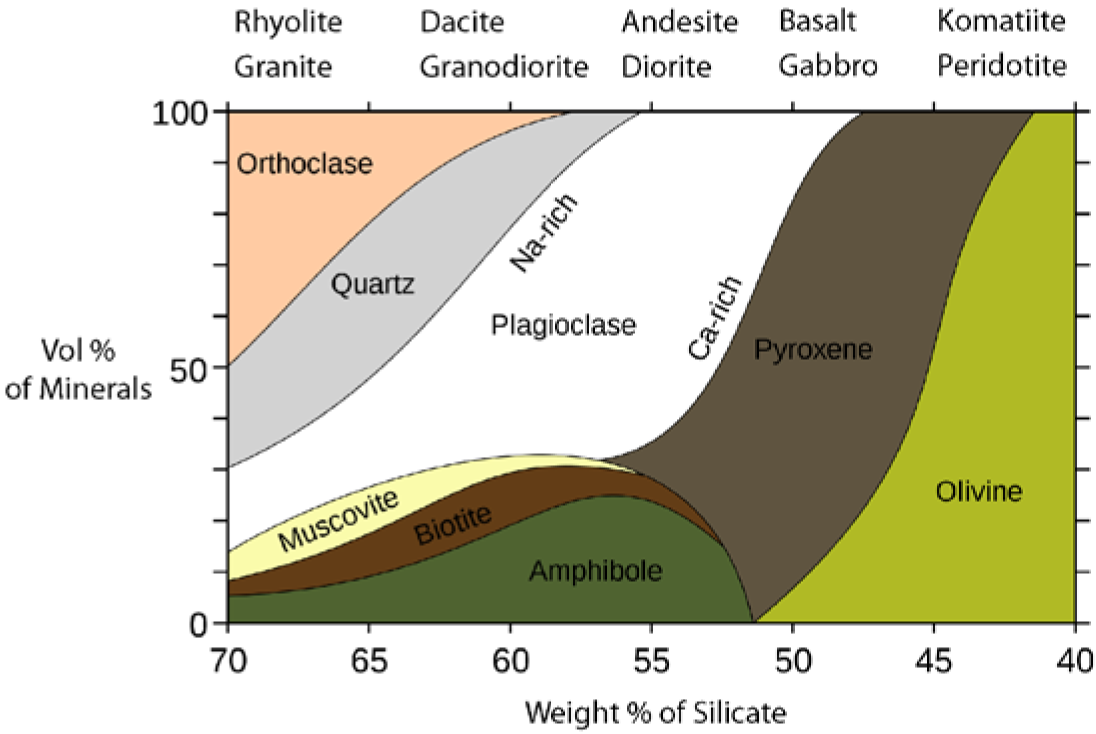

Fig. 4. Phase diagram showing how the mineral assemblages in the primary igneous rock groupings vary with weight percent of silicate.

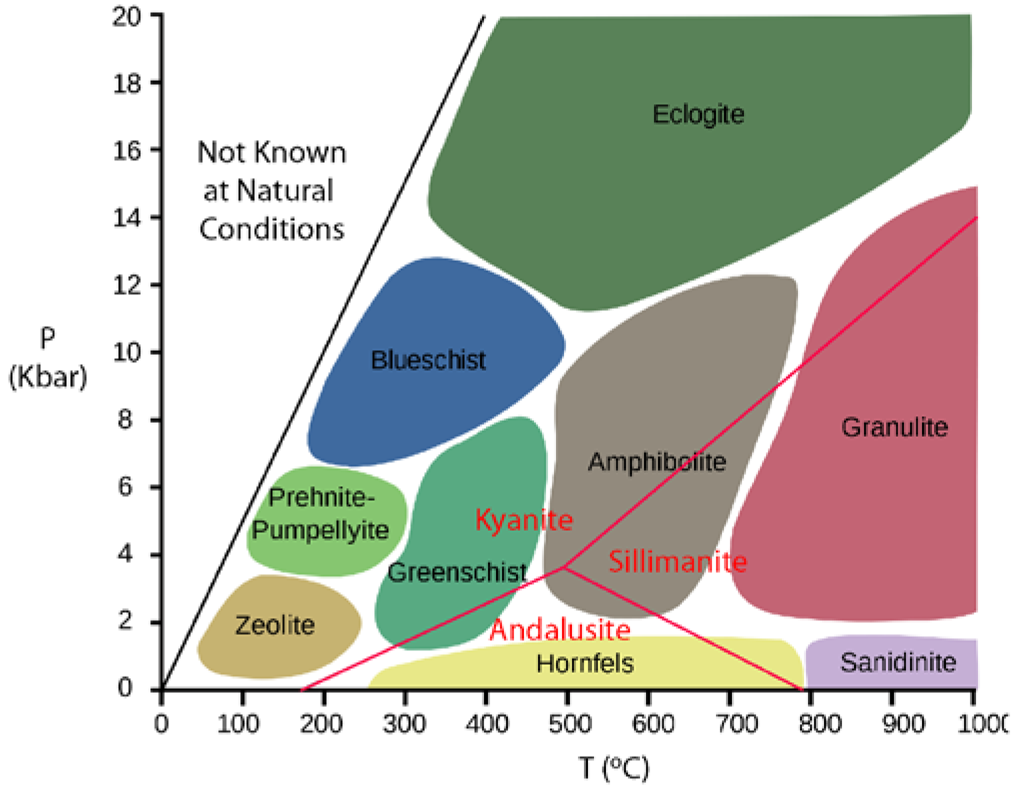

Fig. 5. Metamorphic facies diagram showing the different mineral assemblages which dominate at differing metamorphic pressures and temperatures in the Earth's crust. The range at which the different aluminosilicates (kyanite, andalusite and sillimanite) occur is also shown.

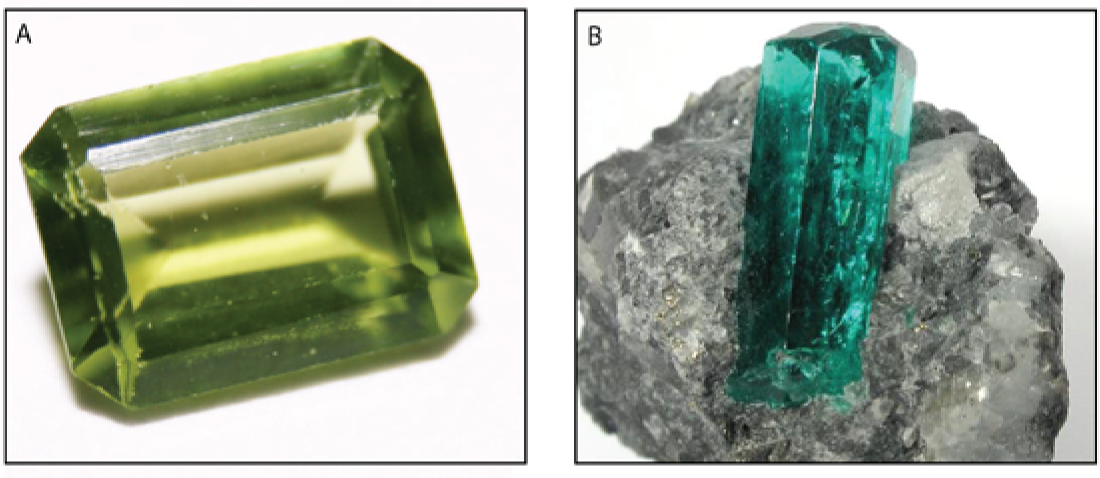

Fig. 6. A. Gem quality forsterite rich olivine known as peridot cut in an emerald style ready to be set in Jewellery; **B.** A 1.2 cm tall emerald sitting in a matrix of calcite; locality Muzo Mine, Colombia.

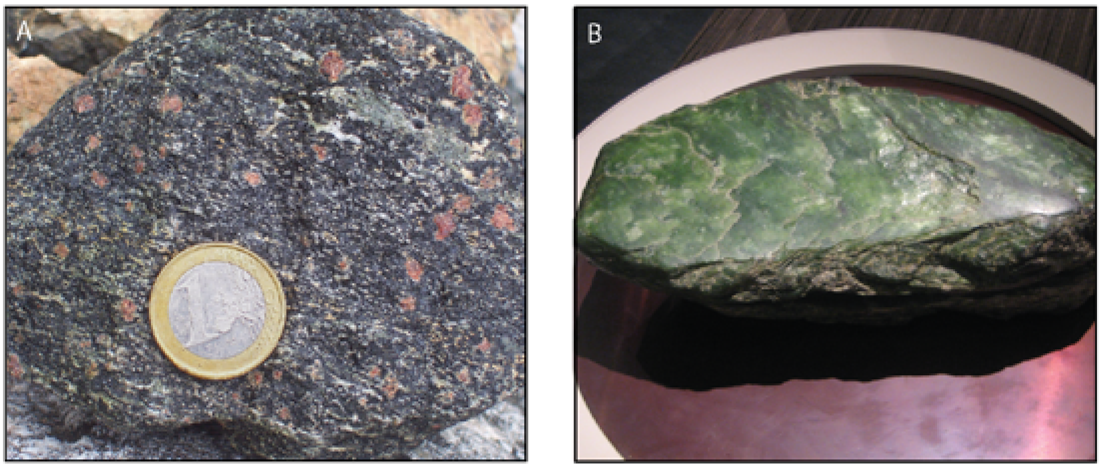

Fig. 7. A. Coarse grained amphibolitic gneiss containing amphibole (black minerals), garnet (red minerals) and plagioclase feldspar (white minerals); locality: Island of Otroy, Norway. **B.** Example of nephrite (i.e. jade) from the Museum of New Zealand, Wellington, New Zealand.

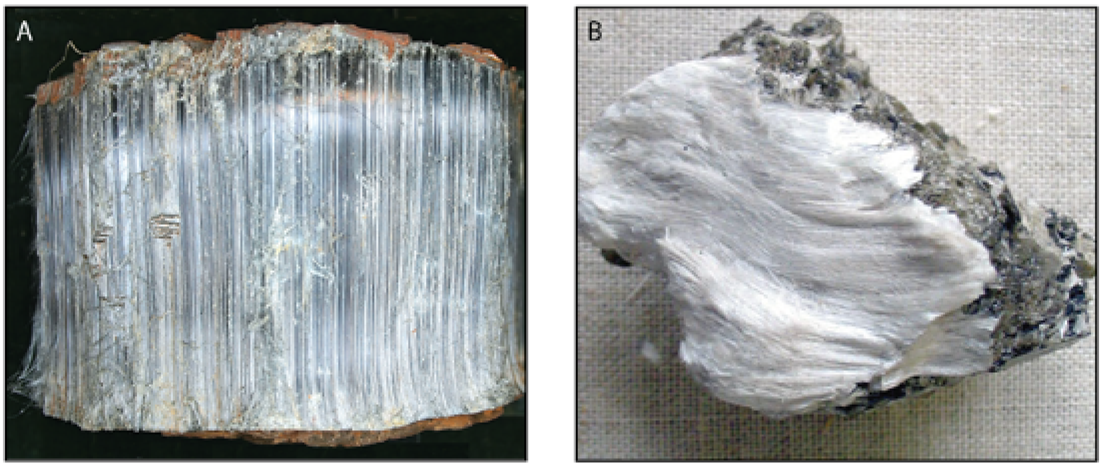

Fig. 8. A. An example of 'blue' asbestos or the amphibole crocidolite; locality: Pomfret Mine, Vyburg. **B.** An example of an actinolite amphibole variety of asbestos, showing nice silky fibres.

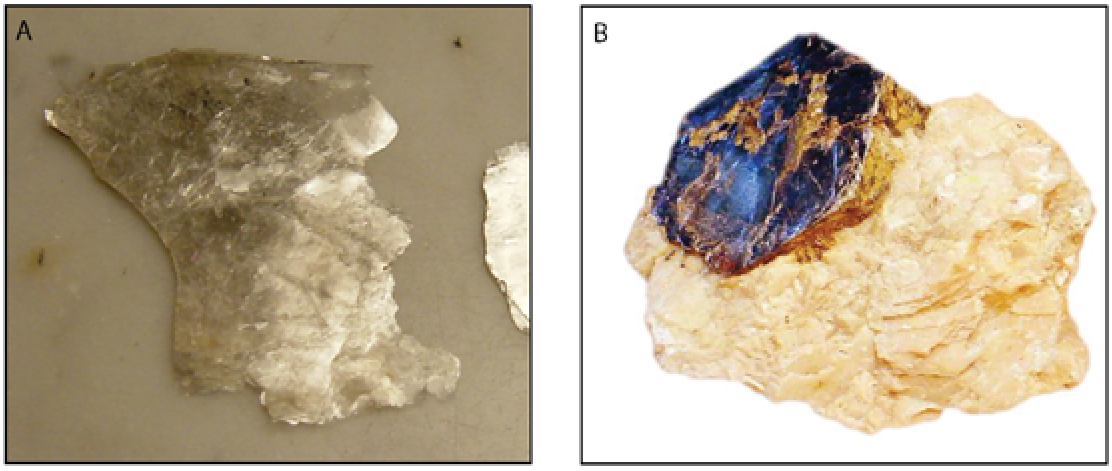

Fig. 9. A. Example of muscovite mica and its characteristic flaky, sheet like appearance. **B.** Example of biotite mica, which is generally much darker than muscovite, often showing an 'oily' like sheen to the mineral surface.

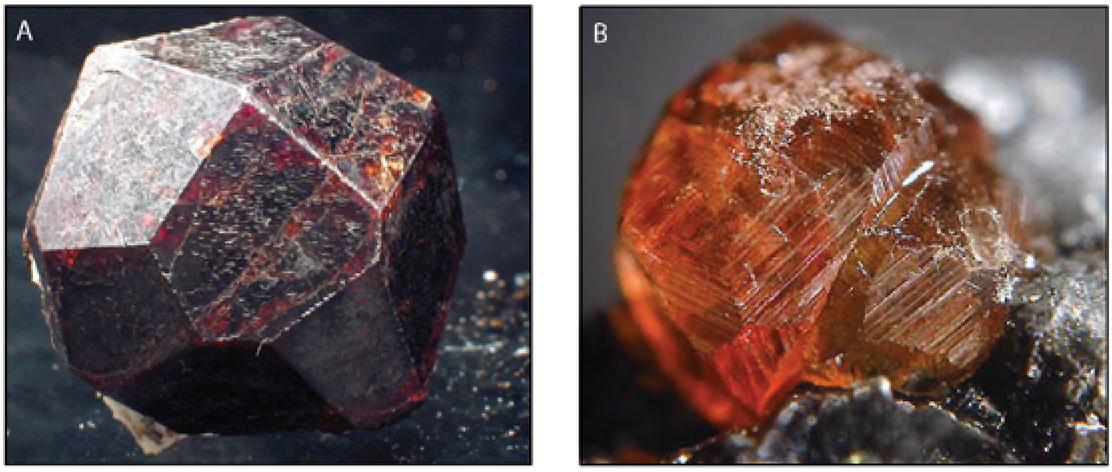

Fig. 10. A. Pyrope variety of garnet, showing the characteristic red colour. **B.** Almandine variety of garnet which can have a much wider array of colours than pyrope, this example is a beautiful orange.

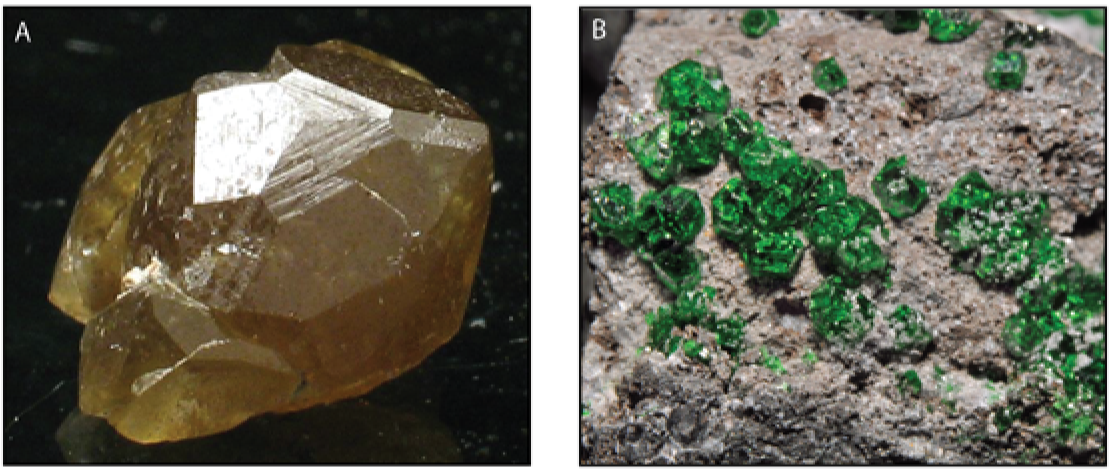

Fig. 11. A. A yellow example of the grossular variety of garnet. **B.** A cluster of characteristic green examples of the garnet uravorite; locality: Russia.

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