CHAPTER 3: MINERALS – THE BUILDING BLOCKS OF ROCKS

This chapter introduces: 1) mineral groups and the properties that allow us to distinguish different minerals; 2) some common rock-forming minerals in the Fells that are also common elsewhere; and 3) some not so conspicuous minerals in the Fells that are important to understanding its geologic history.

(Note: Terms in red and italics appear as entries in the companion glossary.)

3.1 COMMON MINERAL GROUPS AND THEIR CLASSIFICATION

As we learned in Chapter 2, minerals are made of positively charged ions (*cations*) joined to negatively charged ions (*anions*) that form a mineral *compound* or molecule with no net charge. Minerals are classified by anions rather than cations because anions control more of the overall structure (crystal type) and properties of minerals. Cations are important, but minerals with the same cation often have very different properties, while minerals with the same anion frequently share similar properties. In other words, different cations create variations on an anion theme. Some common mineral (anion) groups encountered in rocks are listed below. Of course, there are many more less common mineral groups than are on this list.

silicates (anions composed of silicon and oxygen)
aluminosilicates (anions composed of silicon, aluminum, and oxygen)
oxides (anions composed of oxygen)
hydroxides (anions composed of oxygen and hydrogen)
carbonates (anions composed of carbon and oxygen)
sulfides (anions composed of just sulfur)
sulfates (anions composed of sulfur and oxygen)
phosphates (anions composed of phosphorus and oxygen)
chlorides (anions composed of chlorine)

Silicates and aluminosilicates dominate most rocks, especially igneous rocks (like most rock units in the Fells). Within these two major groups there are sub-groups defined by different arrangements and abundances of the atoms found in the silicate (silicon and oxygen) or aluminosilicate (aluminum, silicon, and oxygen) anions. Also common, but not in the Fells, are rocks that are composed almost entirely of carbonate, for example limestone and marble, which are made of calcite (calcium carbonate, $CaCO_3$).

3.2 MINERAL PROPERTIES

Observations of some simple properties make it possible to identify common minerals in the field and lab without elaborate microscopic analysis of detailed chemical compositions and crystal structures. Geologists rely on visible properties to identify minerals because no one can expect to carry large pieces of high-tech equipment in the field that perform chemical or crystal structure analyses. Geologists also don't subject every mineral in every rock they see to all the simple tests described below. With experience, after seeing the same mineral many times, it becomes possible to recognize it on sight in the field. However, when we are uncertain, we will collect a sample for lab analysis or observation of the mineral in a petrographic microscope.

So, what can you see by yourself when looking at the minerals in rocks? Below are the properties we use to identify minerals in hand specimens. Many minerals share properties with other minerals, but each mineral has a unique set of properties, and some minerals have distinctive properties that may separate them from almost every other mineral.

Color - All mineral samples have a color, but there is considerable overlap between mineral colors, and a single mineral may commonly occur in several colors, sometimes controlled by impurities trapped in the mineral that do not show up in its chemical formula (Fig. 3.1). I should stress that, although easy to see, color can be misleading. Any identification partly based on color should be supported by other information. This will be highlighted below when we look at specific minerals. In identifying rocks, it is useful to understand the difference between "light" or felsic minerals and "dark" or mafic minerals.

Figure 3.1 *– Color can be used as a diagnostic characteristic of minerals, but only with caution. There are some minerals, such as the copper-bearing minerals malachite (A) and azurite (B), that have very distinctive, brilliant green and blue colors. However, impurities that do not appear in the chemical formulas of many minerals can influence color and one mineral can sometimes have a variety of colors. The most common felsic rock-forming minerals, potassium feldspar (C), plagioclase feldspar (D), and quartz (E), are generally light in color because of a lack of iron and magnesium. The mafic minerals like biotite (F), pyroxene (G), and amphibole (see amphibole section below) are dark because of their iron content. Scale in cm.*

Streak color – Streak color is the color produced by a mineral when rubbed on an abrasive ceramic tile or streak plate (Fig. 3.2). It is also the color of a mineral when it is ground to a powder. Streak color is important for telling different oxide and sulfide minerals apart.

Luster – Luster is a measure of the surface reflectance vs. transparency of a mineral (Fig. 3.3). *Metallic* minerals that are shiny like a piece of metal have opaque, highly reflective surfaces (see pyrite and specular hematite on Figs. 3.2-3). Other minerals are *transparent*, *translucent,* or have an *earthy* or *opaque* appearance without reflectance. Oxides and sulfides usually appear opaque and metallic, while silicates and aluminosilicates appear translucent or transparent, especially when observed in a thin section.

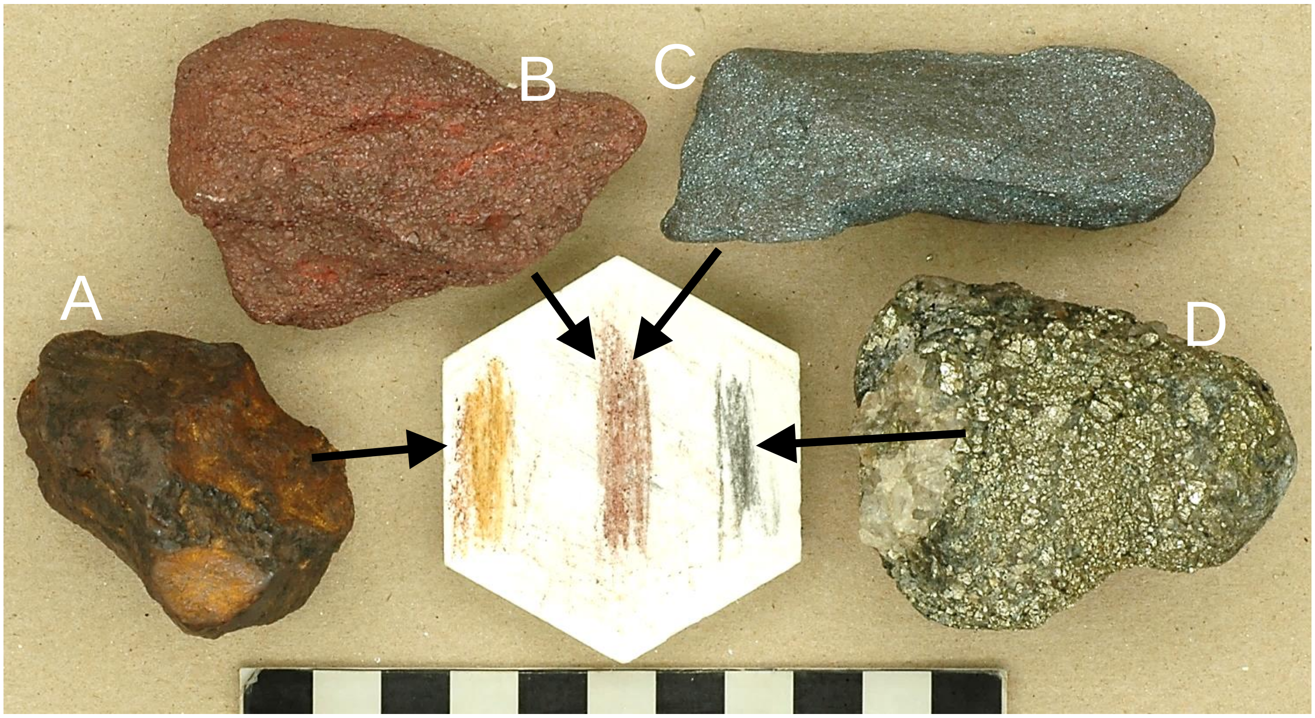


Figure 3.2 *– A very reliable color characteristic is a mineral's streak color, which is the color a mineral has when it is scratched on an abrasive ceramic tile or streak plate. This is also the color a mineral has when it is powdered. Streak color is mostly used to distinguish oxide, hydroxide, and sulfide minerals. The streak color (left to right) of limonite (A), an iron hydroxide, is yellowish brown; hematite, an iron oxide, here shown in earthy (B) and specular (C) forms, is reddish brown; and pyrite, an iron sulfide (D), is gray. Scale in cm.*

Figure 3.3 *– Luster is the overall reflectance and transparency of a mineral. Some minerals are transparent such as quartz (A). Many aluminosilicate minerals are translucent, such as plagioclase feldspar (B), alkali feldspar (C), and pyroxene (D). These minerals are translucent when viewed in thin pieces. Oxide and sulfide minerals (E-G) are opaque. Opaque minerals may have a high surface reflectivity such as specular hematite (E) which is metallic bluish gray. Fine-grained hematite has an earthy opaque luster (F). Pyrite (G) is metallic brassy yellow. Scale in cm.*

Crystal form – Crystal form is the shape a mineral grain has when its growth is not impeded by other solids. Although they are often not visible unless the mineral has had a chance to grow into an open space, the crystal form of a mineral may be distinct (Fig. 3.4). Crystal faces or crystal growth surfaces should not be confused with breakage planes or cleavage (see below).

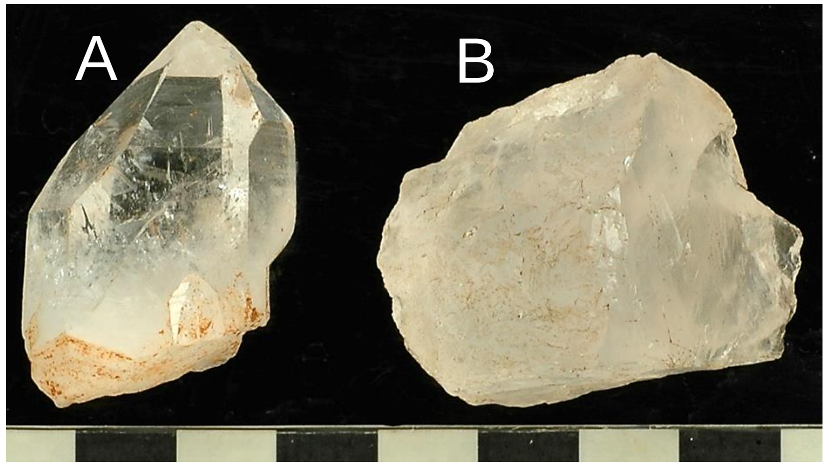


Figure 3.4 *– Quartz is an example of a mineral that commonly shows a crystal form (A) when the surface of the mineral is allowed to grow into an open space of magma or a water solution. Broken quartz (B) has irregular conchoidal fractures. Scale in cm.*

Cleavage and conchoidal fracture – Many minerals, when broken, will form pieces with flat surfaces due to a plane of weakness that occurs in the mineral's three-dimensional crystal structure (Fig. 3.5). Directions in which these flat planes form are called *cleavage directions or planes*. It is common for minerals to have at least one cleavage direction, and possibly others that are not as well developed or as easily seen. Some minerals have as many as three separate cleavage directions with well-defined angles between them. By using a hand lens or rotating a rock in direct light it may be possible to see reflections given off by flat cleavage surfaces. Some minerals break with an irregular surface and have no cleavage plane. These irregular surfaces can have a curved appearance called a *conchoidal fracture*. As an example, glass breaks with a conchoidal fracture and not with flat cleavage planes.

Hardness – The hardness of a mineral is determined by comparing it to the hardness of other minerals or objects. Objects used for testing hardness include things such as your fingernail, a steel nail, a piece of glass, or another mineral (Fig. 3.6). Hardness is determined by the crystal structure and the strength of chemical bonds that hold the atoms in a mineral together. Geologists quantify hardness on a 10-point scale called Moh's Hardness Scale in which talc is the softest mineral (1) and diamond is the hardest (10).

Acid test – An acid test is used to detect calcite (calcium carbonate). When dilute (10% in water) hydrochloric acid (HCl) comes in contact with calcite, it will react by fizzing immediately (Fig. 3.7). Another carbonate mineral, dolomite (calcium magnesium carbonate) will also react, but much more slowly. Powdering dolomite, to increase its surface area, will allow it to react more rapidly. All other common minerals will not noticeably react with this weak acid.

Special properties – Some minerals have properties that are unique (Fig. 3.8). For example, the mineral magnetite is naturally magnetic and will easily be attracted to a magnet. The mineral halite (sodium chloride) is highly soluble in water, has a salty taste, and is the source of table salt.

Figure 3.5 *–Mineral grains can cleave in several different directions. For example: calcite (A) breaks in three separate directions that have 75˚ and 105˚ angles with each other (thin black lines show intersecting edges of different cleavage planes) forming a shape called a rhombohedron or rhomb; feldspar (B) breaks on two planes that are approximately 90˚ to each other (top surface and left and right sides); muscovite or white mica (C) and biotite or black mica (D) have a single well developed cleavage direction and the mineral easily breaks into thin sheets. Some minerals do not break on flat surfaces but instead form irregular break planes. Quartz (E) forms curved break planes or what are called conchoidal fractures. Natural volcanic glass, a form shown here known as obsidian (F), also has conchoidal fractures that allowed Native Americans to flake the rock into very sharp arrowheads, spear points, and tools. Scale in cm.*

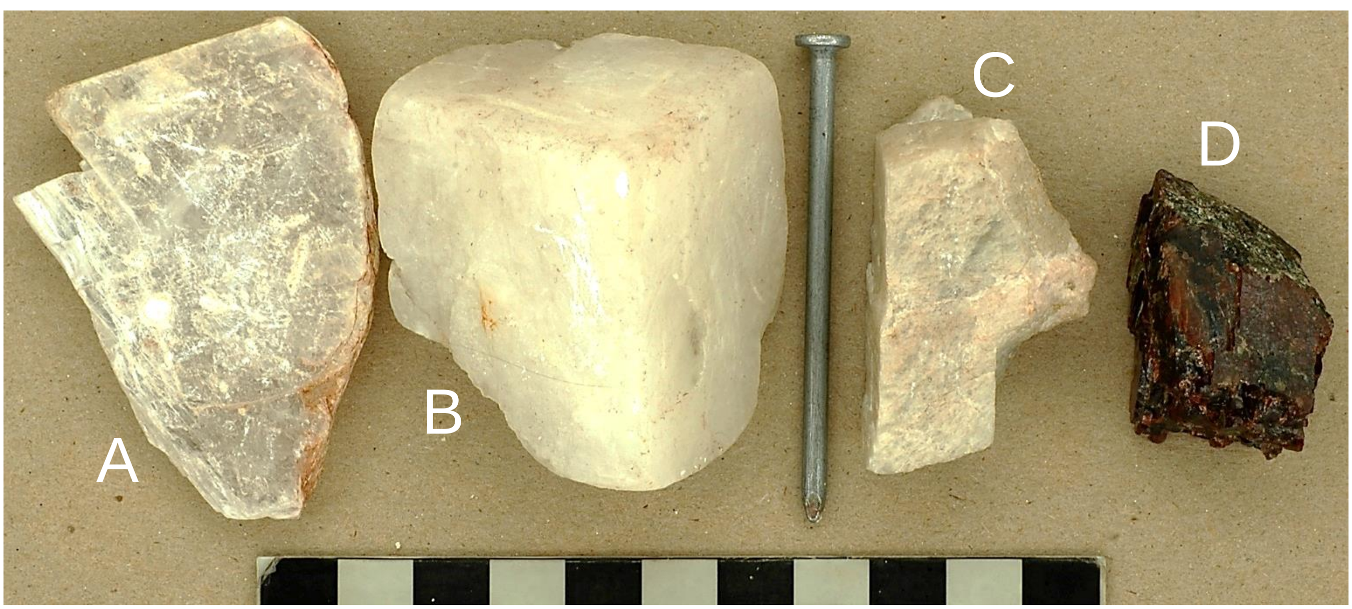


Figure 3.6 *– Some common minerals arranged from left to right according to their hardness. A) Gypsum is easily scratched by a fingernail. B) Calcite can be scratched with a steel nail. C) Feldspar is harder than a steel nail. D) Garnet a very hard mineral sometimes used to produce the abrasive grit on sandpaper. Scale in cm.*

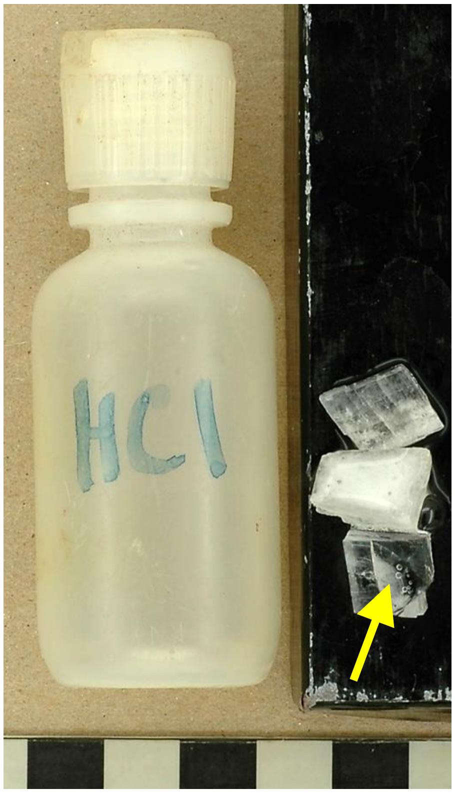


Figure 3.7 (left) – *Dilute (10%) hydrochloric acid (HCl) dispensed with a dropper bottle can be used to test for calcite (calcium carbonate). The acid will make calcite fizz or effervesce (arrow points to small bubbles). Scale in cm.*

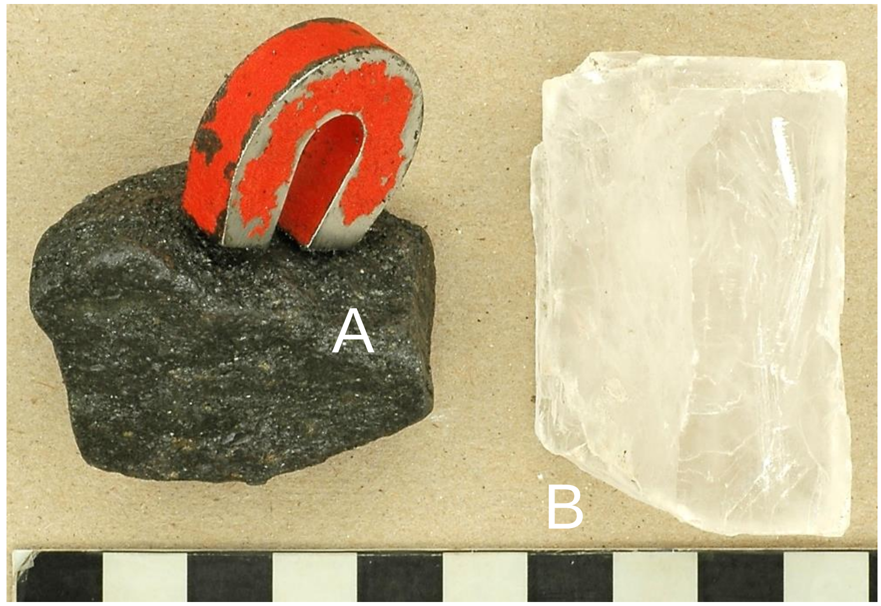


Figure 3.8 (above) – *Some minerals have special properties that allow them to be distinguished from other minerals. A) Magnetite is naturally magnetic, and a magnet will strongly attract this mineral. You may also be able to feel magnetite pull on a steel nail. B) Halite (sodium chloride), which is the source of table salt, has a very salty taste. Scale in cm.*

3.3 COMMON ROCK-FORMING MINERALS

Below are descriptions of the most common rock-forming minerals as well as some others that are relevant to the Fells. A description of each mineral and some important properties are given with its chemical formula. Keep in mind that many of the images are large hand specimens that highlight the mineral's properties. It is much more difficult to identify separate mineral types in a rock sample where each mineral grain is less than a few millimeters across or even microscopic. This is where a microscope thin section view is useful. The thin section images included here were taken in a petrographic microscope using either plane polarized light or crossed polarizers, which not only provides a greatly enlarged view of minerals but also shows some of the unique optical properties of minerals.

To understand the chemical formulas of minerals you will have to know the abbreviations of the elements involved. All atoms of a single element have the same number of protons, with an equal number of electrons orbiting the nucleus, but the number of neutrons in the nucleus can vary. This variation in number of neutrons creates different weights of atoms, varieties known as *isotopes*. Below are the elements (with abbreviations) that make up the common rock-forming minerals in Earth's crust, along with their most common isotope. The isotope number is determined by adding the number of protons and neutrons in the nucleus. The first eight elements on the list ("The Big Eight") are the most common elements in Earth's crust (just the crust, not the Earth as a whole!) followed by some other common elements found in rocks in the Fells.

List of top 8 elements in Earth's crust: (listed by approximate percentages in Earth's crust according to Wikipedia: chemical elements and elements crust. Remember, this is for Earth's crust and does not include its interior which has very high percentages of iron and nickel. The top eight make up over 99% of Earth's crust.

O – oxygen (nucleus of 8 protons + 8 neutrons) - 46%
Si – silicon (nucleus of 14 protons + 14 neutrons) - 28%
Al – aluminum (nucleus of 13 protons + 14 neutrons) - 8.3%
Fe – iron (nucleus of 26 protons + 30 neutrons) - 5.6%
Ca – calcium (nucleus of 20 protons + 20 neutrons) - 4.2%
Na – sodium (nucleus of 11 protons + 12 neutrons) - 2.5%
Mg – magnesium (nucleus of 12 protons + 12 neutrons) - 2.4%
K – potassium (nucleus of 19 protons + 20 neutrons) - 2.0%
All other elements are less than 1%

Some other elements in rock-forming minerals common in the Fells (listed in order of abundance in crust):

Ti – titanium (nucleus of 22 protons + 26 neutrons) - 0.61%
H – hydrogen (nucleus of 1 proton) - 0.14%
P – phosphorus (nucleus of 15 protons + 16 neutrons) - 0.11%
Mn – manganese (nucleus of 25 protons + 30 neutrons) - 0.10%
F – fluorine (nucleus of 9 protons + 10 neutrons) - 0.058%
S – sulfur (nucleus of 16 protons + 16 neutrons) - 0.035%
C – carbon (nucleus of 6 protons + 6 neutrons) - 0.020%
Zr – zirconium (nucleus of 40 protons + 51 neutrons) - 0.016%
Cl – chlorine (nucleus of 17 protons + 18 neutrons) - 0.015%

The chemical formula for a mineral shows the atoms that occur in a single *molecule* of the mineral. In a chemical formula, subscript numbers are used to show how many atoms of each element, or groups of atoms within parentheses, occur in a single molecule. For example, $CaCO_3$ is the formula for calcite, which is calcium carbonate. Its cation is calcium (Ca^{2+}), and anion is carbonate (CO_3^{2-}). The superscript numbers on each ion show its charge. There is 1 calcium atom, 1 carbon atom, and 3 oxygen atoms in a molecule of calcite. $CaMg(CO_3)_2$ is dolomite, which has single calcium and magnesium (Mg^{2+}) atoms as its cations and 2 carbonate anions. Another example is SiO_2, the formula for quartz (silicon dioxide), which has 1 silicon and 2 oxygen atoms.

3.3.1 Common Rock-Forming Silicate and Aluminosilicate Minerals

Below are descriptions of each of the common silicate and aluminosilicate rock-forming minerals. Not only might one expect to find almost all the minerals below in any given field area near Boston, but almost every rock that is out there is dominated by this set of minerals. These minerals are very common. Chemical formulas and other information given for the minerals below can be found in Klein and Hurlbut (1999), but there are many books that list this information without citing references. On Table 3.1 (next page) is a comparison chart of the most common minerals in the Fells.

Table 3.1 - Summary of common minerals of the Middlesex Fells and how they appear in the Fells in hand specimens. Details of the minerals are given in the text.

	Color/Luster	Cleavage	Hardness	Occurrence and form
Felsic (light-colored) minerals				
Quartz	Clear to milky gray transparent	conchoidal fracture	7	Glassy grains in felsic igneous rocks, sandstones and metasandstones. In veins.
Plagioclase feldspar	White to gray transluscent	2 at 90°, one often visible	6	Euhedral crystals in felsic and mafic porphyries. Euhedral to partly euhedral crystals in felsic and mafic igneous rocks. Grains in sandstone and metasandstone.
Alkali feldspar	Creamy white to pink or orange transluscent	2 at 90°, often not visible	6	Grains in felsic igneous rocks. Scattered grains in sandstone and metasandstone.
Epidote	Yellowish, olive and pistachio green	Cleavage not easily seen	6	Areas of alteration in igneous rocks. Common in veins and on fracture planes.
Muscovite mica	Colorless transparent	1 well developed, forms sheets	2.5	Very tiny flakes, not generally visible. Alteration product in felsic igneous and metamorphic rocks.
Mafic (dark-colored) minerals				
Pyroxene (augite)	Faintly purple with dark green alteration	2 at 90°, not usually visible	6	Mafic igneous rocks, especially dikes.
Amphibole (hornblende)	Black	2 at 56° and 124°, at least 1 visible	5.5	Slender crystals in felsic igneous rocks.
Biotite mica	Black transparent	1 well developed, forms sheets	2.5	Small flakes in felsic igneous rocks and less commonly mafic igneous rocks. Small flakes in metasandstone.
Chlorite	Dark green	1, but not as conspicuous as in other micas	2	Alteration product of other mafic minerals along with magnetite or amphibole (actinolite). In veins and on fracture planes.
Magnetite	Black metallic	generally not visible	6	In mafic igneous rocks and possibly as tiny alteration products in other rocks.
Hematite	Bluish gray metallic crystals or reddish brown earthy, reddish brown streak color	none, often crumbly	6	Small amounts in felsic igneous rocks possible. Common in veins and on fracture planes.

Quartz SiO_2

Quartz is commonly a clear to white or smokey translucent silicate that can have a variety of other colors (depending on impurities and microscopic crystal defects). Quartz has conchoidal fracture, a hardness of 7 (very hard), and, if present, crystals with six sides and a point (Figs. 3.4 and 3.9). Quartz is very common and occurs in almost all the rock formations in the Fells (Figs. 3.10-11). It tends to be very clean with little alteration, unlike many other silicate and aluminosilicate minerals.

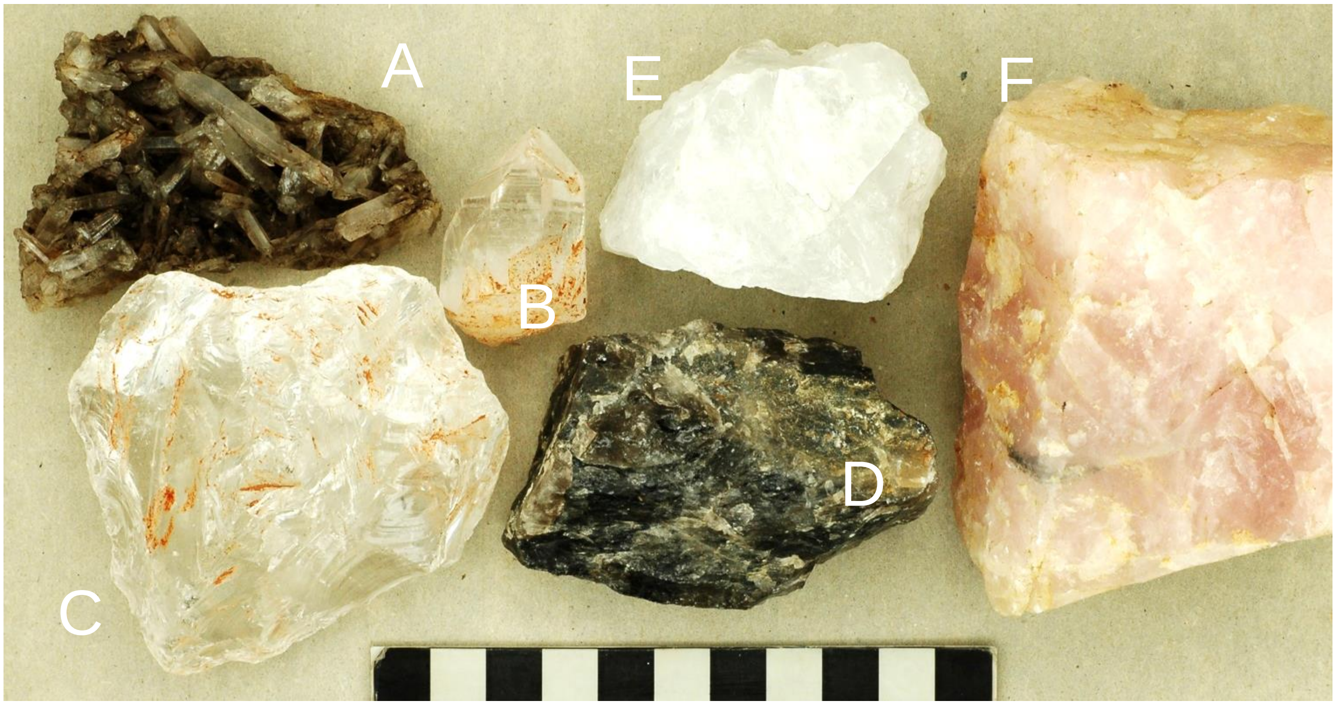
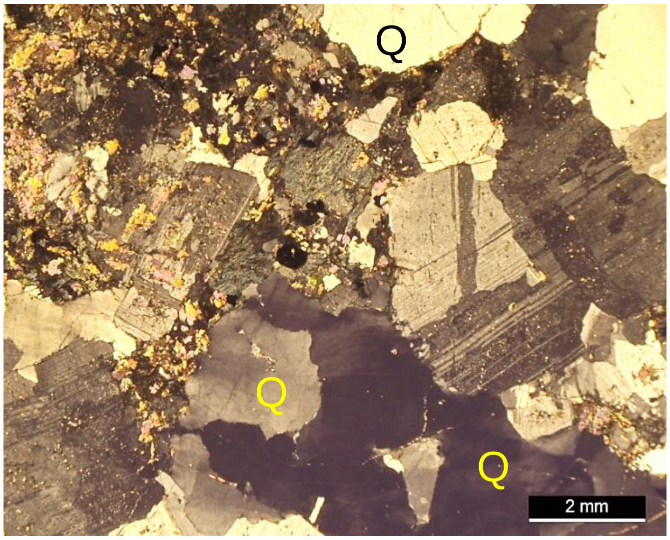


Figure 3.9 *– Quartz (SiO_2) is the hardest common rock-forming mineral. It often shows its crystal form (A and B), an elongate six-sided crystal. When broken (C) it has a conchoidal fracture. Quartz has a variety of colors, too many to show here, but is commonly transparent (B, C), smoky or black to dark gray translucent (A, D) due to the radioactive decay of uranium trapped in the crystal, translucent (E), or pink as in rose quartz (F), which gets its color from microscopic fibers of a pink borosilicate mineral (Nadin, 2007). Scale in cm.*



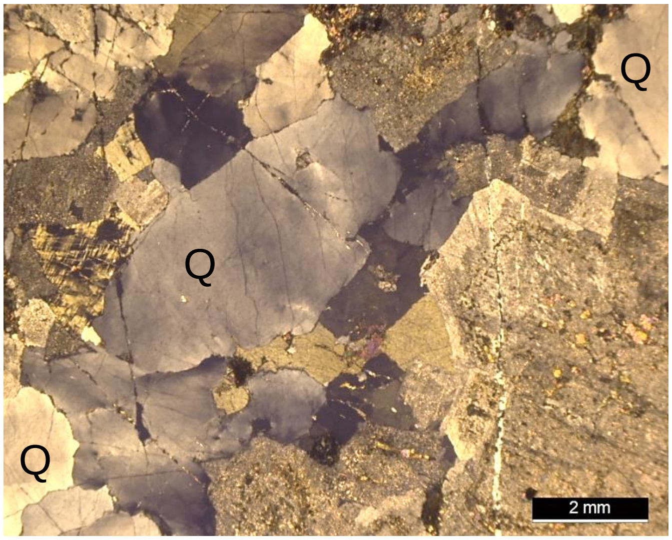


Figure 3.10 *– Quartz in coarse igneous rocks in the Fells. Quartz is the dark to light gray and very bright white clear grains (Q) with a color that changes slightly across each grain. This undulatory shading is due to slight bending of the quartz crystals. Views of thin sections using crossed polarizers. Grains with a dirty appearance (due to alteration) or parallel stripes are plagioclase feldspar (see below).*

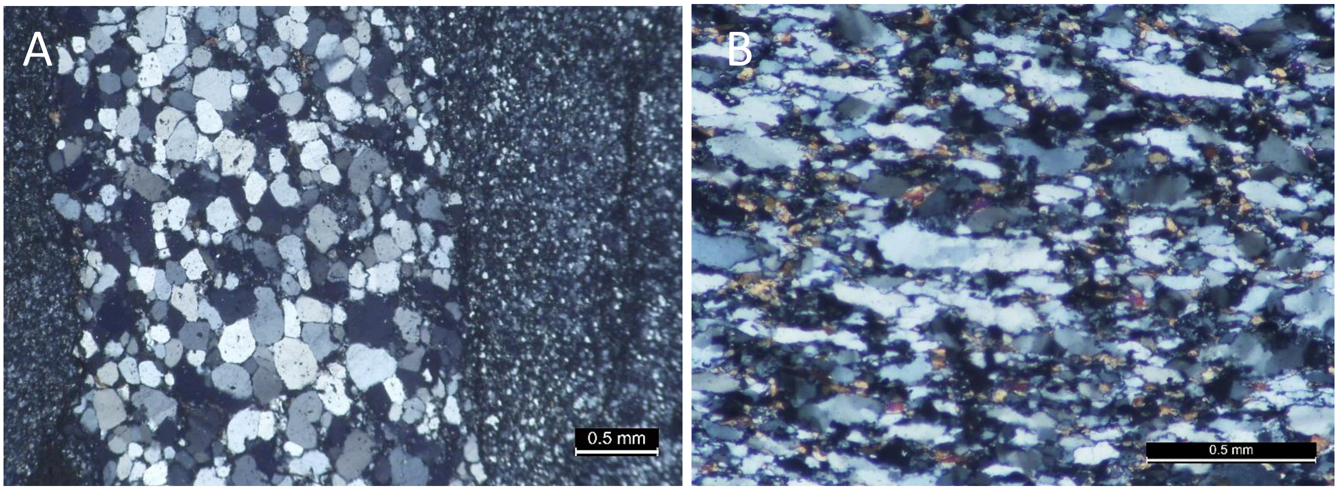


Figure 3.11 *– Quartz in sedimentary (A) and metamorphic (B) rocks in the Fells. Views of thin sections with crossed polarizers. A) In the left center is a layer of quartz sandstone that is oriented vertically on the image. Adjacent dark areas are fine-grained sedimentary rock with tiny quartz grains (siltstone). Note that the quartz grains still have their original round shapes. B) In the metamorphic rock (metamorphosed quartz sandstone) heat and pressure have caused original grains to deform and fuse or suture together with some grains penetrating weaker grains. Between the quartz grains, mica (colorful grains; see below) has formed.*

Feldspar $(Na,Ca)Al_{1\text{-}2}Si_{2\text{-}3}O_8$ or $KAlSi_3O_8$

Feldspar is an aluminosilicate that is the most common mineral in Earth's crust, and it is found in all the rock formations in the Fells. It comes in several varieties depending on the relative percentages of calcium, sodium, and potassium that serve as cations and the amount of aluminum vs. silicon in its anion (Fig. 3.12). Feldspar with a mix of sodium and calcium as its cations is called *plagioclase* ($NaAlSi_3O_8$ to $CaAl_2Si_2O_8$; see Figs. 3.10 and 3.12-13). Percentages of sodium vary from 0 to 100%. Substitution of aluminum for silicon accommodates more calcium. Feldspar with potassium (dominating over sodium) as its cation is *alkali* or *potassium feldspar* (Fig. 3.12 and 3.14), usually as varieties called *orthoclase* or *microcline* (both are $KAlSi_3O_8$). Sometimes alkali feldspar that originally also had some sodium will contain thin bands of sodium plagioclase that separated while the mineral was still hot. This structure is known as a *perthite* (Fig. 3.12D and 3.14B). Many rocks, like granite, have both plagioclase and alkali feldspar in them. All feldspars have a hardness of 6 and usually exhibit one well defined cleavage plane, but a second may be visible. Cleavage planes in plagioclase may have what appear to be almost microscopic parallel lines called striations. In addition to these properties, *plagioclase* is usually translucent white to gray, though other colors are possible. *Alkali feldspar* tends to have a white, light tan, creamy, or pink to reddish orange (salmon) color, though they can also be gray and in rare cases even turquoise (a variety called amazonite).

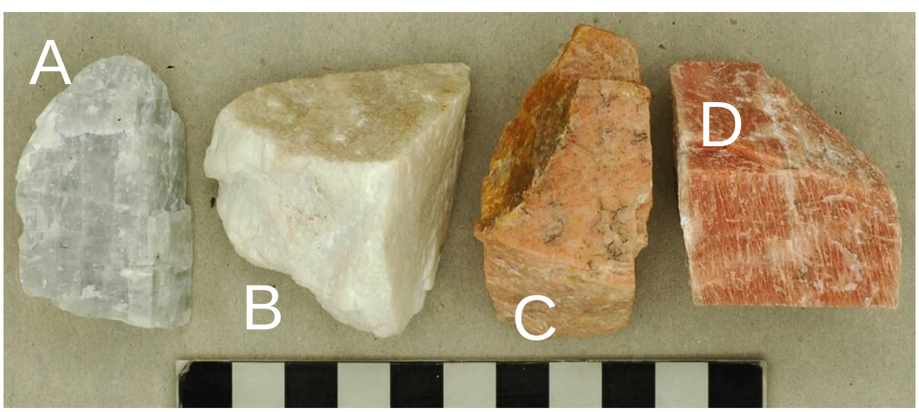


Figure 3.12 *– Types of feldspar. Plagioclase feldspar (A and B) has a continuous variation of cations from all sodium ($NaAlSi_3O_8$) to all calcium ($CaAl_2Si_2O_8$). Alkali (or potassium) feldspar (C and D; orthoclase and microcline are shown here) has potassium as its dominant cation ($KAlSi_3O_8$) with much smaller amounts of sodium. The microcline specimen (D) is perthite. Scale in cm.*

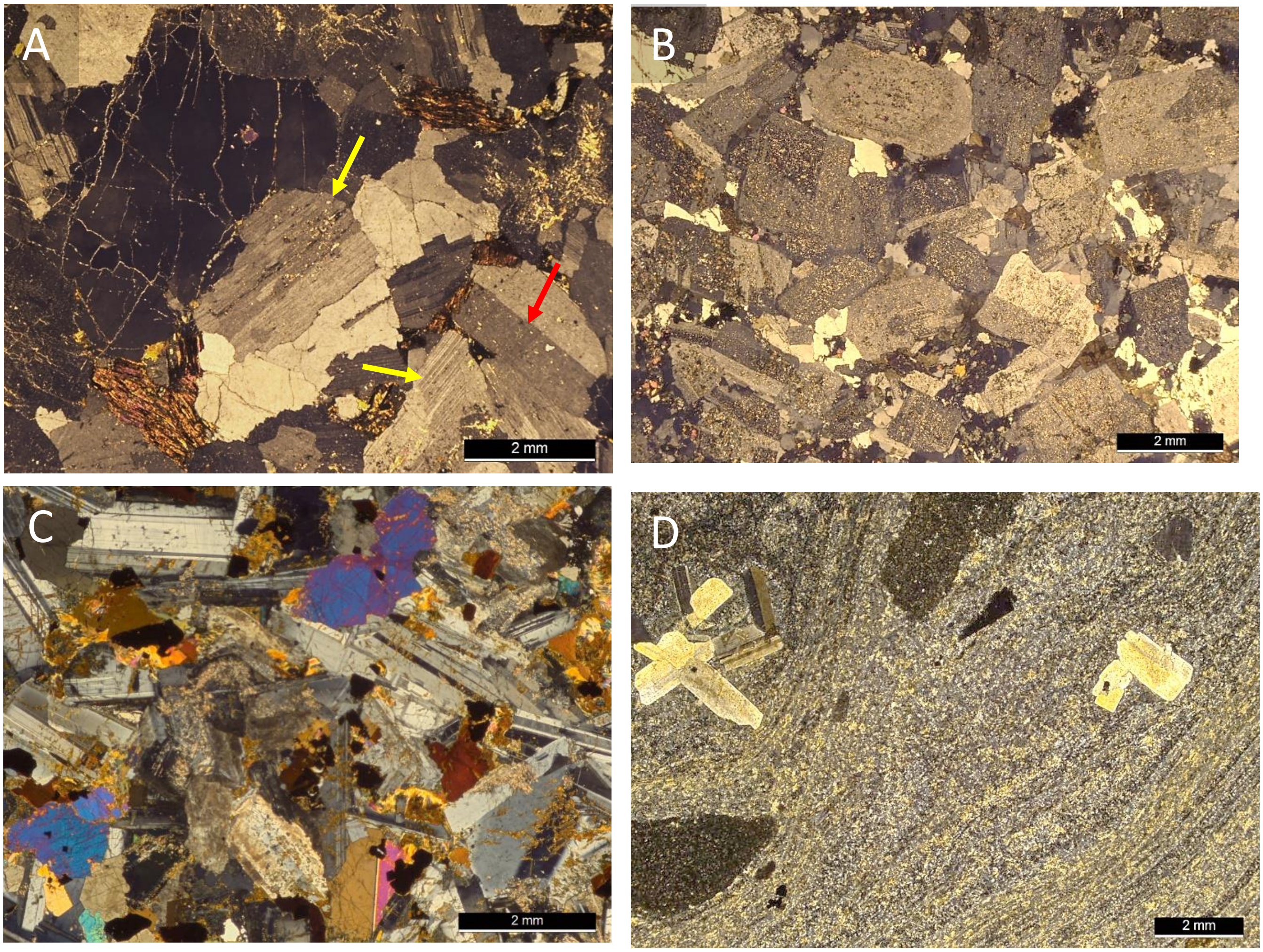


Figure 3.13 *– Plagioclase feldspar in the Fells. Thin section views with crossed polarizers. A) Plagioclase grains often have thin parallel stripes (yellow arrows) or abrupt changes in color within grains (red arrow). The dark clear grain with cracks is quartz. The orangish-red grain is biotite mica altered to epidote and an opaque oxide. B) Mostly blocky to elongate plagioclase grains that are lightly altered (dirty to sparkly appearance). Note the faint concentric growth bands and sudden flips in color within plagioclase grains. C) Plagioclase (dark to light gray striped grains) in a coarse igneous rock with mafic minerals (pyroxene, colorful grains; biotite, brown grains). D) Clusters of elongate or tabular plagioclase grains in a felsic lava. Flat sides on the plagioclase grains are crystal faces.*

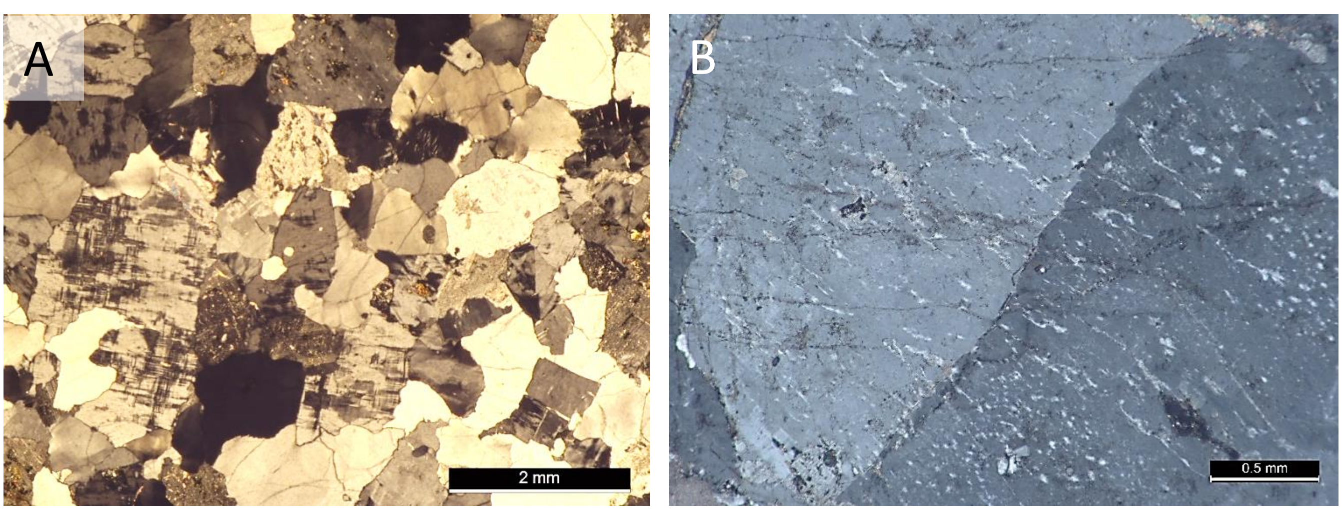


Figure 3.14 *– Alkali feldspar in igneous rocks in the Fells. Thin section views with crossed polarizers. A) The grains with crosshatch (plaid-like or tartan) patterns are microcline among clear quartz grains. B) The light irregular bands and spots (sodium-rich plagioclase) form perthite in an alkali feldspar grain.*

Mica $KAl_2(AlSi_3O_{10})(OH)_2$ or $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$

Mica has one well-defined cleavage plane that makes the mineral break apart into cellophane-like sheets (Fig. 3.15). Clear (or "white") mica is *muscovite* ($KAl_2(AlSi_3O_{10})(OH)_2$), while black, iron-bearing mica is *biotite* ($K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$). When looking at a hand specimen, it is often possible to test a mineral you suspect is mica by digging into it with a pocketknife, in which case mica will begin to flake. In the Fells, mica is low in abundance as a visible mineral, as compared to most areas of New England, where it is often an important and conspicuous constituent of metamorphic rocks. Muscovite occurs in the Fells as microscopic grains formed by the alteration of feldspar by heat and pressure (Fig. 3.16). Biotite occurs in some igneous rocks and as a by product of metamorphism when iron is available (Fig. 3.17).

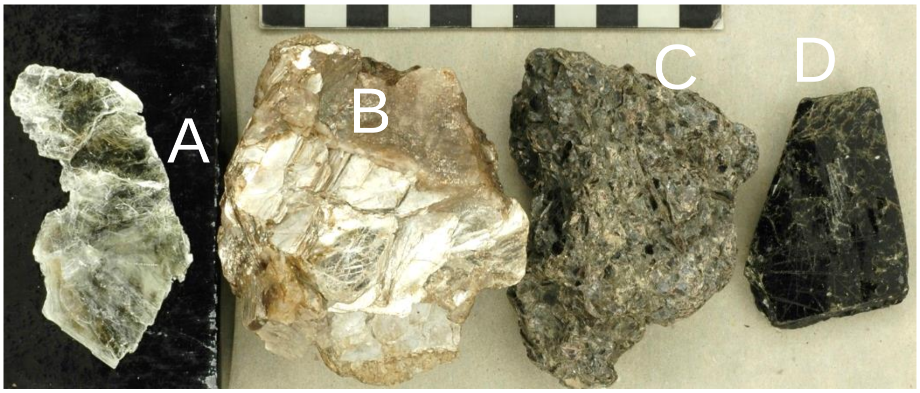


Figure 3.15 *– Mica always has one extremely well-developed cleavage that causes the mineral to split into thin sheets. The two common mica varieties are muscovite, or white (transparent) mica, shown against a black background (A) and in a rock with quartz (B); and biotite or black mica (D), also shown in a metamorphic rock (C). Scale in cm.*

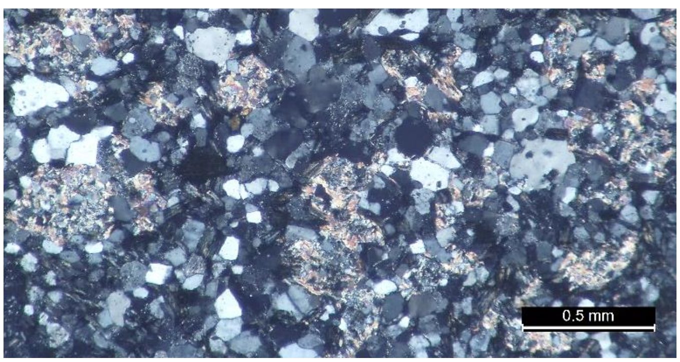


Figure 3.16 *– Muscovite in the Fells formed by the alteration of feldspar during the metamorphism of a sandstone. Muscovite is the colored patches seen between deformed quartz sand grains. Thin section view with crossed polarizers.*

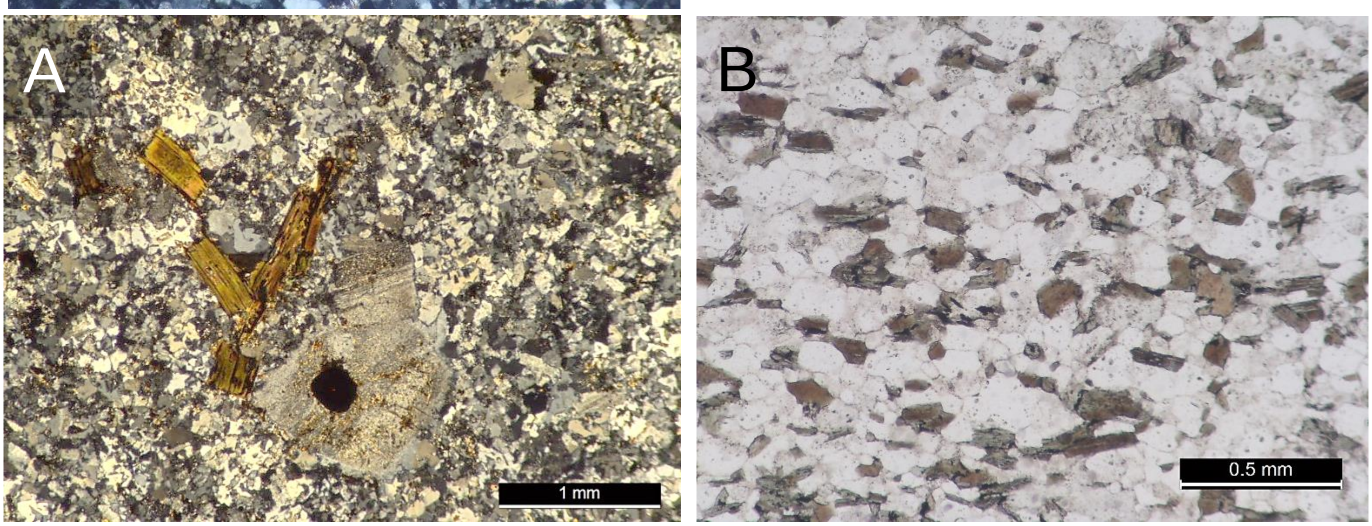


Figure 3.17 *– Biotite in the Fells. Thin section views. A) Biotite crystals (brown) surrounded by very fine quartz and feldspar and adjacent to larger plagioclase crystals in a lava flow. View with crossed polarizers. B) Brown crystals are biotite in a metamorphosed sandstone. Greenish grains are biotite partly altered to chlorite. View in plain polarized light. Clear grains are quartz and light gray areas are feldspar.*

Pyroxene and Amphibole

Pyroxene is a group of minerals with the formula $XY(Si,Al)_2O_6$, where X is most commonly Na, Ca, Fe^{+2}, or Mg and Y is commonly Fe^{3+}, Mg or Ca. Pyroxene is usually dark-colored from its iron and magnesium and has two cleavages at 90° to each other (Fig. 3.18). This may be hard to see in hand specimens, and pyroxene may be difficult to discern from amphibole when it does not display good cleavage. Common pyroxenes are *hypersthene* $(Mg,Fe)SiO_3$, *augite* $(Ca,Na)(Mg,Fe,Al)(SiAl)_2O_6$, and *diopside* $CaMg(Si_2O_6)$. In the Fells, pyroxene is a major constituent of mafic igneous rocks (Fig. 3.13C, 3.18 and 3.20A), but it is often partly altered to actinolite and chlorite (see below). Diopside occurs in metamorphic rocks (Fig. 3.20B) where there was originally a high calcium and magnesium content, usually from metamorphosed calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$).

Figure 3.18 (below left) *– Pyroxene (here the variety augite) comes in many varieties, but they all have two cleavage directions at 90° (top and sides in A). B) Rock with pyroxene (variety augite) crystals. Scale in cm.*

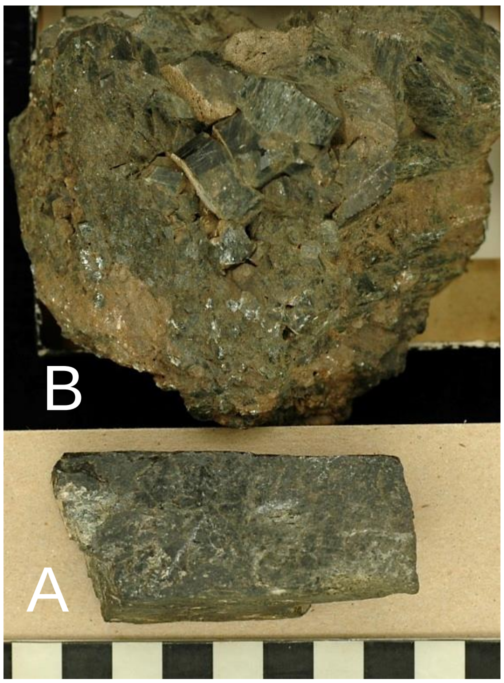


Figure 3.19 (above) *– Shown here is amphibole, the variety hornblende $(CaNa)_{2-3}(Mg,Fe^{2+},Al)_5Si_6(Al,Si)_2O_{22}(OH)_2$. Amphibole has cleavage planes at 56° and 124°. A) amphibole crystals. B) cleavage fragments (white line indicates corner between cleavage faces on one specimen). Scale in cm.*

Amphibole is a complex group of usually mafic and often elongate aluminosilicates that have a wide variety of cations in varying percentages, with aluminum substituting for silicon in some varieties (Fig. 3.19). Common types of amphibole include *hornblende* $(CaNa)_{2-3}(Mg,Fe^{2+},Al)_5Si_6(Al,Si)_2O_{22}(OH)_2$ (Figs. 3.19 & 3.21A-B), *actinolite* $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$ (Fig. 3.21C), *tremolite* $Ca_2Mg_5Si_8O_{22}(OH)_2$ (Fig. 3.21D), and *riebeckite* $Na_2Fe^{2+}_3Fe^{3+}_2Si_8O_{22}(OH)_2$ (south of Boston in the Quincy Granite). Of the minerals listed above, hornblende is the most common in igneous rocks in the Fells, and hornblende, actinolite, and tremolite are common in metamorphic rocks. Amphiboles have many different combinations of cations in them. As a student, I once had a professor tell me that "amphiboles are the garbage can of cations". Amphibole has two well defined cleavages at 56° and 124° to each other (Figs. 3.19B and 3.21B), but in a hand specimen it is often possible to see only one of these cleavage planes. Without clearly seeing a second direction, amphiboles may be hard to distinguish from pyroxene, although amphibole cleavage tends to be more conspicuous. Amphiboles are found in many of the igneous and metamorphic rocks of the Fells as a minor component that can form by alteration of other mafic minerals, and they can be altered by metamorphism and hydrothermal fluids to chlorite and epidote (see these minerals below).

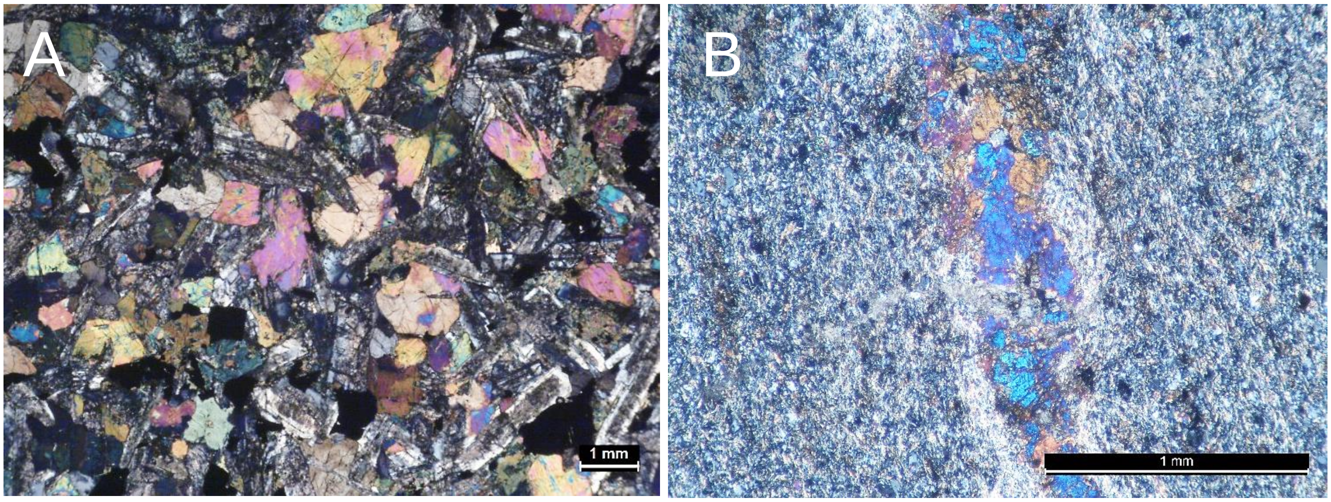


Figure 3.20 *– Pyroxene in the Fells. Thin section views with crossed polarizers. A) Pyroxene (augite, colorful grains) with partly altered plagioclase crystals (dirty-looking black and white blade-like minerals) in a mafic igneous rock. B) Very colorful pyroxene (diopside) crystals in a metamorphosed sedimentary rock that originally had calcite (see below). Surrounding material is mostly the amphibole tremolite.*

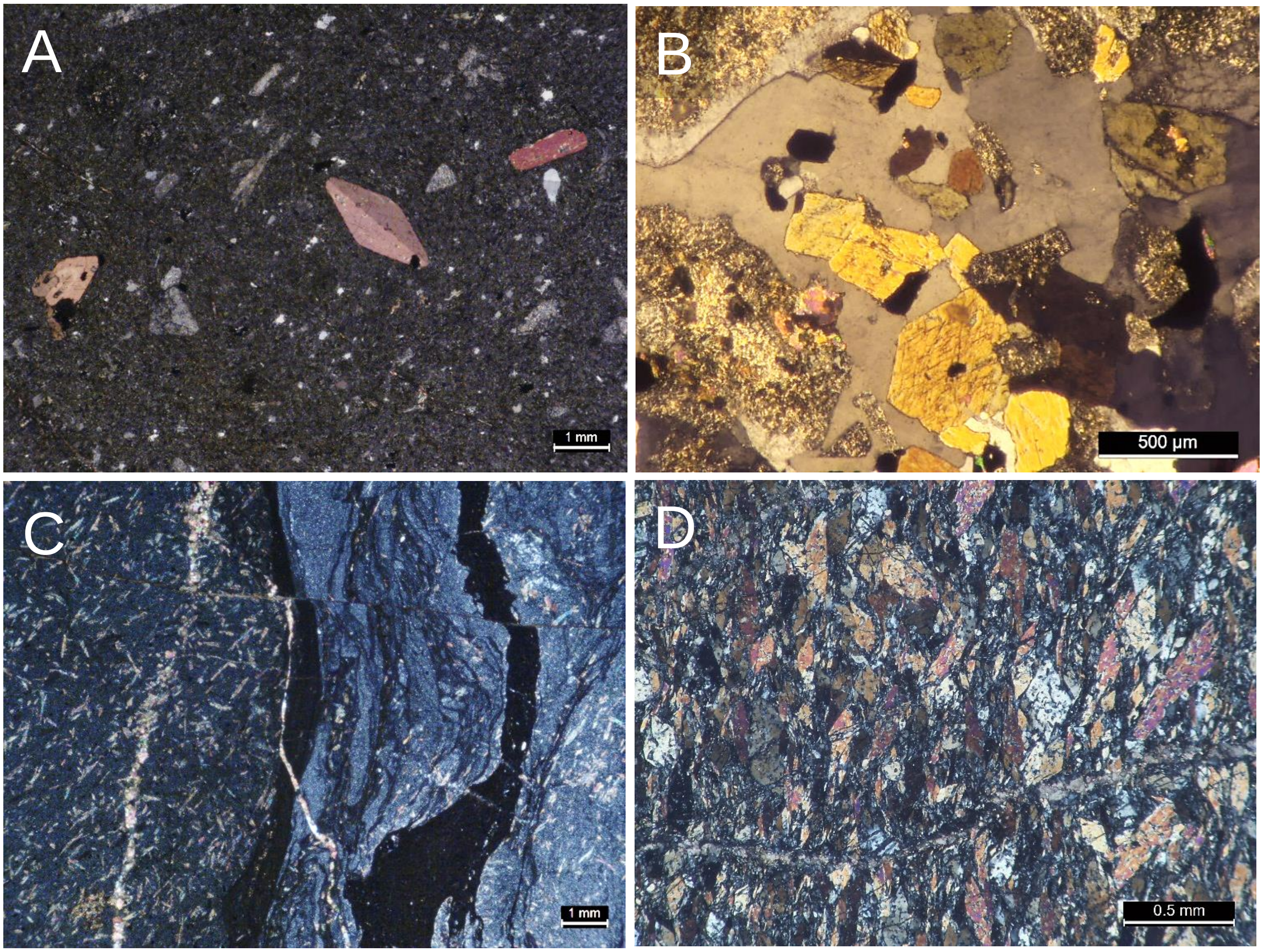


Figure 3.21 *– Amphibole in the Fells. Thin section views with crossed polarizers. A) Beautifully formed hornblende crystals (diamond-shaped orange to reddish-brown) in a fine-grained felsic igneous rock. B) Hornblende crystals (yellow to orangish brown) in a coarse-grained felsic igneous rock. Cleavage plains forming 56° and 124 ° angles are visible in the crystal in the lower center. The heavily altered grains (sparkly) are plagioclase, and the clean background grains are quartz. C) Needle-like actinolite crystals in metamorphosed basalt (left) and iron-rich metamorphosed mudstone (right). D) Tremolite crystals in metamorphosed calcium/magnesium-rich sedimentary rock.*

3.3.2 Some Other Important and Non-Conspicuous Minerals in the Fells

In addition to common silicates and aluminosilicates listed above, there are other common or important minerals found in small percentages in the rocks of the Boston area and the Fells.

Calcite ($CaCO_3$) is a calcium carbonate mineral that is usually transparent, comes in a variety of colors depending on impurities, has a hardness of 4, and has three well-defined cleavage directions at 75° and 105° to each other. Calcite is famous for its double refraction of light (Fig. 3.22). It will immediately fizz when exposed to dilute hydrochloric acid (HCl; Fig. 3.7). Calcite is a common rock-forming mineral in many places because it is the primary constituent of limestone and marble, but in the Boston area and the Fells these rock types are not very common. Calcite is restricted to small veins (Fig. 3.23) and small areas of metamorphic rock in the Fells.

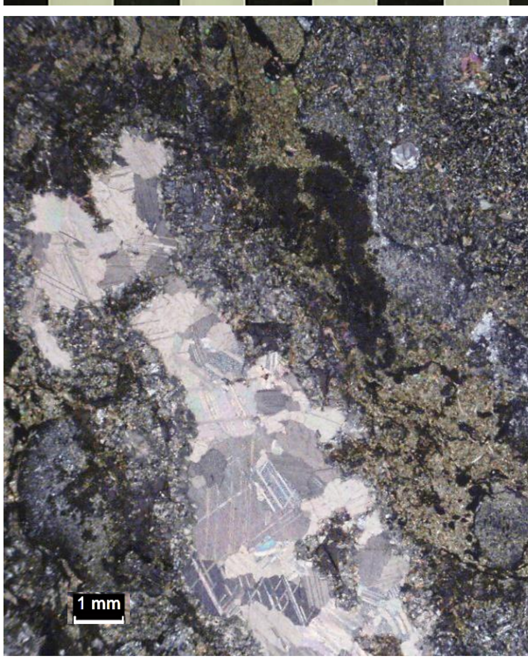


Figure 3.22 (above) *– Calcite ($CaCO_3$) easily cleaves in three directions that have 75° and 105° angles with each other, and the mineral rapidly reacts with dilute hydrochloric acid (Fig. 3.7). Shown on the left above are calcite cleavage fragments or "rhombs". Calcite also has the property that in certain directions it will split light passing through it (double refraction) producing a double image. On the right above is a piece of limestone, almost entirely calcite, with fossil shells. Scale in cm.*

Figure 3.23 (left) *– Calcite (pale pink and gray) forming a vein in metamorphosed fine-grained mafic igneous rock. Note the fine lines that form patterns in the calcite. Thin section view with crossed polarizers.*

Iron Oxides and Hydroxides – Iron easily forms opaque oxide minerals that are important secondary minerals in many rocks. The chemical formulas are given here to emphasize the different crystal and chemical forms that arise from different ratios of iron to oxygen. *Magnetite* (Fe_3O_4) is a dark gray metallic mineral (Fig. 3.24) that is naturally magnetic and exhibits a dark gray streak color. It is common in rocks formed by the cooling of mafic magmas. Magnetite sometimes grows with octahedral (8-sided) crystals in metamorphic rocks (Fig. 3.24B), or with a skeletal structure in mafic igneous rocks (Fig. 3.24C). *Hematite* (Fe_2O_3) has a brick red streak color (Figs. 3.2 & 3.25). When hematite occurs as very fine particles, it has a reddish-brown earthy color (Fig. 3.25A), often as the red cement in sedimentary rocks. As visible crystals, it has bluish-silvery, metallic and flakey grains (specular hematite, Fig. 3.25B), as can be found in veins and along fractures in the Fells (Fig. 3.25C). *Limonite* ($FeO{\cdot}OH{\cdot}nH_2O$) is an iron oxide/hydroxide mineral (Fig. 3.26) with a yellowish to orangish-brown streak color (Fig 3.2) that may form as a product of weathering. It occurs in the Fells due to alteration of iron-bearing minerals and will form in veins or as a stain, i.e., as a rusty coating. Limonite can form by the oxidation of iron sulfide (pyrite, see below).

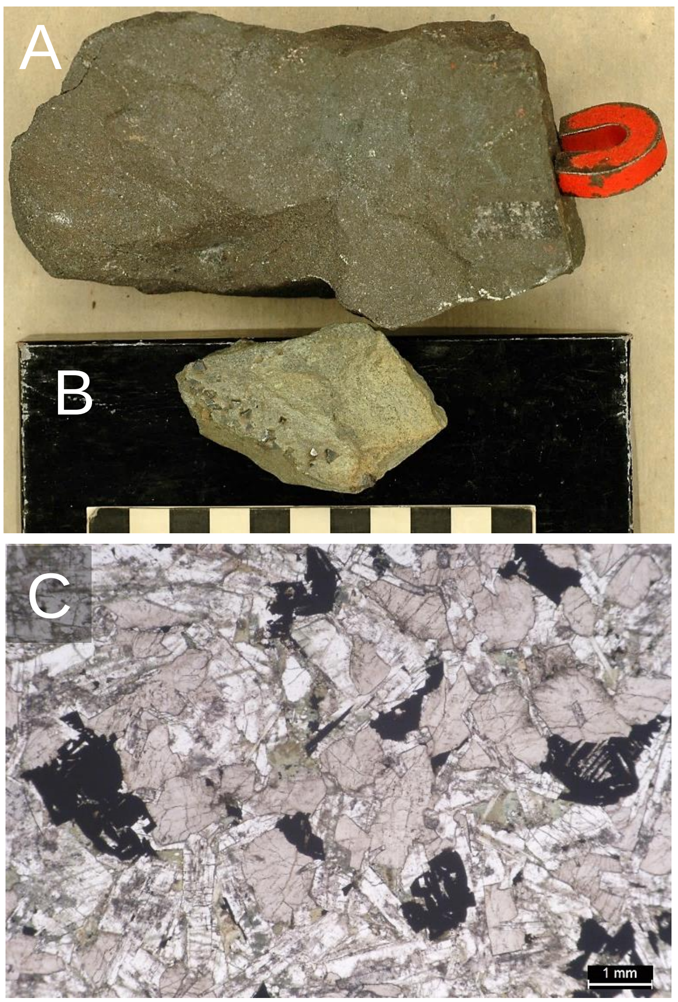
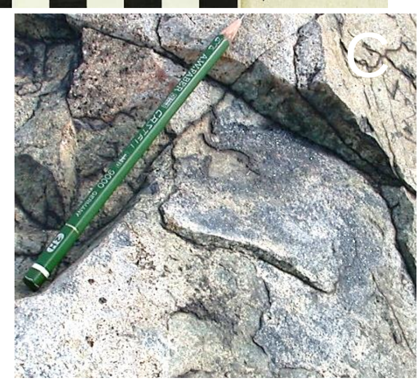


Figure 3.24 (above) *– A) Solid chunk of fine magnetite (Fe_3O_4) grains and B) small octahedral crystals in a metamorphic rock from Vermont. Scale in cm. C) Skeletal growth of magnetite (black opaque mineral) in a mafic igneous rock with plagioclase (white tabular crystals) and pyroxene (pale pinkish grains). Green areas are pyroxene altered to actinolite and chlorite. Thin section view in plane polarized light.*

Figure 3.25 (above and right) *– Hematite (Fe_2O_3) can have either an earthy luster (A) when hematite crystals in the rock are very small, or it can have a bluish gray metallic luster (B & C) when individual flakey crystals are visible.*



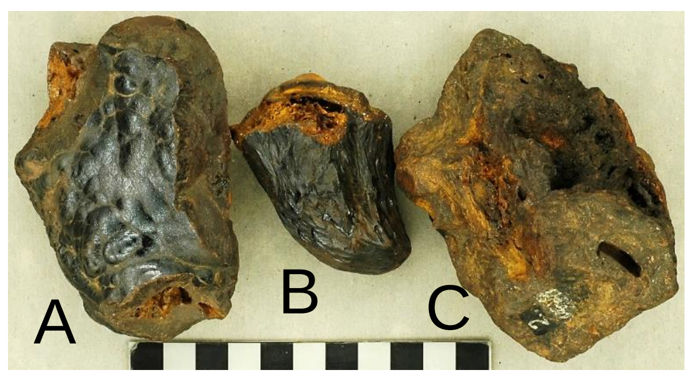


Figure 3.26 (above) *– Limonite ($FeO{\cdot}OH{\cdot}nH_2O$) generally has a grayish to yellowish-brown color and a yellowish- to orangish-brown streak color (see Fig. 3.2). Since it grows from a water solution it may have a bubbly (botryoidal) texture (A) and air spaces (B and C). Broken limonite pieces may exhibit radiating fibrous crystals (B). Scale in cm.*

Pyrite (FeS_2) is the most common sulfide mineral, also known as "fool's gold" (Fig. 3.27). It has a brassy metallic luster when found as crystals (Fig. 3.3), but a dark gray streak color (Fig. 3.2). Rocks that contain this mineral may be coated with limonite from the oxidation of pyrite. Pyrite is a minor microscopic component, but rarely a visible component, in many mafic igneous rocks in the Fells.

***Figure 3.27** – Pyrite (FeS_2) is a brassy metallic mineral (left; see also Fig. 3.3) with a gray streak color (Fig. 3.2). It can sometimes occur as pentagonal dodecahedral (12 sides, all pentagons) or cubic crystals as is shown here in a metamorphic rock (right). Scale in cm.*

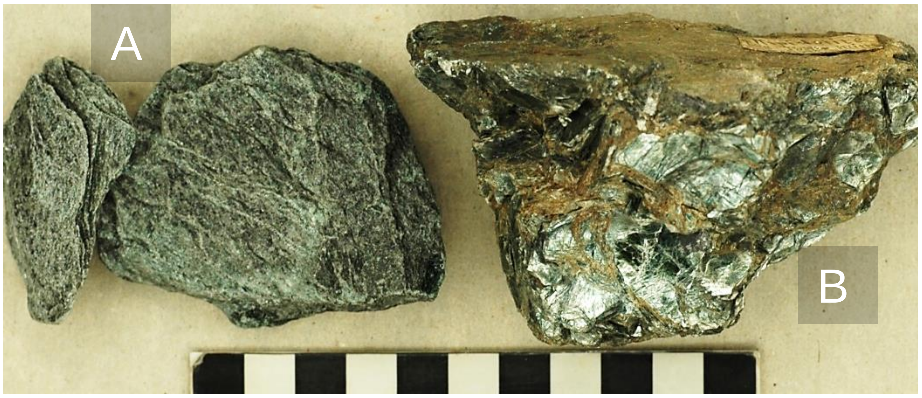
Chlorite $(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2{\cdot}(Mg,Fe)_3(OH)_6$ is a green aluminosilicate mica mineral that is usually formed from low pressure and low temperature (low grade) metamorphism of iron-bearing silicate and aluminosilicate minerals. It commonly occurs in the Fells as very soft, fine grains in altered rocks or on fracture planes, and can be recognized by its distinct dark greenish color if visible in hand specimen (Fig. 3.28). Chlorite indicates low grade and hydrothermal (hot water solution) metamorphism. One of the pyrite samples in Figure 3.27 is in a green metamorphic rock with abundant chlorite.

Epidote ($Ca_2(Al,Fe)_2Al_2O(SiO_4)(Si_2O_7)(OH)$) is a yellowish or olive- to pistachio-green aluminosilicate that forms as a result of the hydrothermal alteration of silicate and aluminosilicate minerals. It is almost impossible to find an outcrop of rock formed from magma in the Fells that does not have minor amounts of epidote, either where it has replaced minerals as an alteration product or was formed in veins (Fig. 3.29).

3.3.3 Some Other Minerals of Interest in the Middlesex Fells

These minerals are rarely visible except with a microscope, but they give us important information about rocks in the Fells.

Ilmenite ($FeTiO_3$) is a dark steely gray, metallic to earthy iron titanium oxide (Fig. 3.30) with a dark gray streak. It is very mildly magnetic. Ilmenite would not normally be on the list of common minerals, but it occurs microscopically with magnetite in the rocks of the Fells and indicates a relatively high titanium content in some igneous rocks.



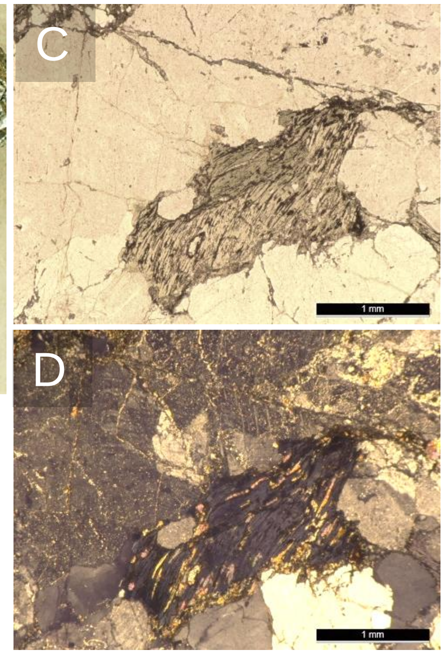


__Figure 3.28__ – Chlorite ($(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2 \cdot (Mg,Fe)_3(OH)_6$) is a dark green mica that is very soft. A) Pieces of metamorphic rock called schist made of chlorite. B) Large chlorite crystals. Scale in cm. C-D) Thin section view in a petrographic microscope of chlorite formed by alteration of biotite mica. Thin section in plain polarized light (C) shows green color and cleavage lines. Dark lines are magnetite. With crossed polarizers (D) chlorite has a very dark purple color. Light lines are epidote (see below). E) Chlorite (green grains) that has mostly replaced biotite in a metamorphosed sandstone. White grains are quartz and gray grains are altered feldspar. Thin section view with plain polarized light.

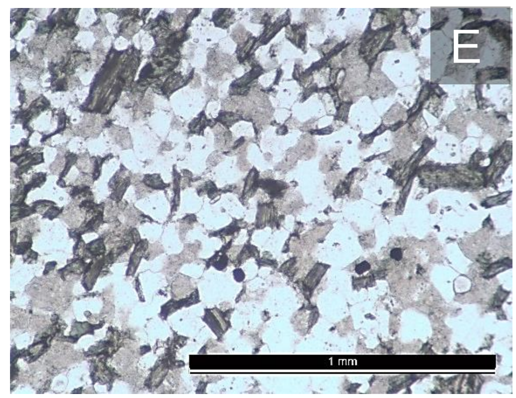
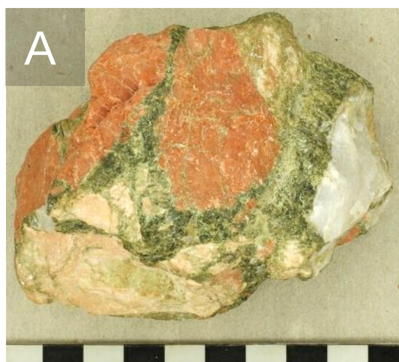
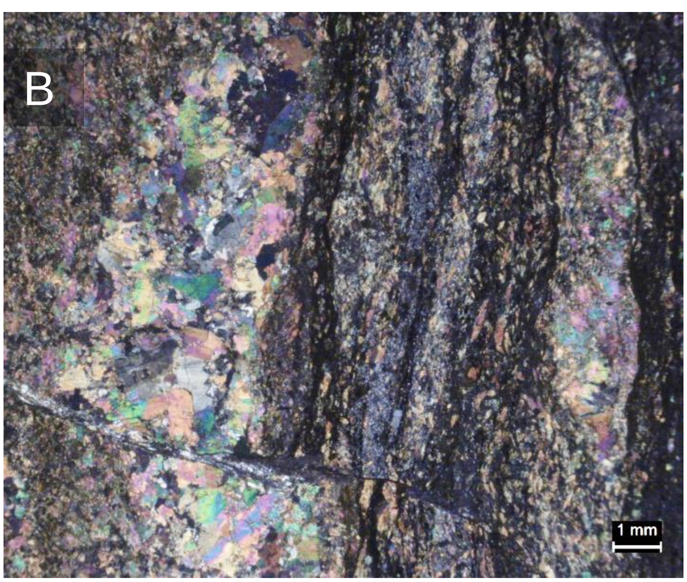


__Figure 3.29__ – A) Epidote ($Ca_2(Al,Fe)_2Al_2O(SiO_4)(Si_2O_7)(OH)$) in veins with its distinctive olive to yellowish-green (pistachio) color. It occurs here with quartz and alkali feldspar. This is a very coarse example not from the Fells. Scale in cm. B) Colorful band of epidote with fine chlorite, actinolite and plagioclase in metamorphosed mafic igneous rock in the Fells. Thin section view with crossed polarizers.





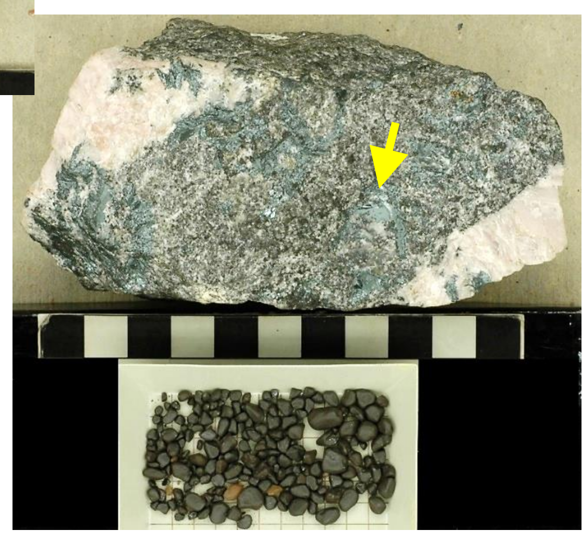


__Figure 3.30 (above)__ – Ilmenite ($FeTiO_3$) with a steely gray, dull metallic appearance (top, at arrow) on a freshly broken rock surface. It only occurs as microscopic mineral grains in the Fells. Ilmenite may be concentrated in some sand and gravel deposits (bottom), where it can be an ore for titanium. Scale in cm.

Olivine ($(MgFe)_2SiO_4$) is an iron magnesium silicate with a bright olive-green, transparent, glassy appearance and no cleavage (Fig. 3.31). It forms at high temperatures during the cooling of mafic magmas or in some metamorphic rocks but is frequently altered later during the continued cooling of a magma or when it is subjected to heat, pressure, and hydrothermal solutions. In the Fells, olivine occurs as a minor constituent in mafic igneous rocks, but it is largely altered (Fig. 31B).

Garnet ($(Mg,Fe,Ca,Mn)_3Al_2Si_3O_{12}$) is an aluminosilicate mineral of varying color with no cleavage that forms in igneous or metamorphic rocks (Fig. 3.32). Garnets are most commonly dark red in color, but variations in the cations and substitution by iron and chromium in the formula above for aluminum can cause a wide variety of colors. Garnet is the hardest mineral found in the Fells, but it is not common. In the Fells, it only occurs in mafic igneous rocks that have been metamorphosed by heat from a nearby igneous body (known as contact metamorphism; Fig. 3.32E-F). It also occurs as sand particles in the area's glacial sediment. In glacial deposits, it was transported from areas further north where garnet is common in metamorphic bedrock units.

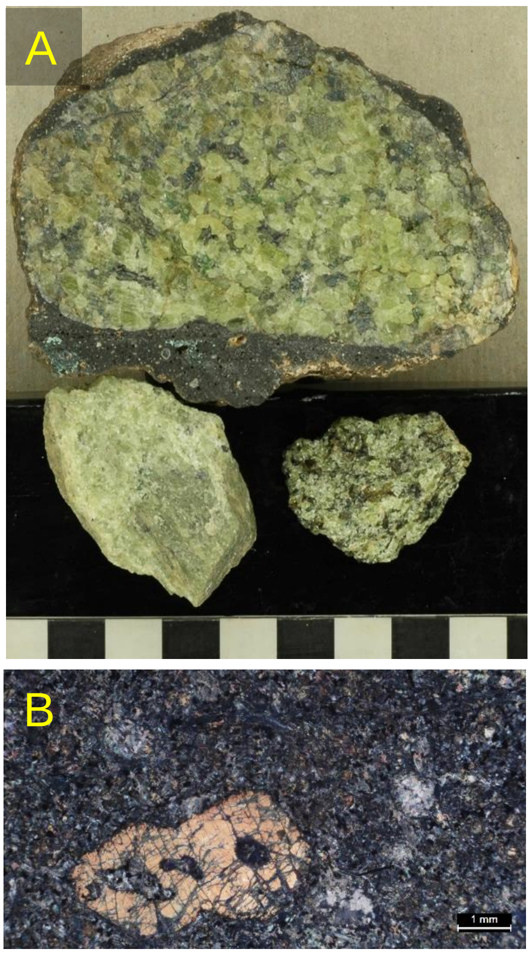


Figure 3.31 *– A) Olivine ($(MgFe)_2SiO_4$) is a bright olive-green mineral that commonly occurs in mafic igneous rocks as isolated crystals or crystals that have settled in magma as they form. Olivine is easily altered or weathered. Scale in cm. B) Partly altered olivine crystals in a fine-grained mafic igneous rock in the Fells. Thin section view with crossed polarizers.*

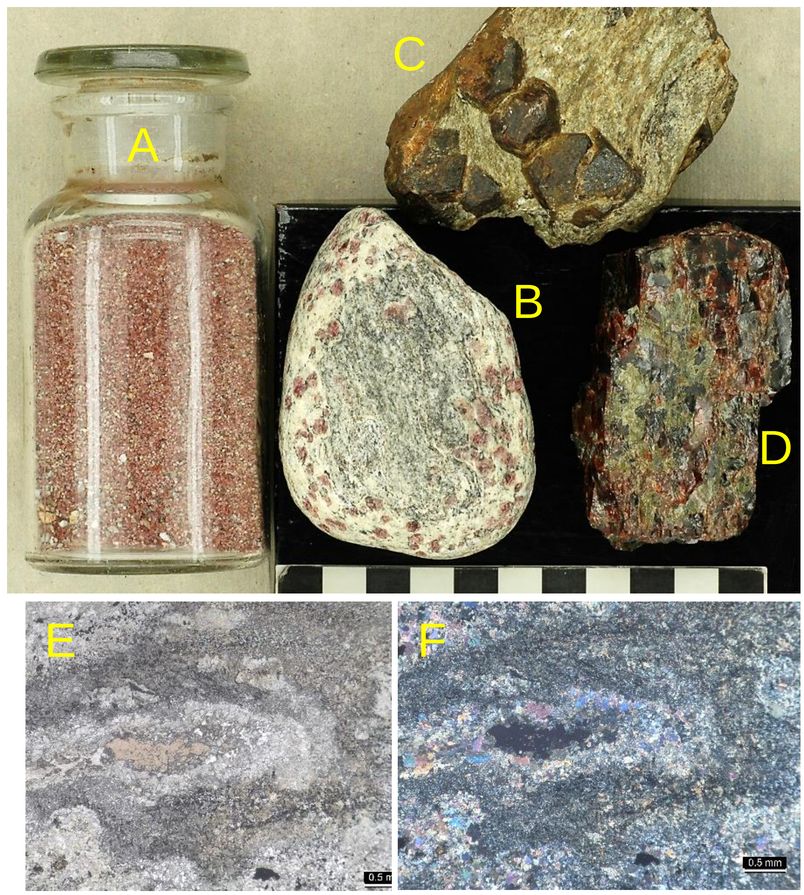
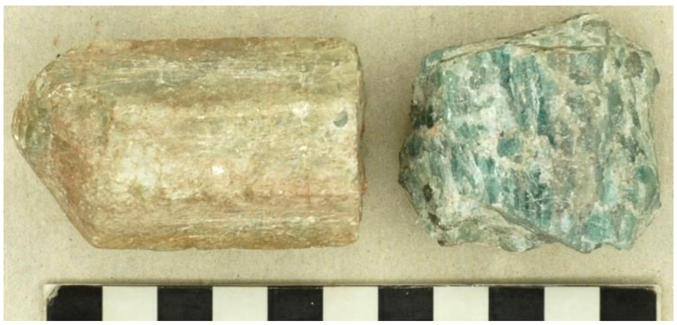


Figure 3.32 *– Garnet ($(Mg,Fe,Ca,Mn)_3Al_2Si_3O_{12}$) is produced in metamorphic rocks. Garnet is often a major constituent of beach sand (A) and metamorphic rock units (B-D) with tiny to very large crystals. Garnet forms dodecahedral (12-sided) crystals (C) and breaks without cleavage (D). Scale in cm. In the Fells (E & F), garnet is found in metamorphosed mafic igneous rocks. In a thin section in plain polarized light garnet is pale brown grains (E), which do not transmit light with crossed polarizers (F). Surrounding colorful mineral grains are epidote with chlorite (dark) and fine actinolite and plagioclase.*

The last four minerals described below are only found in the Fells as microscopic grains in thin sections. Two are important because of their phosphorus (apatite) and titanium (titanite, also called sphene) content. The third mineral (zircon) is critical to determining numerical ages for rock units. The fourth mineral (zoisite) occurs as an alteration product in calcium-rich rocks. It is unlikely that you would be able to identify any of these minerals in outcrops or hand specimens, even when using a hand lens.

Apatite ($Ca_5(PO_4)_3(F,Cl,OH)$) is a calcium phosphate mineral that occurs as clear, pale green, slender microscopic crystals within plagioclase feldspar, biotite, and chlorite in some of the coarse igneous rock units in the Fells, especially the Medford Dike (Fig. 3.33). Your teeth are made of a form of apatite.



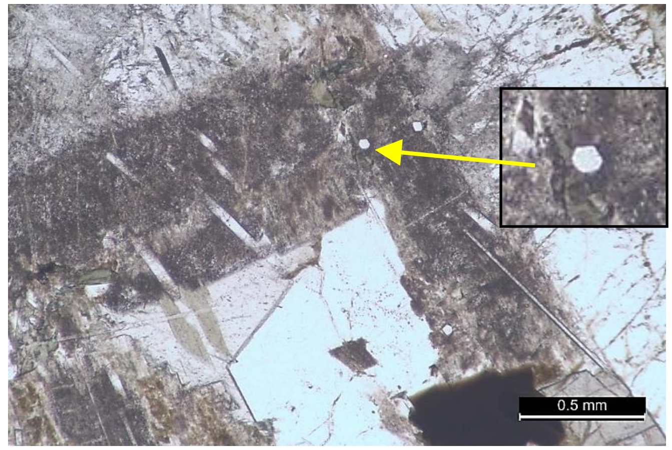
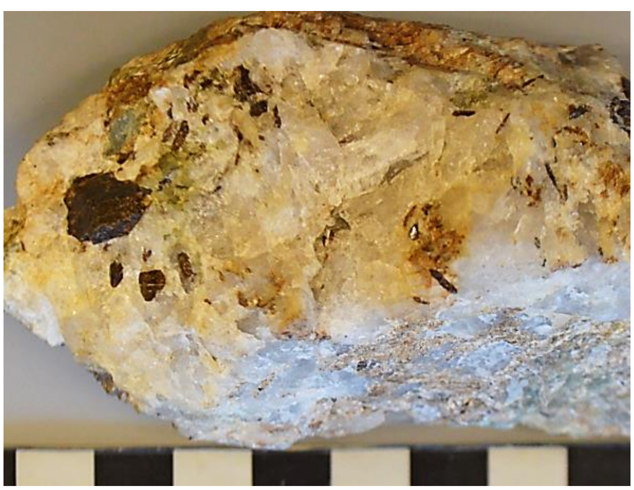


Figure 3.33 *–Shown to the left are a large hexagonal pale green apatite crystal and a broken fragment of bluish-green apatite. Scale in cm. (above) Thin section view in plain polarized light with microscopic needle-like apatite cutting across altered plagioclase crystals in the Medford Dike. When these crystals are viewed on end (inset above), they are hexagonal (arrow) like the large crystal on the left image.*

Titanite (a.k.a. Sphene) ($CaTiO(SiO_4)$) is a titanium calcium silicate mineral that usually has a resinous brown color and prominent cleavage planes. It occasionally occurs in the tiny spaces between quartz and feldspar crystals in coarse felsic igneous rocks in the Fells (Fig. 3.34).



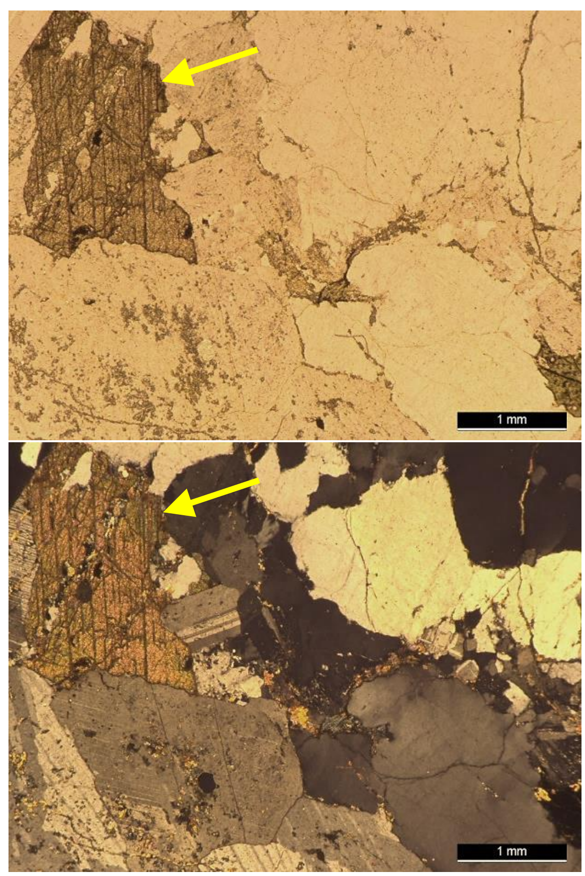


Figure 3.34 *– Titanite (sphene, $CaTiO(SiO_4)$) is shown above as rare large crystals. Titanite crystals are usually brown in color with prominent cleavage planes. Titanite only occurs in the Fells as sand-sized crystals between much larger quartz and feldspar grains in coarse felsic igneous rocks (thin section images on right at arrows). Above right is thin section in plain polarized light while below is the same view with crossed polarizers.*

Zircon ($Zr(SiO_4)$), is a zirconium silicate mineral found in the Fells as scattered microscopic crystals in all felsic igneous rocks (volcanic and plutonic) and as sand grains in metamorphosed sandstone (Fig. 3.35). Zircon is extremely hard, resistant to chemical weathering, and resistant to metamorphism. It also contains trace amounts of radioactive uranium isotopes that make it a useful mineral for determining the numerical ages of rocks (see Chapter 8).

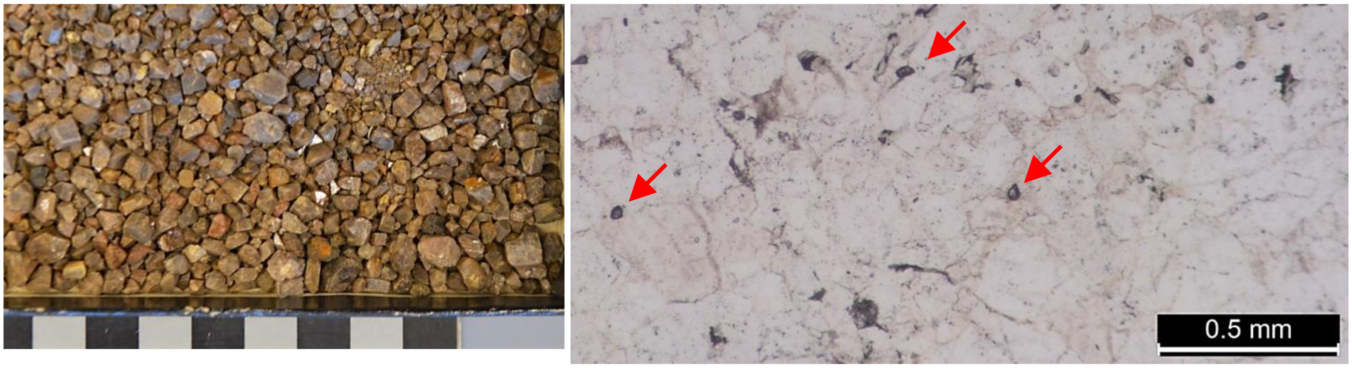


***Figure 3.35** – Zircon ($Zr(SiO_4)$) occurs in the Fells as only very small microscopic crystals in igneous rocks or as sand grains in metamorphosed sandstone. (left) Zircon granules not from the Fells. Scale in cm. (right) Microscopic zircon grains in metamorphosed sandstone in the Fells (arrows). Concentrations of zircon grains like this are rare and zircon is usually difficult to see in a thin section both because of its grain size and scarcity. To get an age on zircon crystals the rock will have to be crushed and the zircon crystals separated. It would be nice to be able to find large grains like on the left. Thin section view in plane polarized light.*

Zoisite ($Ca_2Al_3(SiO_4)(Si_2O_7)O(OH)$) is a calcium aluminosilicate related to epidote that is found in calcium-rich metamorphic rocks. It is recognized by its common concentric crystal banding and anomalous blue colors when viewed with crossed polarizers in a petrographic microscope. In the Fells it has been found only microscopically (Fig. 3.36). You should not expect to see visible crystals in the field.

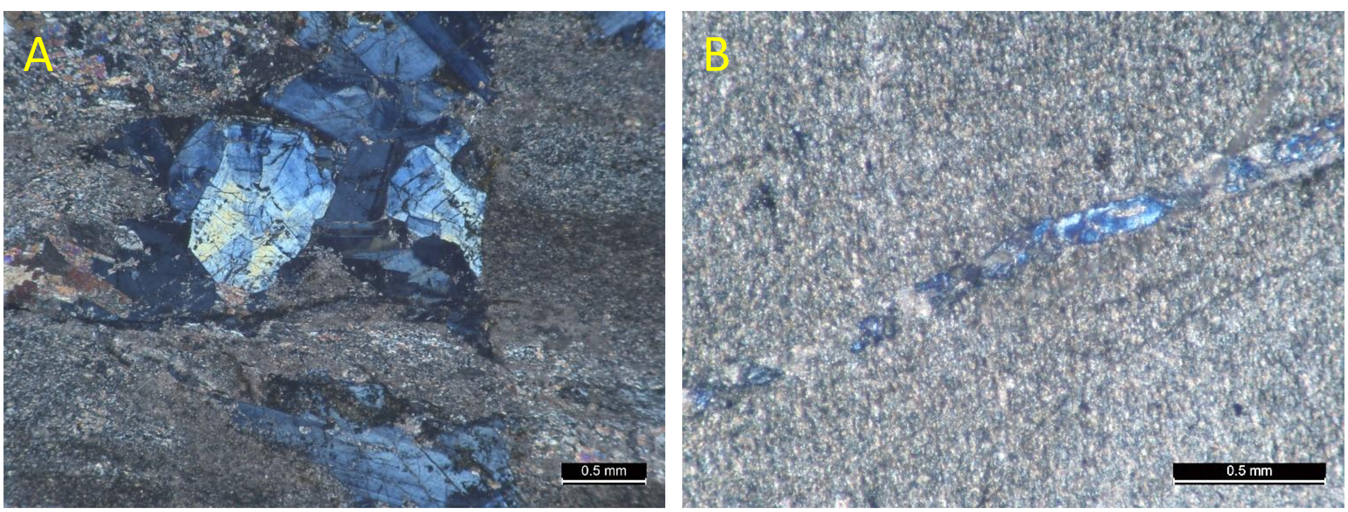


***Figure 3.36** – Zoisite ($Ca_2Al_3(SiO_4)(Si_2O_7)O(OH)$) has only been found microscopically in the Fells and is recognized by its concentric banding and anomalous blue colors. Thin section views with crossed polarizers. (left above) Zoisite in metamorphosed calcareous sedimentary rock in Virginia Wood with very fine crystals of amphibole (tremolite). (right above) Zoisite as a vein mineral in a sedimentary rock on Whip Hill. Vein runs across relict bedding, which is faint and vertical in this view. Heating of the rock next to an intrusion caused tremolite to grow parallel to bedding.*

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