CHAPTER 6: METAMORPHIC ROCKS

This chapter describes processes involved in metamorphism and the characteristics of metamorphic rocks. For a more advanced treatment of this subject see Sanders (2018) and Winter (2010).

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

Metamorphism includes any process that alter a rock after its initial formation as a result of temperature and/or pressure changes. Heat and pressure can do several things to change rocks. During metamorphism:

1) new minerals become stable and can grow from the components of minerals that become unstable,

2) mineral grains can recrystallize into larger or smaller grains either as a result of mineral grains of the same type forming larger single grains or through expansion of mineral grains from components of unstable minerals, and

3) mineral grains can change shape as a result of deformation when they are weakened at higher temperatures and as they are exposed to greater stresses. As a result, both lineations and foliations can develop.

In these cases, not only does the temperature and pressure regime matter, but also important is the time over which conditions are applied and the fluids (chemical solutions) circulating through the rock. The fluids in the rock contain dissolved components derived from chemical reactions at high temperatures and pressures.

A *metamorphic rock* is defined as one that has experienced alterations due to changes in temperature and pressure. This includes the metamorphism of igneous, sedimentary, or existing metamorphic rocks. It is tempting to think of this simply as rocks being changed by exposure to higher temperatures or pressures. However, once rocks become stable at elevated temperatures and pressures, they can also be changed when temperature and pressure decrease, which is called *retrograde metamorphism*. Whether this happens is dependent on how fast the change occurs. Many metamorphic rocks exhibit either minor or limited retrograde metamorphic changes. The transition of rocks from Earth surface conditions to metamorphism at relatively low elevated temperatures and pressures can be an indistinct boundary, but there are easily recognizable changes when temperatures and pressures get higher. At the other extreme, if temperatures and pressures get high enough, eventually reaching the point where minerals begin to melt, magma will start to form. Remember the rock cycle in Chapter 2.

6.1 REGIONAL METAMORPHISM AND METAMORPHIC GRADE

Regional metamorphism is caused by the heating and squeezing of rocks over a large area of the crust (think on the scale of whole mountain ranges). The degree to which a rock is regionally metamorphosed is known as its *metamorphic grade*. Rocks that have been metamorphosed at low temperatures and pressures have a low metamorphic grade, while rocks subjected to high temperatures and pressures, and that have been altered substantially, have a high metamorphic grade. With higher grades of metamorphism, fewer mineral grains survive without change, and many are completely reconstituted.

The original rock that was altered to form a metamorphic rock is known as the *protolith*, which has a large influence on the composition of the resulting metamorphic rock. In the naming of metamorphic rocks, it is sometimes customary to apply the prefix “meta-” to the name of the protolith; for example: metaconglomerate, metasandstone, and metabasalt (Fig. 6.1). In some cases, it is not possible to determine the protolith without doing a chemical analysis because the texture and minerals of the protolith have been completely altered. In addition to the names above, there are other names applied to metamorphic rocks based on their overall composition and structure.

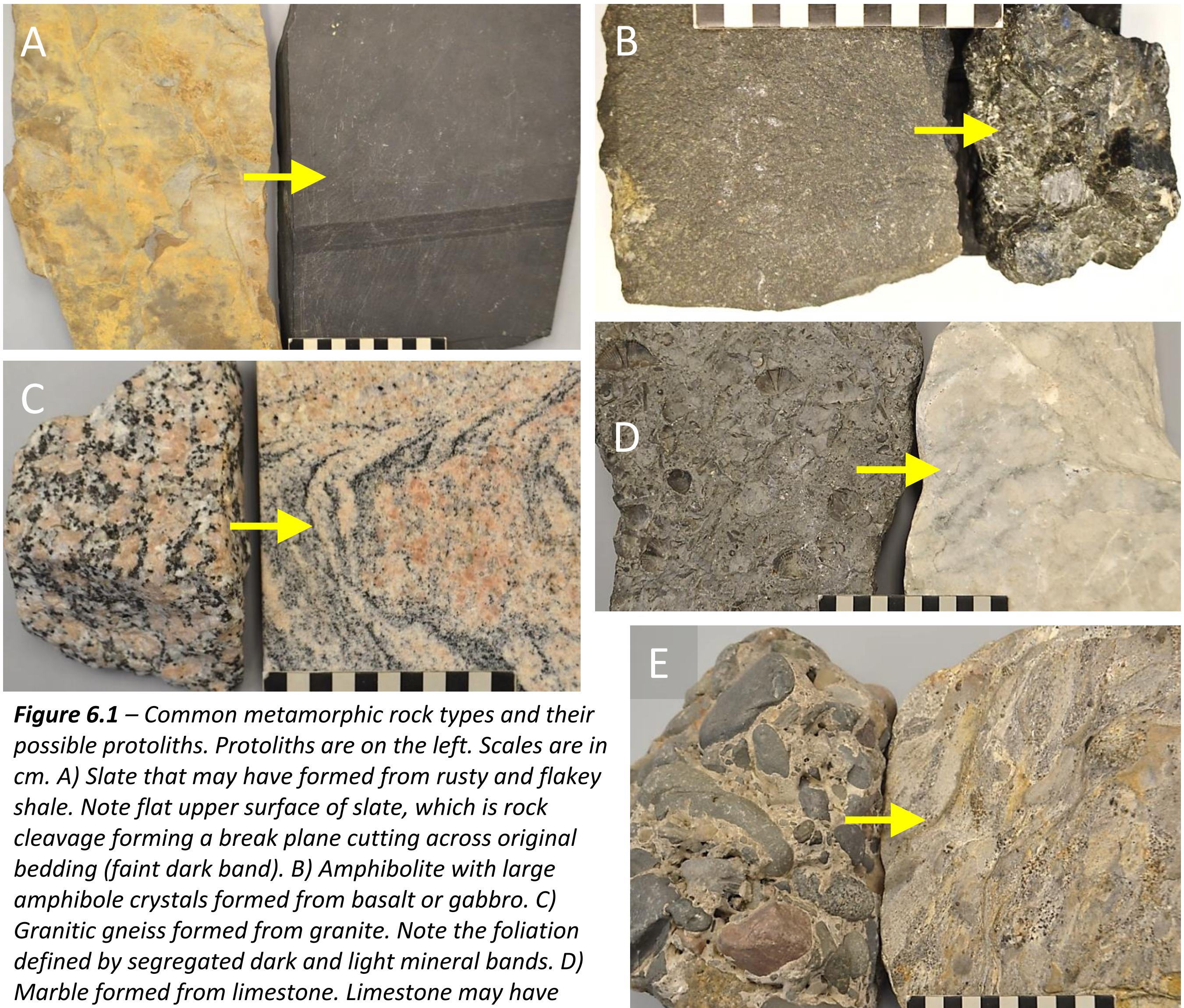


Figure 6.1 *– Common metamorphic rock types and their possible protoliths. Protoliths are on the left. Scales are in cm. A) Slate that may have formed from rusty and flakey shale. Note flat upper surface of slate, which is rock cleavage forming a break plane cutting across original bedding (faint dark band). B) Amphibolite with large amphibole crystals formed from basalt or gabbro. C) Granitic gneiss formed from granite. Note the foliation defined by segregated dark and light mineral bands. D) Marble formed from limestone. Limestone may have abundant fossils (shown here are brachiopods) that are wiped out by recrystallization of calcite. E) Metaconglomerate formed from conglomerate. Note the stretched and flattened pebbles.*

As metamorphic grade gets higher, *regional metamorphism* induces more changes to mineral grains and will eventually destroy original structures such as bedding and fossils (Fig. 6.1). Minerals may change to other minerals that are more stable at higher pressure and temperature, or they can recrystallize into larger grains of the same mineral. Even lower pressures and modest temperatures may cause mineral grains of new or recrystallized minerals to align themselves with an orientation that is more compatible with the direction of stress being applied to the rock. Geologists categorize metamorphic grade by looking for key minerals that are indicators of specific pressure and temperature thresholds. Based on these minerals, metamorphism can be categorized by different temperature and pressure regimes, with each *metamorphic grade* having its own characteristic minerals. Some minerals formed by regional metamorphism in the Fells are chlorite, muscovite mica, diopside, tremolite, actinolite, and hornblende (see Chapter 3).

In most places in the Fells, original structures and protoliths of metamorphic rocks are still recognizable in the field. Regional metamorphism has altered the rocks less than many other areas of New England, which have significantly higher metamorphic grades. However, it should be emphasized that this does not necessarily mean that the rocks in the Fells have not been exposed to moderate pressures and temperatures. It is possible, if the rocks have not been deformed significantly (sheared), for original structures to survive. If you want to see metamorphic rocks of a high grade that have had their original protolith structures altered and have some of the minerals traditionally recognized as "metamorphic minerals," this can easily be accomplished by driving west or north of Boston on the Mass Pike, Rt. 2 or Rt. 93, which have many road cuts in regionally metamorphosed rock (Skehan, 2001; or see guidebooks at NEIGC, 2021).

6.1.1 Regional Metamorphic Structures and Rock Types

Regionally metamorphosed rocks are often squeezed and stretched (sheared) at high temperature and pressure conditions. This can produce several types of linear and planar features (lineations and foliations). For example, it is not uncommon for individual mineral grains to become elongate and form a linear feature in a rock (Fig. 6.2). Pebbles in a conglomerate can also get flattened and elongated. Lineations and foliations indicate the direction in which the rock has been stretched and flattened. Foliation in metamorphic rocks includes *fractures* or *joints*, *slatey cleavage*, *schistosity*, and *gneissic banding* (Fig. 6.3). Foliations can also be folded and may represent either folding of layers originally in the protolith, such as bedding in a sedimentary rock, or the folding of earlier foliations that were developed during earlier metamorphism (Fig. 6.4).

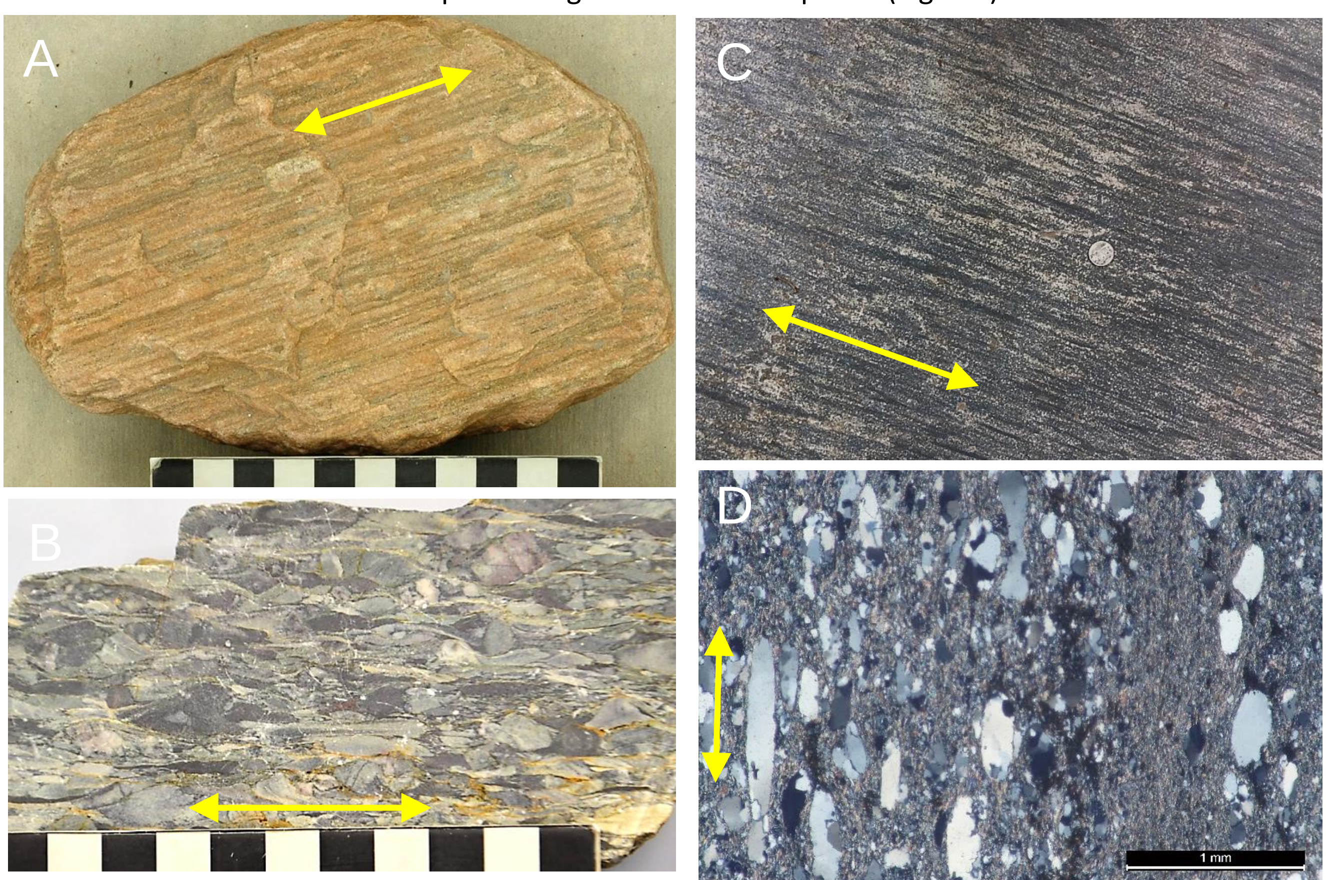


Figure 6.2 *- (caption on next page)*

Figure 6.2 (previous page) *– Some common lineations found in metamorphic rocks. A) Linear stretching and elongation (yellow arrow) of quartz and alkali feldspar grains on a foliation plane in gneiss from the Adirondacks of New York. Scale in cm. B) Elongation of pebbles in a metaconglomerate on a foliation plane in the Harvard Conglomerate in Harvard, Massachusetts. The pebbles are also flattened parallel to a foliation plane and the matrix of the rock has deformed to compensate for the stronger pebbles. Scale in cm. C) Foliation plane in mica-rich rock (schist) with a lineation defined by dark minerals on the plane. Light areas are muscovite mica. Sidewalk slab on Main Street, Nantucket, Massachusetts. Quarter for scale. D) Thin section view with crossed polarizers of flattened quartz grains in metasandstone in the Fells. Quartz grains are sutured where in contact with each other and have serrated edges and internal changes in color due to bending of the grains and recrystallization of different parts of single original sand grains. Pink-colored fine background grains are tremolite that grew from a calcium-rich matrix material (see Chap.3).*

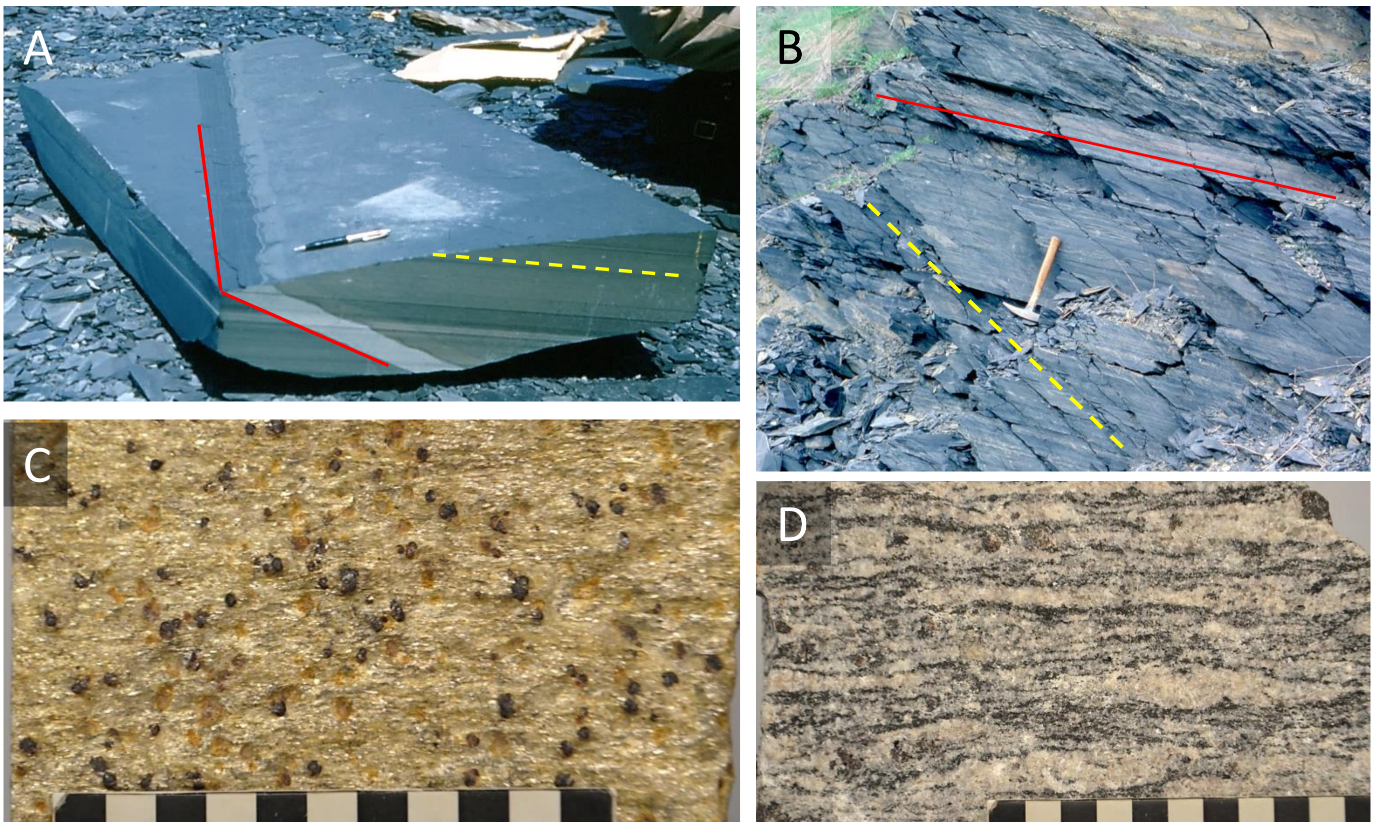
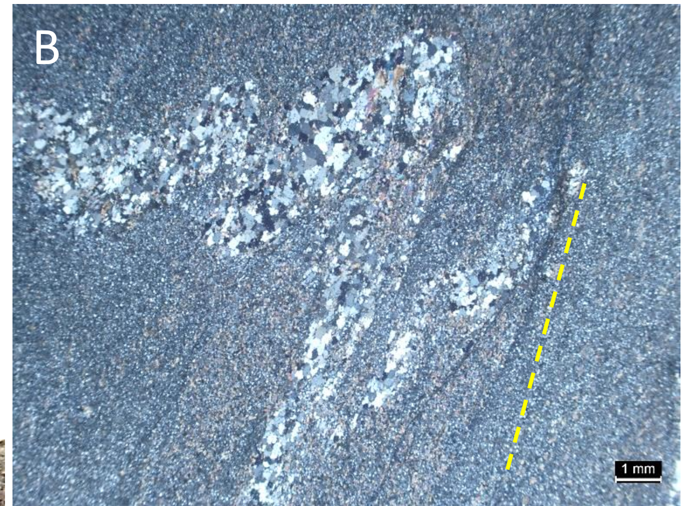


Figure 6.3 *– Some common foliations found in metamorphic rocks. In addition to fractures and joint planes (Fig. 1.9) there can be: A) slatey cleavage that forms flat planes (top surface of block) that cut across bedding (red line) as a result of the growth of microscopic mica in a uniform direction. Lines on the near and left face of the rock that cut bedding are saw marks (yellow). Image courtesy of James D. Hume. Pen for scale. B) Slatey cleavage (dashed yellow line) cutting across original bedding (red line) in the Martinsburg Formation in southeastern New York. Rock hammer for scale. C) Schistosity, which is often wavy, that results from the macroscopic planar growth of mica (shiny mineral grains). The example is a garnet (dark grains) schist viewed down onto the foliation plane. Scale in cm. D) Gneissic banding in garnet gneiss formed from the stretching, preferential orientation, and segregated recrystallization of coarse mineral grains including quartz and feldspar pods, biotite mica, and amphibole. See also Figure 6.1C.*



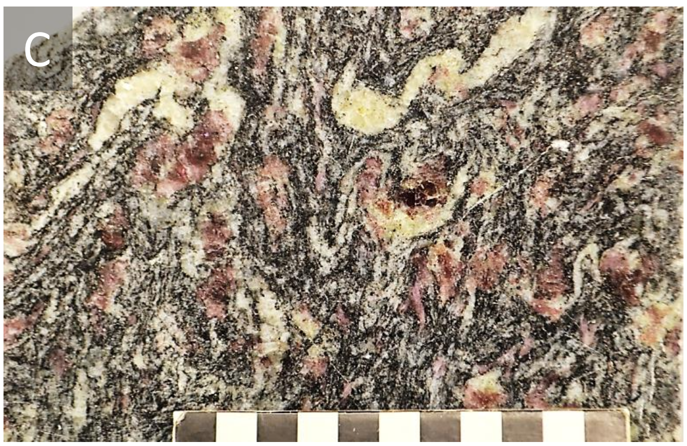


Figure 6.4 *– Folds formed in metamorphic rocks. A) Folding of sedimentary layers of a protolith in chloritic banded iron formation at the Iron Mountain Mine near Atlantic City, Wyoming. Chlorite gives the rock its green color. Image about 1 m across. B) Quartz layer (likely an original sandstone layer) that is highly folded and recrystallized in metamorphosed argillite with faint cleavage development (dashed yellow line). The rock was heavily compressed, or shortened, perpendicular to cleavage, causing the tight folding of the quartz layer. C) Gneiss with folded foliation that was not in the original protolith. Earlier metamorphism created the gneissic banding, which was later folded. The purplish-red grains are garnet. Black bands are mostly biotite mica and light bands are feldspar and quartz. Scale in cm. This rock would make a beautiful countertop!*

Many of the foliation structures seen in regional metamorphic rocks are easy to recognize, and geologists have developed names for rocks with these structures. Any time hard rocks are put under stress, they will eventually fail if the stress is high enough. Parallel fractures, or *joints*, will develop with an orientation determined by the direction of the stress applied to the rock and the rock's mechanical properties (see Fig. 1.9B). Joints tend to form at relatively low temperatures when the rocks are still brittle (more on brittle vs. ductile rocks in Chapter 7). The orientations of joints make it possible to determine the direction of the stress that was applied to the rocks when the joints formed.

At low grades of metamorphism, sedimentary rocks that have clay in them begin to undergo mineralogical changes with the microscopic recrystallization of clay minerals to mica. This is aided by the dissolution of minerals and loss of mass as the rock is squeezed. Dissolved constituents greatly aid the recrystallization process and formation of mica. Mica grains grow as sheets perpendicular to the stress being applied to the rock, which is usually at a different orientation than sedimentary bedding. The rock will tend to break more easily in the direction of mica growth, leading to the development of *slatey cleavage* and the rock is called *slate* (Fig. 6.3A-B, 6.4B). Slatey cleavage takes the form of closely-spaced parallel fractures that cut across bedding. With intense metamorphism, mica grains grow to a size where individual flakes can be recognized without a microscope. The rock starts to develop a shiny *micaceous* appearance and is said to have *schistosity* (Fig. 6.3C). The rock will split more easily parallel to wavy surfaces defined by mica flakes. This type of rock is called *schist*.

In rocks that are dominated by a combination of mineral grains other than mica, including quartz, feldspar, and silicate and aluminosilicate mafic minerals, there is often a segregation of minerals of different types as the rock recrystallizes. While this rock is being sheared at high temperature and pressure, layers of rock with different compositions will develop as *gneissic (or metamorphic) banding*. A rock that displays this banding is called *gneiss* (Fig. 6.3D & 6.4C).

6.2 CONTACT METAMORPHISM

A second way in which a rock can be metamorphosed is by being in an area heated by intruding magma. The magma loses heat to the surrounding host rock, which induces changes in the host rock's mineral grains. At shallow depth, the rock is heated but doesn't develop a foliation because of a lack of shearing or deformation. In this environment, metamorphism is caused by chemical reactions between chemical-laden fluids and the heated minerals that become unstable. This is known as *contact metamorphism* and is often referred to as *baking*. Contact metamorphism is a common phenomenon, but its extent is usually restricted to a limited area as compared to *regional metamorphism*. Adjacent to small intrusions, especially along dikes, it may be possible to see a baked zone, but it rarely extends very far away from the intrusion, perhaps only a meter or two, and the effects of contact metamorphism may be subtle. However, adjacent to large intrusions, more heat must be dissipated for the magma to cool, and a larger region is baked. As a result, the rock surrounding a large magma chamber is usually subjected to higher temperatures for a longer time than rock next to a small dike.

6.2.1 Hornfels Formation

When shale or other fine-grained rocks are baked, it has the effect of creating a hard, brittle rock called *hornfels* (Fig. 6.5). When clay and silt are baked, the hornfels is effectively a ceramic material like would form in a kiln. In the Boston area, a good place to see hornfels is at the eastern-most tip of the Nahant peninsula where sedimentary rocks, originally thin shale and limestone beds of the Weymouth Formation, were baked in proximity to many basaltic dikes and sills and adjacent to a large body of gabbro (Fig. 6.5).

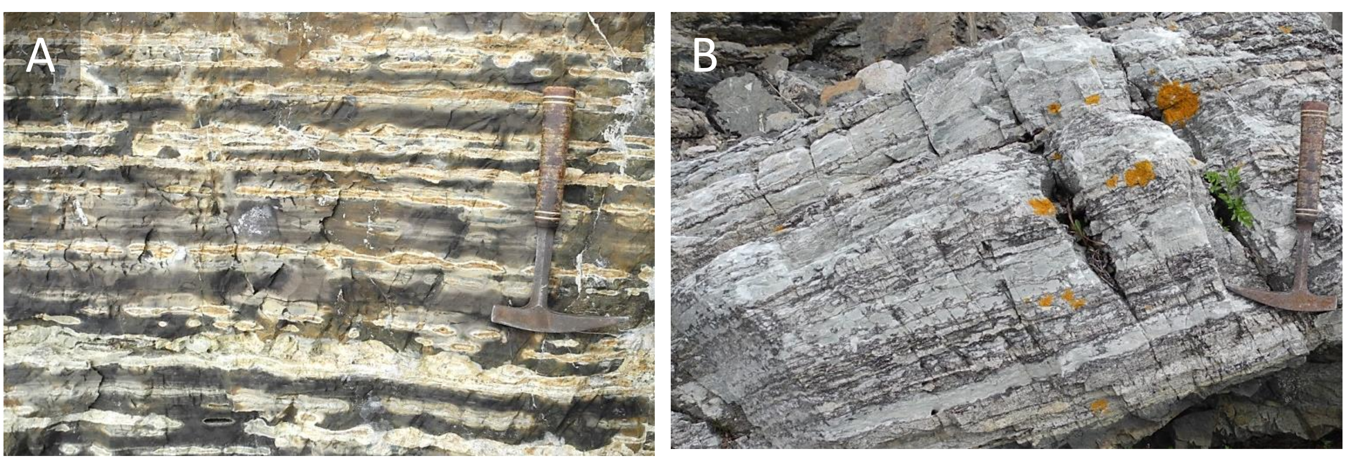


Figure 6.5 *– Hornfels formed from the baking of shaly sedimentary rock during contact metamorphism of the Weymouth Formation at East Nahant, Massachusetts. A) Contact metamorphism of calcareous shale with pod-like areas where carbonate rock layers were baked, resulting in a change in their shape as they lost* CO_2 *and the adjacent shale beds dehydrated. The dark hornfels layers have the appearance of chert but are not pure silica. B) Limestone beds, apparently baked less extremely than in (A), that have been recrystallized to marble interbedded with calcareous shale layers that form thin hornfels layers. Rock hammer for scale.*

6.3 METAMORPHISM OF ROCKS WITH CARBONATE MINERALS

Regional or contact metamorphism of limestone or dolostone can cause not only their recrystallization to marble but also the formation of many new minerals that take advantage of the high calcium and magnesium content of the carbonate rock. Marble (with either calcite or dolomite) and new calcium/magnesium-silicate minerals together form what is known as skarn when carbonate rocks have been contact metamorphosed. *Skarn* is not common in the Fells, but it does have a tiny occurrence at the north end of Middle Reservoir near a large granite intrusion. Also, Ca-Mg silicate and carbonate layers in Virginia Wood are the result of regional metamorphism of calcite and dolomite bearing sedimentary rocks. These rocks have minor calcite with calcium/magnesium minerals (Fig. 6.6) including magnesium-rich amphibole (tremolite), calcium-rich pyroxene (diopside), and a calcium silicate related to epidote (zoisite). The original rock was probably not limestone or dolostone but instead argillite or sandstone with a carbonate cement.

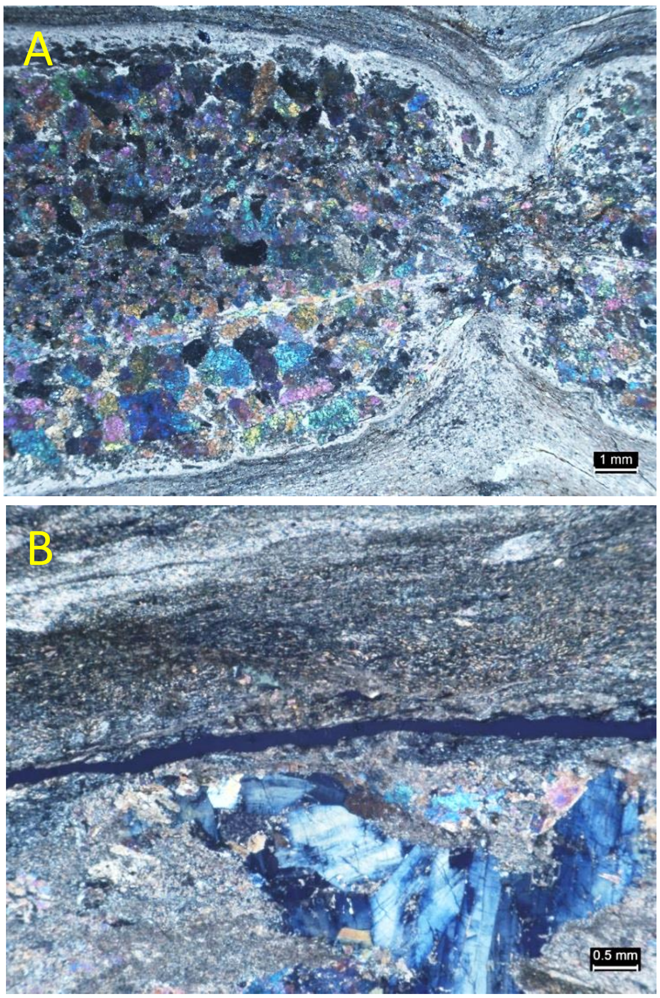


Figure 6.6 *– Calcium magnesium silicate minerals in Virginia Wood where carbonate layers were metamorphosed within the sandstone and argillite. Thin section views with crossed polarizers.*

A) Pod of diopside crystals (brightly colored) in heavily foliated layers of very fine tremolite, quartz, and chlorite. Within the pod are fine crystals of calcite. The whole pod has been stretched and separated on the right side.

B) Heavily foliated very fine tremolite, quartz and chlorite with large crystals of diopside (bright blue and pink) and zoisite (grayish blue). The dark line in the center is a fracture in the thin section (open space).

6.4 CONTACT METAMORPHISM OF METASANDSTONE

In many places in the Fells, metasandstone was intruded by large bodies of igneous rock that caused mineralogical changes (Fig. 6.7). In both contact areas and inclusions of metasandstone, matrix materials, and minor amounts of feldspar, were converted to very fine muscovite mica (sericite), chlorite, and biotite, and occasionally hornblende (amphibole). In addition, the quartz in these rocks has been recrystallized, and contacts between quartz grains have flat, sutured boundaries.

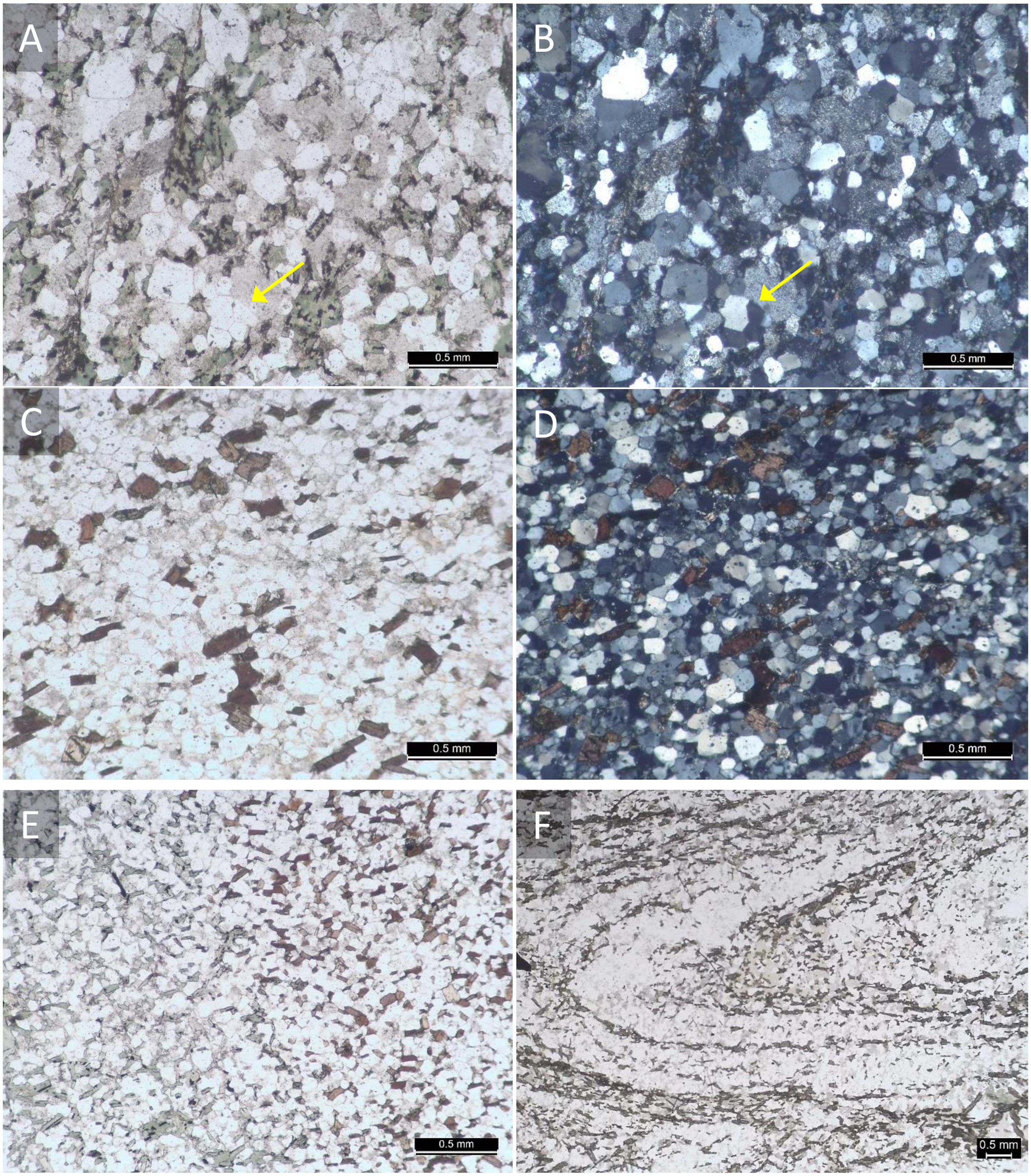


Figure 6.7 *– Contact metamorphism of metasandstone in thin sections. Examples shown here are from inclusions in granitic plutons of the Fells. Images A,C,E and F are thin sections in plane polarized light; B and D are with crossed polarizers. In plane polarized light, chlorite is green, biotite is orangish-brown, feldspar is light gray and fuzzy due to alteration to sericite, and quartz is clear. In crossed polarizers, chlorite is dark gray to black, biotite is brown with faint colors, feldspar is gray and speckled, and quartz is white to black and very clear (non-speckled). Chlorite is likely an alteration product of biotite. A-B (same view): Metasandstone with matrix material recrystallized to chlorite and black opaque mineral (magnetite), and dusty gray feldspar partly altered to sericite. Note flat sutured grain boundaries between quartz grains (arrows). C-D (same view): Metasandstone with matrix material altered to biotite and minor chlorite. Quartz grains also have flat boundaries with each other. E: Metasandstone with separate areas of chlorite (left) and biotite (right) in the same sample. F: Folded quartzite with layering defined by bands of a chlorite and biotite mixture. This is likely heavily altered original bedding that was first folded.*

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