CHAPTER 2: AN INTRODUCTION TO EARTH MATERIALS

Before you can understand the geologic history of an area you must have a fundamental understanding of what Earth is made of: rocks. The purpose of this section of the book is to provide you with introductory knowledge of the materials that make up Earth's crust. It does not provide a detailed discussion of rocks specific to the Middlesex Fells, which will come later, but focuses on an introduction to the building blocks of rocks, what we call minerals, and the fundamental rock types.

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

2.1 WHAT ARE ROCKS AND MINERALS?

Given that geology or Earth science is the study of Earth's processes, formation, and history it will be essential that we know something about the materials that Earth is made of: rocks and minerals. *Minerals* are defined as: **naturally-occurring, inorganic, solid materials, with a crystalline structure, and a well-defined chemical composition that can be written as a *chemical formula***. Geologists give proper names to different minerals. Individual minerals can be identified because each mineral has a unique combination of properties determined by their chemistry and crystal structure.

What does it mean when something is *crystalline*? This means that the atoms and molecules in a mineral are arranged in a repeated 3-dimensional pattern. Crystalline structures are created in two ways: 1) the cooling of *magma* (molten rock) to or below its crystallization (or freezing) temperature, or 2) the precipitation of crystals from a water solution that becomes saturated with a dissolved constituent such that it can't hold any more of that material in solution. You have almost certainly experienced both processes. When ice forms, a liquid (water or the magma) is cooled to its crystallization temperature (0°C at 1 atmosphere) to produce ice (a crystalline solid). So, ice is a mineral! You can also produce crystals by dissolving salt in water and then letting the water evaporate. Eventually, evaporation will concentrate the salt in solution to the point where it can't all stay in solution and the salt will start to crystallize, i.e., the water solution has become saturated. If you try this experiment on your own be forewarned that it can make a mess because salt crystals will grow up the side of the container when the solution gets saturated. You will also be amazed at how much salt can be dissolved in a glass of water.

Different minerals may have the same chemical composition but are different because of varying crystal structures. For example, the minerals graphite and diamond are identical in terms of their chemical makeup. Both are pure carbon, but they have very different crystal structures. Diamond has a crystal structure in which carbon atoms are very tightly bound together and the mineral is very hard. It is the hardest naturally occurring mineral. On the other hand, carbon atoms are held together very loosely in graphite, and it is very soft. Because of how soft it is, graphite is used as a dry lubricant, while diamonds are used to cut or abrade other materials.

All minerals are *compounds* composed of *ions*, which are atoms or groups of atoms that have a net charge because they can either take up or lend *electrons* when attached to other ions of opposite charge. Positively charged ions that take up electrons from other atoms are called *cations* and negatively charged ions that give up electrons to other atoms are called *anions*. All mineral compounds have a charge balance or what we refer to as no net charge. In other words, cations and anions are bound together in various combinations such that their charges cancel. A simple example is the mineral *halite* (or common salt), which has a positively charged sodium atom (cation) bound to a negatively charged chlorine atom (anion) that produces sodium chloride (NaCl). There are well over 5000 known minerals. It is not necessary to know all the minerals (almost no one does!!) and most geologists become familiar with less than 100 minerals during their careers. While many minerals may be important to some facet of geology, less than 20 minerals are considered common rock-forming minerals.

Minerals are the primary building blocks of *rocks*, which are: **naturally occurring solids composed of minerals and/or other materials** (Fig. 2.1). Some of the non-mineral materials that can occur in rocks include organic materials and natural glass. For example, *coal* is a rock composed almost entirely of the decomposed remains of plants, while *obsidian* (a natural glass) results from the very rapid cooling of magma that produces a non-crystalline material, thus it is not made of minerals.

Figure 2.1 *– An example of different minerals that make up a common rock type found in the Fells - granite. Granite (below), seen here in a polished floor tile purchased at Home Depot, is made up of (left to right above) potassium or alkali feldspar, plagioclase feldspar, quartz (in this case smoky quartz with a dark gray color), and biotite (black mica). Granite is a coarse-grained igneous rock made of quartz and two different types of feldspar and in which alkali feldspar is greater than or equal to plagioclase. The mica is an accessory mineral that makes up a small percentage of the rock and does not have to be in the rock for it to be called granite. The other three minerals are required for a rock to be called granite. The most abundant mineral in the granite shown here is potassium feldspar, followed by quartz and then plagioclase. Scale in cm.*

2.2 ROCK AND MINERAL IDENTIFICATION

The identification of different rock types in the field from hand specimens, or in the laboratory using a microscope, is critical to understanding the formation and history of rocks and minerals because it is the key to determining the chemical components of which they are made and the processes that made them. One must be able to identify not only the types of minerals and other materials in a rock but another critical characteristic of rocks and minerals, their texture. *Texture* is the size and arrangement of particles and crystals in a rock. We often call the particles or crystals that make up a rock its *grains*, for example, like sand grains on a beach.

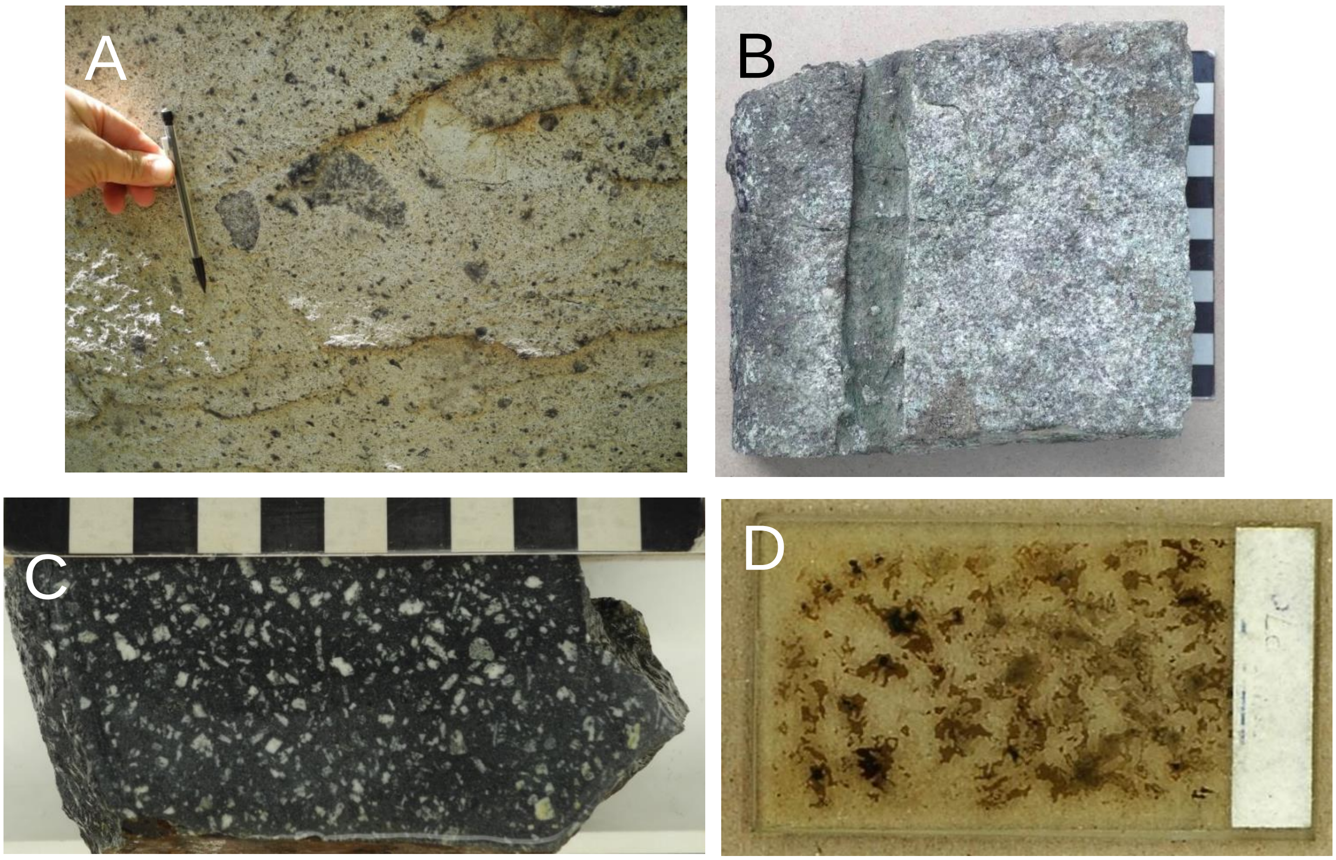


Figure 2.2 *– Observations of rocks and minerals can be made on several scales including: A) at outcrops, which are just bedrock exposures in the field; B) in hand samples with weathered surfaces or fresh surfaces created using a rock hammer; C) in cut or sawed samples (slabs), where a very flat, smooth surface of the rock is created using a rock saw and then observed wet or polished, revealing the shapes of grains in the rock and the rock's internal structure or texture (see the granite slab on Fig. 2.1); D) microscopic views of rocks using dissecting or petrographic microscope views of thin sections, which are thin slices of rocks mounted on a microscope slide in which many minerals appear transparent.*

How do we make observations that will lead to the correct identification of a rock and its composition? This depends to a certain extent on the detail that we are shooting for, but there are several things that we can do. We can make observations of:

1) *outcrops*, either from a distance or using a hand lens (Fig. 2.2A);
2) *hand samples* with weathered surfaces or fresh surfaces created using a rock hammer (Fig. 2.2B);
3) cut or sawed samples called *slab samples*, where a very flat, smooth surface of the rock is created using a rock saw and then observed when wet or polished (Figs. 2.1 and 2.2C). This often clearly reveals the shapes of grains in the rock and the rock's internal structure, i.e., its texture;

4) microscopic views of rocks using dissecting or petrographic microscope views of "*thin sections*", which are thin slices of rocks in which many minerals appear transparent (Figs. 2.2D, 2.3 and 2.4); and

5) microscopic images and analyses using high-tech pieces of equipment that allow detailed views of texture, crystal structures, and chemical analyses. High tech devices include X-ray machines, scanning electron microscopes (SEMs), electron microprobes, and mass spectrometers.

A staple of rock analysis for the last two centuries has been the viewing of *thin sections* using a *petrographic (or polarizing) microscope*, which displays different minerals in a way that reveals their detailed characteristics (Fig. 2.3). A *thin section* is just what the name implies – a very thin slice of the rock mounted on a glass microscope slide (Fig. 2.4). To produce a thin section, a flat polished surface of a trimmed rock sample (a "chip") is glued to a microscope slide with clear epoxy. All except about 30 microns (0.030 mm) of the rock is then ground off the slide leaving behind an exceedingly thin slice. The rock slice is so thin that most mineral grains are transparent when viewed in a microscope. However, different minerals react differently to polarized light, producing different colors and patterns depending on their chemical compositions and crystal structures. This makes them much easier to identify and their structures and textures much easier to study in detail. Petrographic microscopes provide two main ways of viewing thin sections: 1) with *plane polarized light*, where just one polarizer is in the light path below the thin section, and 2) with *crossed polarizers*, where there are two perpendicular polarizers in the light path, one below and one above the thin section.

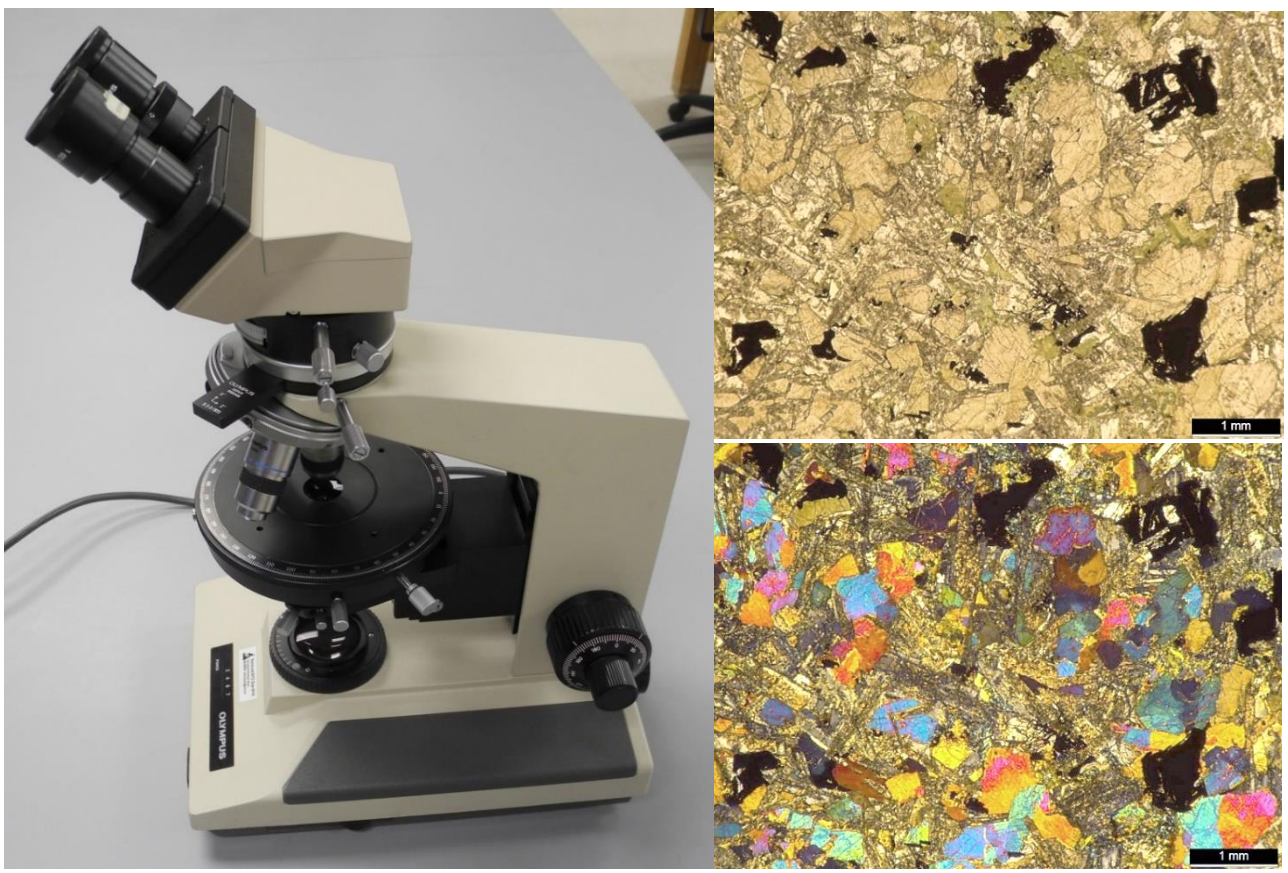


Figure 2.3 *– A petrographic microscope in the Department of Earth and Ocean Sciences at Tufts University. This microscope takes advantage of polarized light to make different minerals in a thin section appear with different textures and colors. The minerals are then easier to identify. On the right are images of the same view of a rock called dolerite in plane polarized light (above) and with crossed polarizers (below). On the image above the tannish crystals are pyroxene (colorful below) and the green areas are amphibole and chlorite formed by alteration of pyroxene. The tabular light-colored dusty grains are plagioclase feldspar (faintly striped below), and the black (opaque) grains are magnetite.*

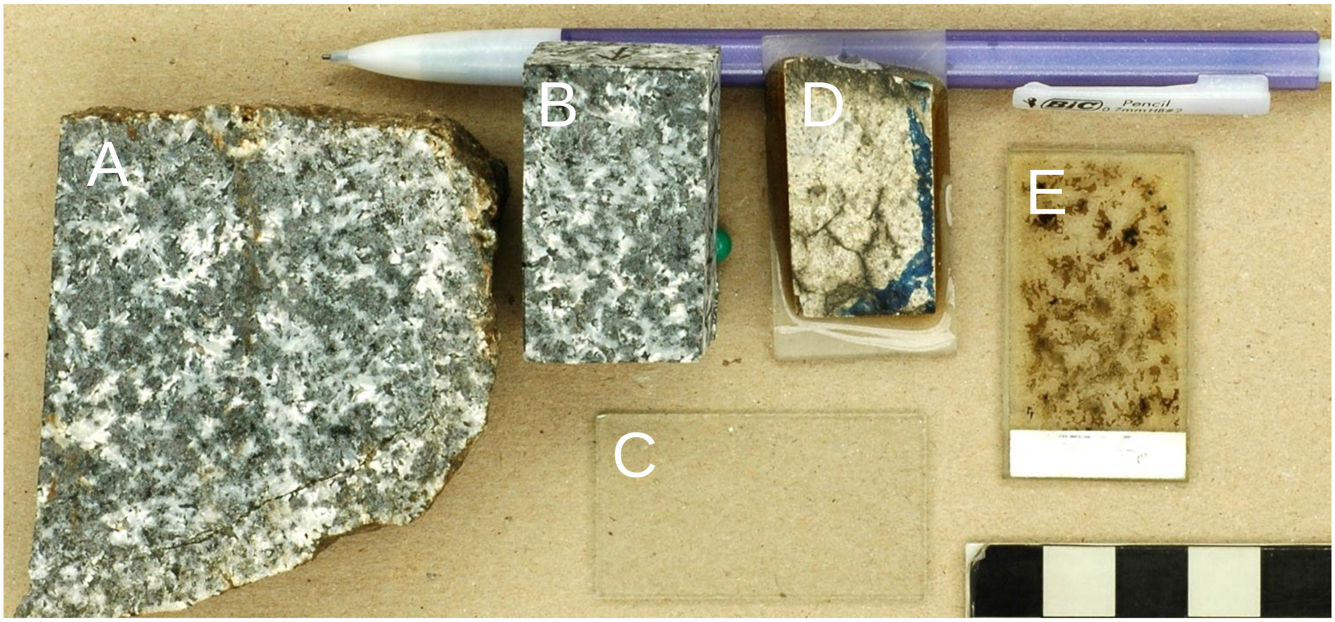


Figure 2.4 *– Making a thin section starts with cutting a rock sample (A) into a rectangular chip of rock (B) that is a little smaller than a glass microscope slide (C). One face of the rock chip is polished and glued to the slide with epoxy (D). Most of the rock is ground away from the slide leaving a layer about 30 microns (0.030 mm) thick (E). Many minerals on a thin section are transparent when viewed in a petrographic microscope. A thin section can either be covered with a glass cover slip or polished on its upper surface so that it can be analyzed in high-tech lab devices. Scale in cm.*

2.3 ROCK FUNDAMENTALS

2.3.1 Major Rock Types and the Rock Cycle

Rocks are classified into three major types according to how they form: igneous, sedimentary and metamorphic rocks. We can usually place rocks into one of these categories with a few simple observations and some practice.

A good starting place to develop an understanding of rock classification is to begin with *magma*, or molten (liquid) rock, which was the dominant material at the beginning of Earth's history some 6 to 4.5 billion years ago. Magmas are very hot liquids that generally move upward beneath Earth's surface because they tend to be hotter and therefore lighter, or less dense, than surrounding solid rocks. Not until magma spills out onto Earth's surface is it called *lava*.

How hot are magmas when they get near Earth's surface? Anywhere from about 800 to 2500°C, depending on the magma's chemical composition, what depth the magma is generated at, and how much heat the magma has already lost. The coolest magmas (~800°C or ~1470°F) are at a temperature about 3 times higher than the temperature of a typical kitchen oven set on broil. Magmas are not generated at the center of the Earth but rather have their origins much closer to Earth's surface. They are generated by changes in temperature and pressure in Earth's outer two layers, the outer mantle and crust. If they came from deep in Earth's interior, they would have a very different composition (see Chapter 9). They would be molten metal instead of having the components that commonly crystallize in rocks with silicon, aluminum, and oxygen.

When magmas lose heat, they may eventually reach a temperature and pressure that forces them to begin to freeze to a solid and begin the crystallization process. This is what happens to water (magma) in your freezer when it turns to ice (crystalline solid) as the air in your freezer removes heat from the water. However, the difference between water in your freezer and magma in Earth's subsurface is that the magma is not only much hotter than water as a liquid, but it is also not composed of just one molten compound, i.e., not just water. It contains the components (ions) of several minerals that all have different crystallization temperatures. In other words, magmas will form crystals of several different minerals that crystallize at different temperatures and times during the cooling process (Fig. 2.5).

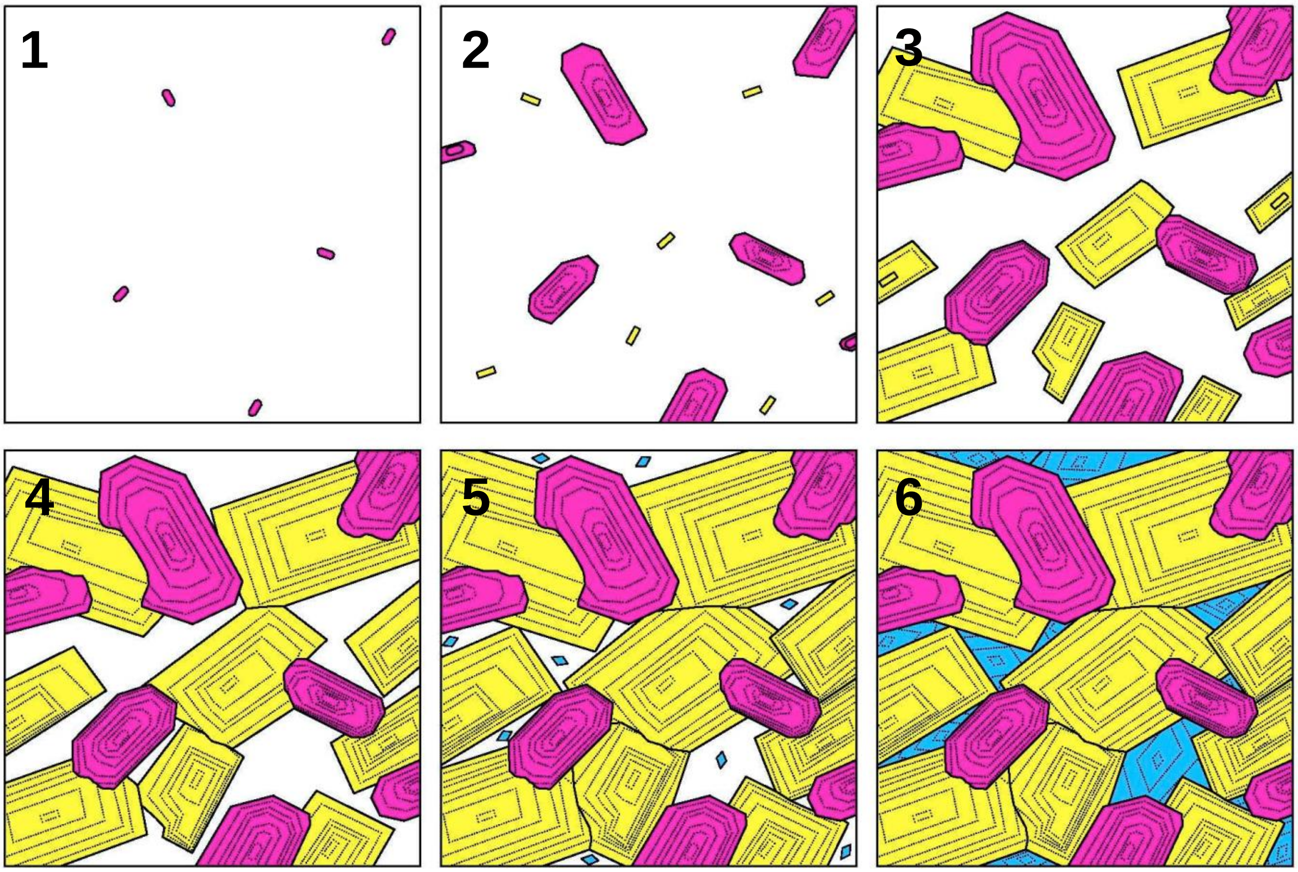


Figure 2.5 *– A hypothetical, and highly simplified, crystallization sequence (1-6) forming a 3-component igneous rock. 1) White represents magma that initially has tiny crystals of mineral A (magenta) starting to grow in it at a high temperature. 2) As temperature falls, grains of mineral A continue to grow while tiny crystals of mineral B (yellow) start to grow. 3) Minerals A and B continue to grow and compete for space where they are in contact, forming a crystal "slush". 4) Mineral B continues to grow after mineral A stops growing and B begins to enclose crystals of A forming an interlocking texture that is a porous framework. Mineral A may stop growing because some critical ion in the magma has been used up, or pressure and temperature conditions favor the growth of another mineral. 5) Mineral B continues to grow as tiny crystals of mineral C (blue) come into existence. 6) Mineral B stops growing, mineral C fills the remaining spaces, and a completely solid rock is formed. (See the granite slab in Figure 2.1.)*

Rocks that are formed by the cooling and solidification of magma are known as *igneous rocks*. Magma solidification can occur in the subsurface when the magma's upward movement is retarded, producing magma chambers that freeze inside other rocks that they have invaded, or intruded. These are *intrusive igneous rocks* (Fig. 2.6). A large body of igneous rock that has formed this way is called an *intrusion* or *pluton*. If magma reaches Earth's surface it is squeezed out or extruded, sometimes explosively, leading to *extrusive* or *volcanic igneous rocks*.

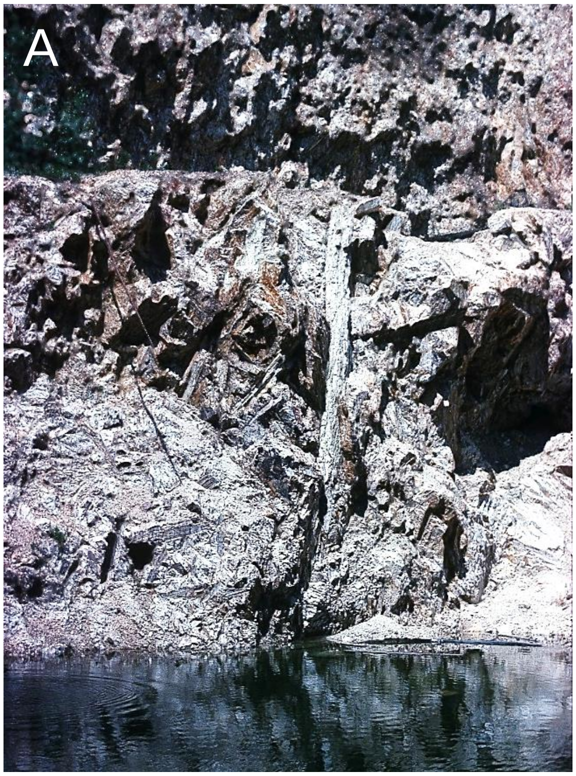


Figure 2.6 *– Igneous rock examples. A) Intrusive igneous rock: Quarry face with very large log-like crystals of spodumene, a lithium silicate mineral, in coarse granite in the center of the Black Hills in South Dakota. B) Extrusive igneous rock: lava flow in the Coso Volcanic Complex on Google Earth image south of Owens Lake, California. Scale bar in lower left is 1 km.*

Regardless of how igneous rocks may have formed, either by intrusion or extrusion, they can later be exposed to conditions at Earth's surface. Intrusive igneous rocks may be in a section of Earth's crust that is uplifted by tectonic processes (see Chapter 9), and *erosion* then removes all the material above them until they are exposed at Earth's surface. Extrusive igneous rocks are already exposed at Earth's surface while they cool. Exposure to lower pressures and temperatures, water with acids, oxygen and carbon dioxide, and physical processes at Earth's surface will cause the rock to deteriorate by physical and chemical processes. Break down of a rock to smaller particles and new minerals that are more stable under surface conditions is known as *weathering* (Fig. 2.7).

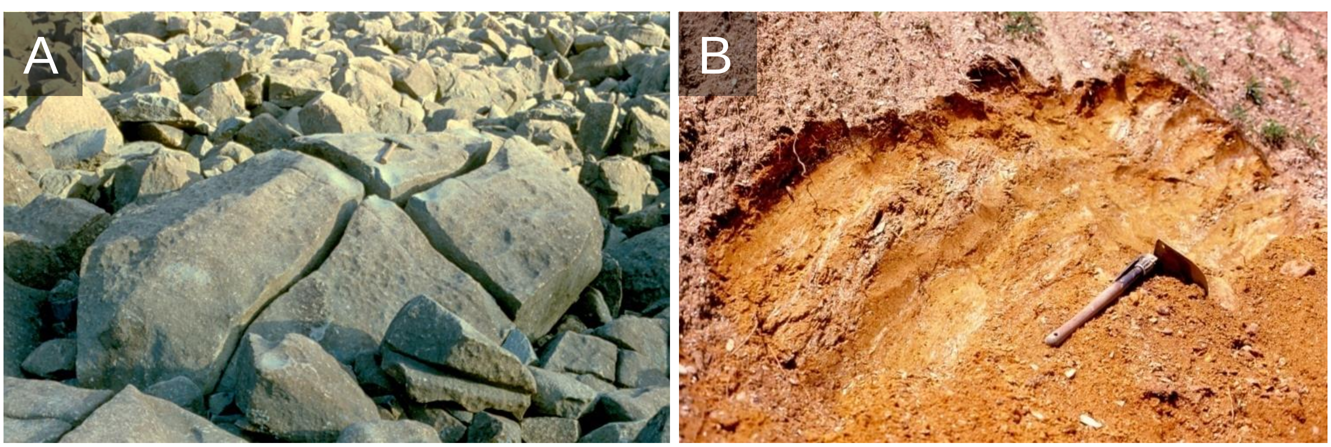


Figure 2.7 *– Examples of rock weathering. A) Mechanical or physical weathering of a large boulder that has split into pieces at Ringing Rocks County Park in Upper Black Eddy, Pennsylvania. Rock hammer for scale. B) Chemical weathering of sedimentary rock (limestone and shale) in highway exposure in Bethlehem, Pennsylvania. The minerals in the rocks have been highly altered by chemical reactions leaving behind iron oxide and clay, giving the outcrop its orange color. Shovel for scale.*

Figure 2.8 *– Example of erosion of sedimentary rock formations along the Genesee River in Letchworth State Park in western New York. The canyon was cut in the last ~12,000 years since the last ice age.*

Erosion, or removal of weathered material (Fig. 2.8), leads to the development of grains of *sediment* (eroded particles). *Transport* is performed by such things as runoff during rainstorms and snow melt, rivers, glaciers, the wind, ocean currents, and gravity transport or what is called *mass movement* (for example, landslides). (*In Chapter 10 of this book is a section on surface processes and it will describe in more detail the processes that erode the land surface.)* Organisms such as ants and worms also break down and transport sediment. Weathering and erosion not only create and remove solid particles but also dissolved material as ions (cations and anions) that are transported in water solutions both at Earth's surface and in the subsurface in *groundwater*.

Sediment can be transported to places where it can no longer move, and there it accumulates to form a sedimentary deposit. This may be at the mouth of a river, in sand dunes, on the floor of the ocean or a lake, on flood plains, and in a variety of other places. Dissolved ions can also chemically precipitate from solutions, either when solutions become saturated or as a result of organic processes that remove ions from solution. Deposits may build up in thickness over time, especially where deep basins are available to accumulate enormous volumes of sediment. Eventually, the accumulated weight of sediment may compact it and squeeze out water. The slow seepage of groundwater carrying dissolved ions through pore spaces in the sediment may lead to precipitation of chemical compounds (minerals!), that along with compaction, hardens the sediment to form *sedimentary rock* (Fig. 2.9). In addition to grains of sediment that are eroded from other rocks, organically-generated or chemically precipitated constituents can also contribute to sediment accumulation. This includes plant and animal debris, beds of salt left by evaporation, and the chemical precipitation of calcite to form stalactites and stalagmites in caves. The places with the thickest accumulation of sediment are in the ocean along the edges of continents because erosion and transport on land dump large volumes of sediment into the adjacent ocean. This explains why more than 90% of all sedimentary rocks on Earth today were formed in marine environments.

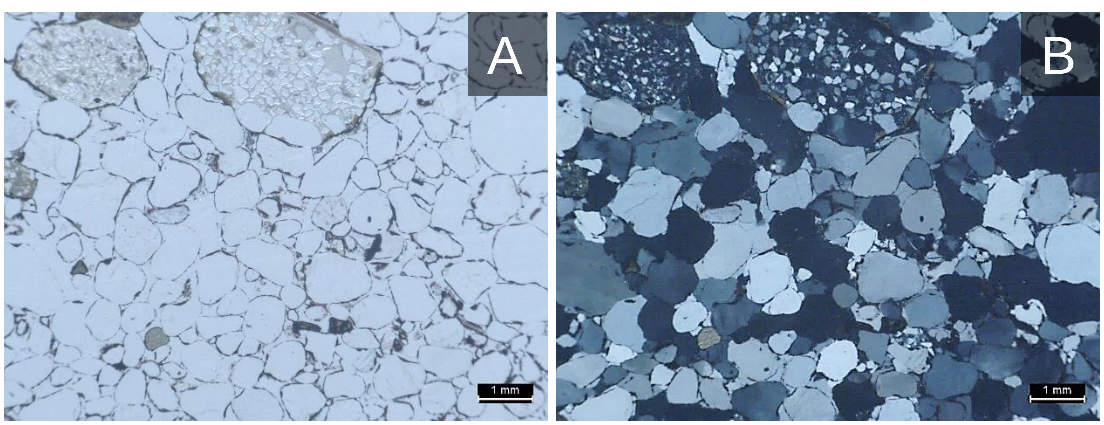


Figure 2.9 *– Sedimentary rock, sandstone in Clinton Red Beds of central New York. Thin section view with A) plane polarized light and B) crossed polarizers. Open spaces between rounded grains is mostly quartz cement with dark iron oxide coatings on grains. At top are two rounded grains of fine sandstone.*

When a pile of sediment becomes very thick (more than a few kilometers), or is squeezed by other forces in the crust, minerals and other materials in sedimentary rocks are subjected to increasing temperatures and pressures. Higher temperatures and pressures cause some of the minerals to become unstable. New minerals form that are more stable under the new conditions at the expense of the minerals that become unstable. Some minerals will recrystallize into mineral grains that have a larger size or a different crystal orientation that is more compatible with the new conditions. They begin to yield to the stresses created by high pressures and become deformed. These processes are called *metamorphism* and the new altered rocks are known as *metamorphic rocks* (Fig. 2.10). All This can occur while the rock is still a solid, but one that is physically weakened and more susceptible to chemical reactions. The minerals in the rock get softer as temperatures and pressures increase. One geology professor of mine used to say, “the rock turns to taffy!” If a rock gets too hot and pressure conditions are favorable, it will eventually start to melt and produce *magma*.

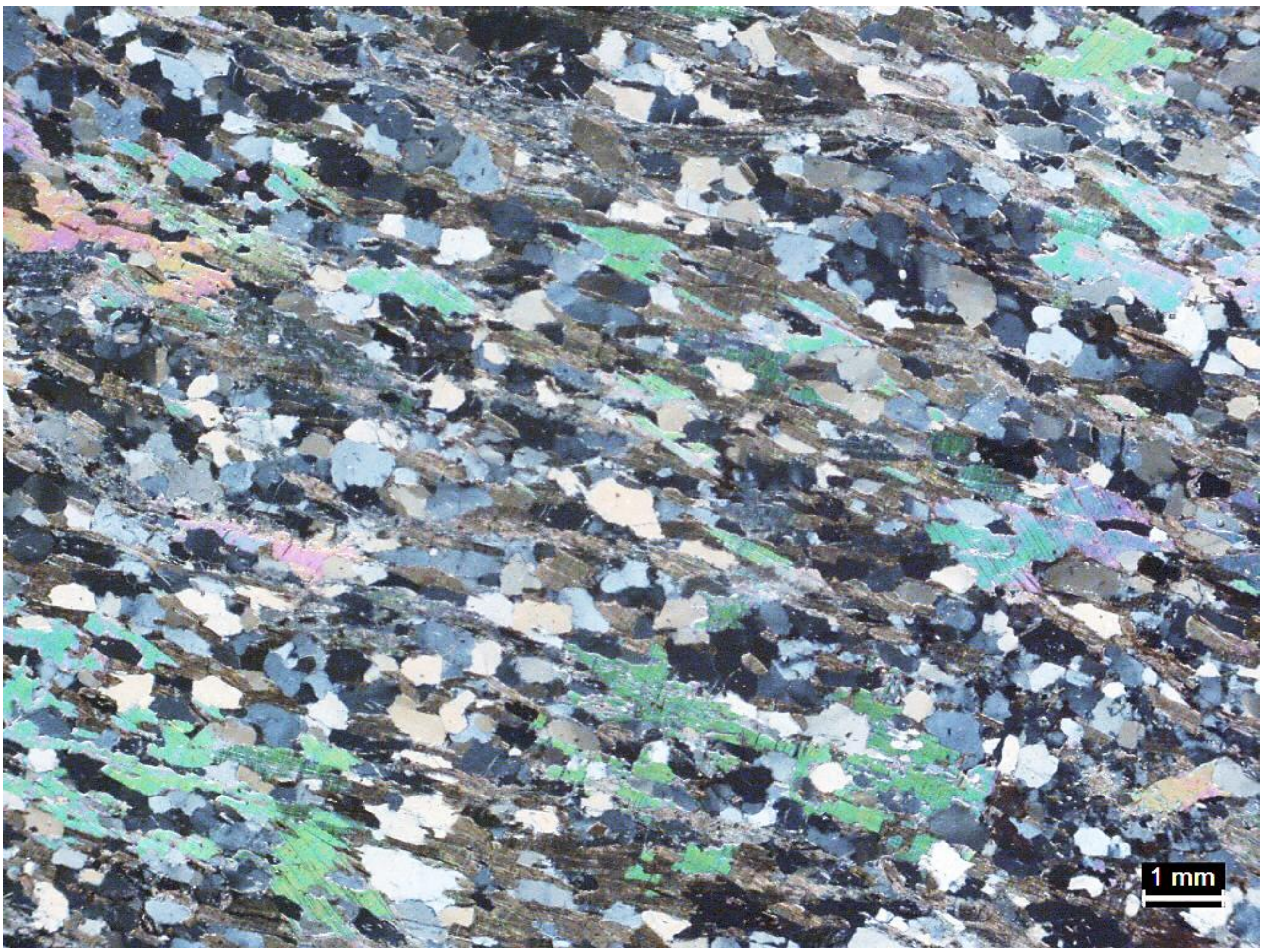


Figure 2.10 *– Metamorphic rock with well-oriented mica (bright green and pink colors are muscovite mica, olive gray grains are biotite mica) with grains of feldspar and quartz (white to dark gray grains). Thin section view with crossed polarizers. Chapter 3 explores the common minerals seen in rocks.*

So, we have come full circle, starting and ending with magma. Geologists call this recycling and series of changes that rocks may experience the *rock cycle* (Fig. 2.11).The rock cycle presented here simplifies our view of how rocks form and change over time, and for the first time we get a sense of how long it must take for this to happen. There are also some ways in which there can be short cuts on the cycle or reversals. For example, igneous rocks can be directly changed by metamorphism without first being eroded to form sediment and sedimentary rock. Metamorphic and sedimentary rocks can also undergo weathering and erosion, turning them into sediment before they have a chance to melt and form magma. It's like those games we played as a kid, *Chutes and Ladders* or *Candy Land*, where we spend the whole game slowly trying to make your way to the finish, only to have our progress interrupted occasionally by having to go back to some earlier step. (And there's no cheating in the rock world!) There is no guarantee that the cycle will ever get completed. Later we will learn what makes the rock cycle so dynamic and causes the recycling of rocks, something called plate tectonics (Chapter 9).

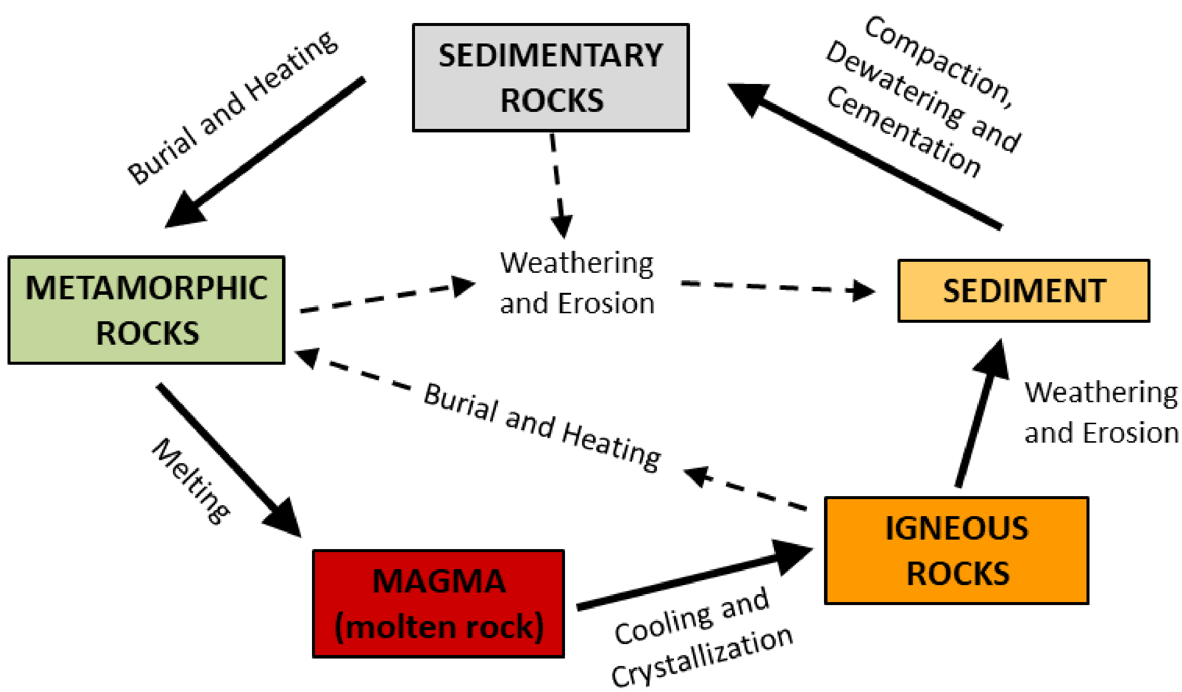


Figure 2.11 *– The rock cycle shows how rocks are formed and change over time. Rocks are formed and recycled as a result of processes deep in Earth's crust that cause magmas to form, solidify, and uplift. Erosion of land surfaces produces sediment that gets buried, exposed to high pressures, and heated. An ideal cycle (solid arrows) starts with magma that forms igneous rock that erodes and produces sediment. The sediment forms sedimentary rock that gets buried and is exposed to high pressures and temperatures to form metamorphic rocks. Metamorphic rocks, if exposed to high enough temperatures, may eventually melt to again form magma. This cycle is often interrupted (dashed arrows).*

2.3.2 Why Do We Classify Rock Types? (Isn't it just a rock?)

In order to interpret a geologic history, it is important to assemble as many detailed observations as we can from rocks and other geologic features in order to determine how they formed and their relative ages. Subtle differences are potentially important. So, this is where geologists behave a little like zoologists, giving each rock type a separate name, looking for similarities, subtle differences, and possible relationships between rocks that tell us about their origins. We are definitely “splitters” and not "lumpers", preferring to split hairs rather than be over-enthusiastic about lumping things together, but at least we don’t have to remember Latin names! Names for rock types are usually derived from places, have ancient Latin and Greek origins, or can be old mining terms, possibly created by mine workers or prospectors. Our level of knowledge has advanced to the point where we are no longer able to improve our understanding of Earth history and processes by simply being able to identify rocks as just igneous, sedimentary, or metamorphic. We need a more detailed mode of communication.

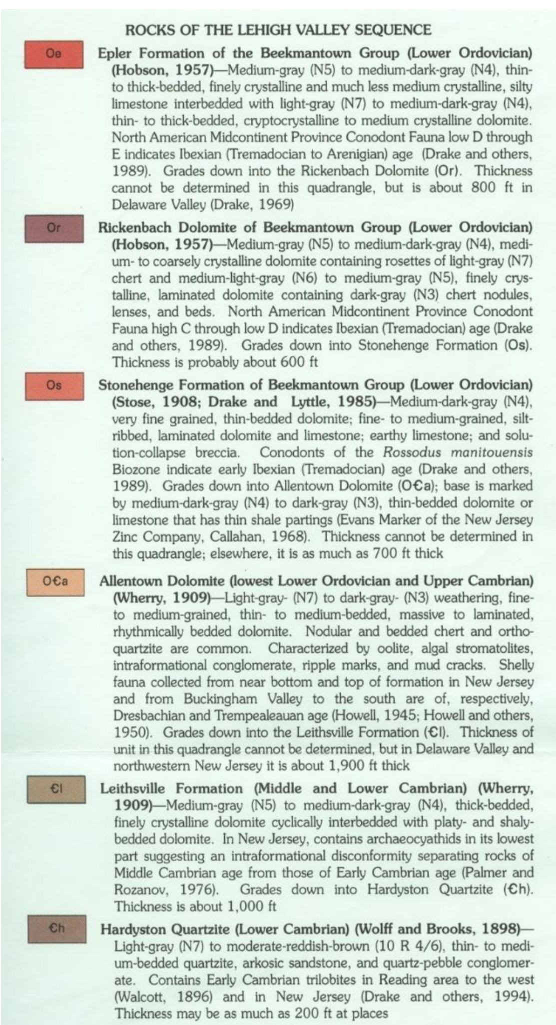
The classification scheme that is used in the Earth and Ocean Sciences Department at Tufts University in our introductory courses is introduced in Chapter 4 and is one that can be applied to rocks in the field relatively quickly by introductory students. It helps them discern the differences between the first rocks that they see in the field, and indeed some of this early learning takes place in the Fells. There is a more detailed classification that we teach to students beyond our introductory courses, but it requires lab observations to break into this more detailed name calling. As an example, in our field classification we might use the word ‘felsite’ as a general term to describe any light-colored, fine-grained igneous rock. Later, we’ll learn that this group includes many more specific rock types such as rhyolite, dacite, andesite, welded and non-welded tuffs, and lava flows that have different compositions and mechanisms of formation. In the discussion below, we will spend more time talking about the details of igneous rocks as compared to sedimentary and metamorphic rocks because this text is geared toward the Fells, where igneous rocks dominate the landscape.

2.3.3 Formal Names for Rock Units

Geologists not only identify very specific rock types but also give names to rock units where they can be consistently traced over distances that can be displayed on a map. By convention in the U.S., rock units are given a formal name if they can be shown on a map at a scale of 1:24,000 (1cm = 240 m, 1 inch = ~600 m or 2.6 inches = ~1 mile). The formal name of a rock unit is created using a place or area name where the rock unit is exposed and can be described in detail. This place or area is referred to as the *type section* or *type area* for the rock unit. Formal names have a hierarchy of *groups*, which are split into *formations*, which may then be split into *members*. The main rock units that are identified are formations. Formal formation names can have a rock type as part of their name (sandstone, limestone, granite, etc.), but also may simply be given the designation “formation” if the rock unit being identified has more than one intermingled rock type. For example, the Roxbury Formation is best categorized with the name formation rather than conglomerate, as it was years ago, because this unit is composed of both conglomerate and sandstone with occasional shale beds. The Roxbury Formation and the Cambridge Argillite make up a larger unit known as the Boston Bay Group. The Roxbury is also subdivided into the Brookline, Squantum, and Dorchester members. Naming of rock units also includes igneous rocks. The Dedham Granite, Quincy Granite, Mattapan Volcanic Complex, and Lynn Volcanic Complex are some igneous rock formations in the Boston area.

It may seem like creating more names only complicates things. However, it makes communication easier. Detailed names attempt to provide some order to the multitude of details that exist. Here is a typical overly complex statement a geologist might have to make without formal rock names: “The poorly sorted conglomerate beds on the south side of Boston that are interbedded with laminated fine sandstone, siltstone, and slatey shale, and occur at the top of the large section of well sorted conglomerate on the south side of the Boston Basin, appear to have pebbles of coarse granite like is exposed in various areas around the sides of the Boston Basin and is overlain by conglomerate at Nantasket." There is lots of information here that is used to indicate specifically which rock units the geologist is talking about in terms of their locations, rock types, and age relationships. It is obvious that the rock units are extensive, and someone has studied them such that they should be given formal names. Here is the statement above using rock terminology and formal names: "The diamictite of the Squantum Member of the Roxbury Formation appears to have pebbles in it from the Dedham Granite." Much simpler!

The formal naming of rock units also has some implications in terms of age. Rock formations represent a past period, and if they can be correlated it goes a long way toward transferring age relationships. The naming of rock formations also provides a means of subdividing units on geologic maps, with each formation or member getting its own symbol and color. This visually organizes the view one has on a geologic map (Fig. 2.12). Naming rock units helps make the geology understandable and mappable. Until recently, geologists resisted giving formation names to units on surficial geologic maps because the units were often thin and discontinuous, had a spotty occurrence, or were often being used to indicate the sediment types and origins of units, rather than simply age and rock type as occurs on a bedrock geologic map.



ROCKS OF THE LEHIGH VALLEY SEQUENCE

Oe — **Epler Formation of the Beekmantown Group (Lower Ordovician) (Hobson, 1957)**—Medium-gray (N5) to medium-dark-gray (N4), thin- to thick-bedded, finely crystalline and much less medium crystalline, silty limestone interbedded with light-gray (N7) to medium-dark-gray (N4), thin- to thick-bedded, cryptocrystalline to medium crystalline dolomite. North American Midcontinent Province Conodont Fauna low D through E indicates Ibexian (Tremadocian to Arenigian) age (Drake and others, 1989). Grades down into the Rickenbach Dolomite (Or). Thickness cannot be determined in this quadrangle, but is about 800 ft in Delaware Valley (Drake, 1969)

Or — **Rickenbach Dolomite of Beekmantown Group (Lower Ordovician) (Hobson, 1957)**—Medium-gray (N5) to medium-dark-gray (N4), medium- to coarsely crystalline dolomite containing rosettes of light-gray (N7) chert and medium-light-gray (N6) to medium-gray (N5), finely crystalline, laminated dolomite containing dark-gray (N3) chert nodules, lenses, and beds. North American Midcontinent Province Conodont Fauna high C through low D indicates Ibexian (Tremadocian) age (Drake and others, 1989). Grades down into Stonehenge Formation (**Os**). Thickness is probably about 600 ft

Os — **Stonehenge Formation of Beekmantown Group (Lower Ordovician) (Stose, 1908; Drake and Lyttle, 1985)**—Medium-dark-gray (N4), very fine grained, thin-bedded dolomite; fine- to medium-grained, silt-ribbed, laminated dolomite and limestone; earthy limestone; and solution-collapse breccia. Conodonts of the *Rossodus manitouensis* Biozone indicate early Ibexian (Tremadocian) age (Drake and others, 1989). Grades down into Allentown Dolomite (**O€a**); base is marked by medium-dark-gray (N4) to dark-gray (N3), thin-bedded dolomite or limestone that has thin shale partings (Evans Marker of the New Jersey Zinc Company, Callahan, 1968). Thickness cannot be determined in this quadrangle; elsewhere, it is as much as 700 ft thick

O€a — **Allentown Dolomite (lowest Lower Ordovician and Upper Cambrian) (Wherry, 1909)**—Light-gray- (N7) to dark-gray- (N3) weathering, fine- to medium-grained, thin- to medium-bedded, massive to laminated, rhythmically bedded dolomite. Nodular and bedded chert and orthoquartzite are common. Characterized by oolite, algal stromatolites, intraformational conglomerate, ripple marks, and mud cracks. Shelly fauna collected from near bottom and top of formation in New Jersey and from Buckingham Valley to the south are of, respectively, Dresbachian and Trempealeauan age (Howell, 1945; Howell and others, 1950). Grades down into the Leithsville Formation (**€l**). Thickness of unit in this quadrangle cannot be determined, but in Delaware Valley and northwestern New Jersey it is about 1,900 ft thick

€l — **Leithsville Formation (Middle and Lower Cambrian) (Wherry, 1909)**—Medium-gray (N5) to medium-dark-gray (N4), thick-bedded, finely crystalline dolomite cyclically interbedded with platy- and shaly-bedded dolomite. In New Jersey, contains archaeocyathids in its lowest part suggesting an intraformational disconformity separating rocks of Middle Cambrian age from those of Early Cambrian age (Palmer and Rozanov, 1976). Grades down into Hardyston Quartzite (**€h**). Thickness is about 1,000 ft

€h — **Hardyston Quartzite (Lower Cambrian) (Wolff and Brooks, 1898)**—Light-gray (N7) to moderate-reddish-brown (10 R 4/6), thin- to medium-bedded quartzite, arkosic sandstone, and quartz-pebble conglomerate. Contains Early Cambrian trilobites in Reading area to the west (Walcott, 1896) and in New Jersey (Drake and others, 1994). Thickness may be as much as 200 ft at places

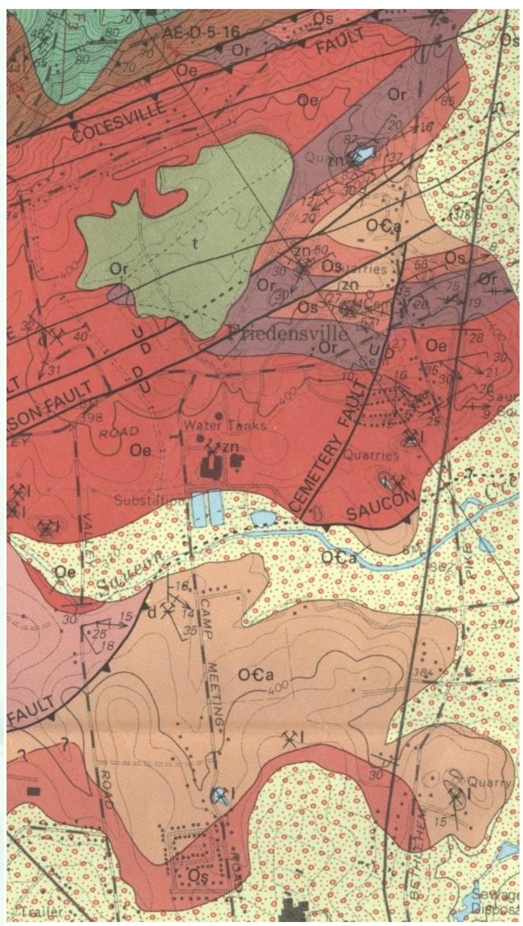


Figure 2.12 - *Part of the explanation of a geologic map (left) showing the proper names and formal descriptions of bedrock units (formations) and their symbols with part of the geologic map (right) showing how the unit symbols are used. On the map are areas also marked as "t" (mine tailings) and a light yellow unit with red circles and dots to indicate glacial and other surficial deposits that obscure the bedrock. The green unit at the top of the map is a younger rock unit not described on the part of the explanation shown here. Various symbols are used to indicate faults (heavy lines) with triangular teeth or U/D symbols), folds, and the orientations of rock units where they are exposed. USGS map by Drake (1999) from Allentown, Pennsylvania.*

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