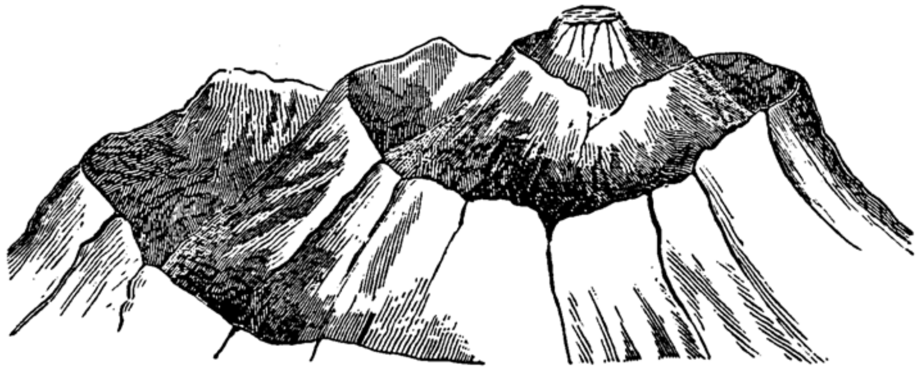


Chapter 2

Igneous Rocks

Most students find the definition of a mineral to be rather long and cumbersome. In contrast, the definition of a **rock** is short and sweet. A rock is any naturally occurring aggregate of 2 or more minerals, and they are classified as either igneous, sedimentary, or metamorphic depending upon their origin. **Igneous rocks** are formed from molten rock. **Sedimentary rocks** are made of particles or grains of earlier rock which have been deposited, compacted and ultimately re-cemented into new rock. Other sedimentary rocks precipitate from solutions rich in ions derived from the decomposition of previously formed rock material or through organic activity. **Metamorphic rocks** are made from any existing rock that has been changed either in surface appearance or mineralogy by the forces of heat, pressure and/or chemically active fluids.

The first rocks that you will encounter in GY 111 are those of igneous origin. Igneous rocks tend to be easier to deal with than the others because they are frequently made up of readily identifiable minerals, most of which you have already encountered (e.g., feldspars, quartz, olivine etc.). All molten rock originates deep in the Earth's interior due to a combination of geothermal gradient, heat generated through radioactive decay of unstable elements like

Figure shows a cross-section of Mt. Vesuvius, a stratovolcano circa 1756. This volcano blew up in 76 A.D. with spectacular and tragic consequences. From: LeConte, J., 1905. Elements of Geology. D. Appleton and Co., New York, NY, 667p.

uranium, and heat and pressure associated with tectonic activity (e.g., divergence or subduction of lithospheric plates). Molten rock below the Earth's surface is called **magma.** Molten rock that makes it up to the Earth's surface via volcanoes is called **lava.** Igneous rocks form through the process of **crystallization** as a magma or lava cools and hardens into a solid mass. Between the temperature of 1800°C, above which mineral structures can not exist, and 200°C, below which magmas become completely solidified, individual minerals crystallize over specific temperature ranges. **Bowen's Reaction Series** is a description of the cooling path that most (but not all) magmas take on the way to becoming igneous rock. The series identifies the minerals that can occur together at specific temperatures and is a tool for predicting the composition (mineral content) of igneous rocks (see Figure 2.1, Table 2.1 and your lecture notes).

Magmas which cool and crystallize wholly within the Earth's interior (e.g., within a magma chamber) generally do so very slowly, possibly over tens of thousands or millions of years. Lavas cool much more quickly, perhaps only hours or days after the eruption. The faster that molten rock cools, the shorter the period of time the crystals have to grow. Consequently, lavas generally form rocks with very small crystals that are often too small to be seen with the naked eye whereas magmas form rocks with large (visible) crystals. It is the rate of cooling and ultimately crystal size that is used to subdivide the igneous rocks into three major divisions. Igneous rocks containing visible crystals formed from slow-cooling magmas are said to be **plutonic** or **intrusive**. Igneous rocks that form through the rapid cooling of lava are said to be **volcanic** or **extrusive**. The third division of igneous rocks are called **pyroclastic** because they are blasted out of volcanoes as particulate material (e.g., volcanic bombs and ash). Pyroclastic eruptions are among the most powerful events that nature produces. The 1980 Mt. St. Helen's eruption generated a pyroclastic surge consisting of hot ash (800 °C) that traveled down slope at speeds greater than 120 km/hr. As great as this eruption was, it pales in comparison to historical eruptions in other parts of the world. The entire island of Krakatoa was destroyed when it blew up during a pyroclastic eruption in 1908. The greatest historical pyroclastic eruption of them all may have occurred about a thousand years ago in New Zealand. It was so powerful that residents in China at that time claimed to have heard the explosion (This is no mean feat; China is about 9,100 km away from New Zealand!).

The surface appearance or **texture** of an igneous rock is directly determined by its speed of cooling. Igneous rock nomenclature is based on the visual determination of a rock's texture and composition. Texture is judged by estimates of crystal size and the composition of the rock is determined by the types of minerals present. Magmas of specified composition may be cooled at an infinite number of speeds and rocks may be produced which vary in crystal size from microscopic to as large as a tabletop. It is obvious that two rocks of the same composition would look completely different if cooled at different speeds. The converse is also true. Magmas of very different composition may cool at equal rates and produce rocks with equally large crystals but dissimilar mineral content. For this reason both texture and composition are necessary in the identification of an igneous rock.

2.1 Composition

Four compositional categories, **ultramafic, mafic, intermediate** and **felsic**, are used to classify igneous rocks. These categories are directly related to the low, medium, high and very high temperature divisions of Bowen's Reaction Series (Figure 2.1, Table 2.1). Because specific ions can only bond over discrete temperature ranges, certain minerals are only produced at certain phases in the cooling history of a magma. Minerals can occur together in a rock only when their cooling ranges overlap. Specific minerals are, therefore, associated with each compositional category. Knowing which mineral combinations are possible under specific conditions helps greatly in the identification of igneous rocks as well as in the determination of a rock's origin.

ULTRAMAFIC: At temperatures above 1200° pyroxene and olivine are the only minerals that can crystallize. These minerals are rich in iron and magnesium and usually appear black, dark gray or green in color. Rocks in this temperature range are further identified by the fact that they contain no feldspar. Ultramafic rocks can form from lavas, but they are primarily of an intrusive origin. Consequently, you will need to know three ultramafic rock types: (1) **dunite** (100% olivine); (2) **peridotite** (olivine + pyroxene); (3) **pyroxenite** (100% pyroxene).

MAFIC: Only three common minerals can form at temperatures between 1200 and 900°C; olivine, pyroxene and calcium plagioclase. As these minerals are all dark in color, mafic rocks also tend to be relatively dark (black to dark-gray), but they may exhibit iron staining on weathered surfaces. Mafic rocks can be distinguished from the ultramafic variety on the basis that they almost always contain plagioclase feldspar. The striated cleavage faces of feldspar crystals can easily be identified with a 10X hand lens in intrusively mafic rocks (e.g., **gabbro)**. The extrusive mafic rocks (e.g., **basalt**) will appear as a smooth, black rock. Only under

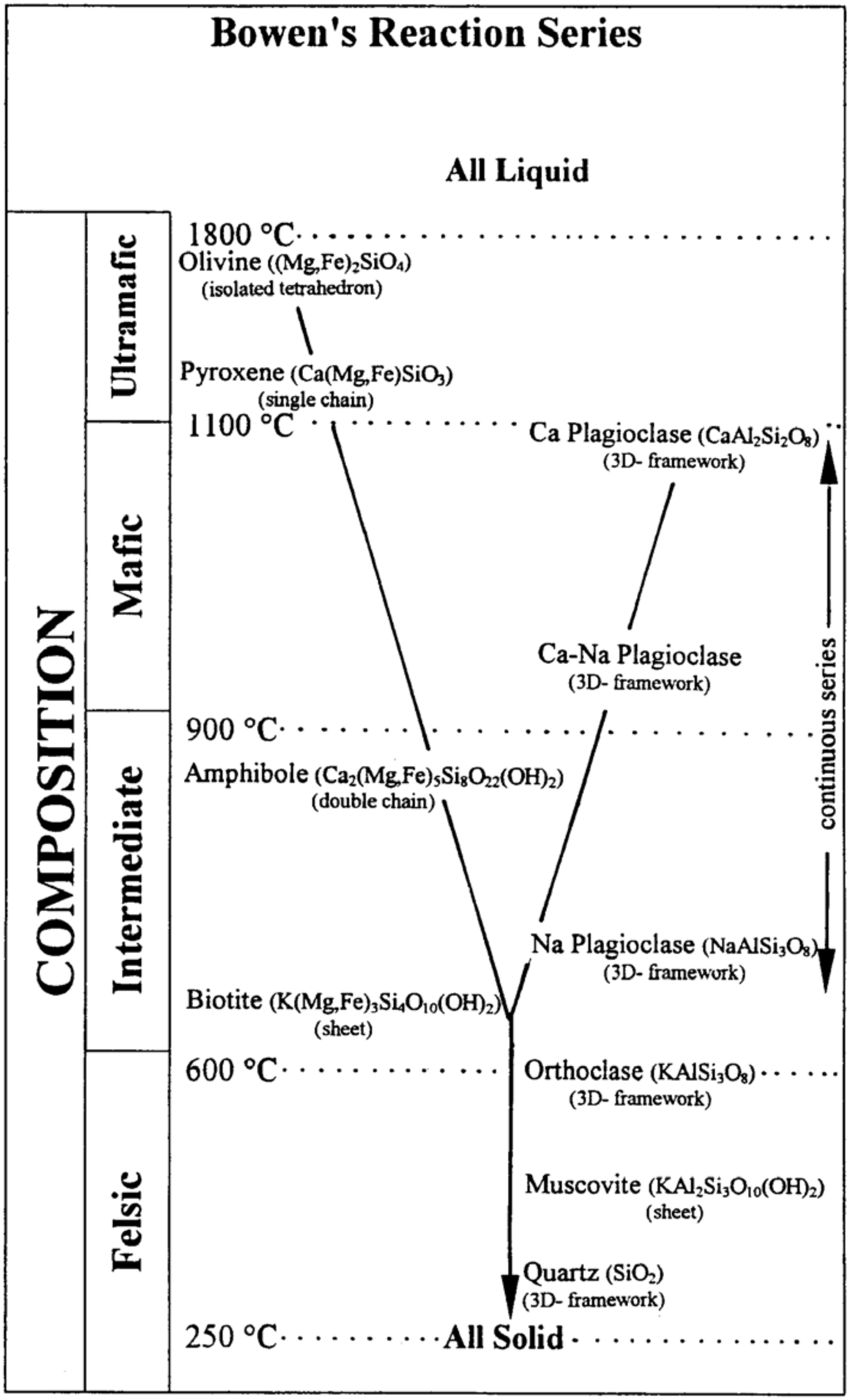
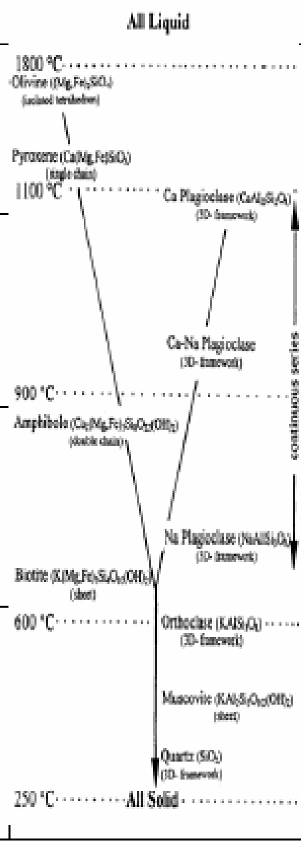


Figure 2.1. Bowen's reaction series showing the order of mineral crystallization (versus temperature) from a slowly cooling magma.

Table 2.1. Classification of the igneous rocks organized according to texture and composition. Hatched cells indicate rocks that are uncommon or which do not occur in nature. Shaded cells indicate rocks that occur in nature, but you are unlikely to see them in the GY 111 laboratory.

Bowen's Reaction Series



Composition	Major Minerals ()-minor minerals	Glassy (no crystals)		Aphanetic (Microscopic crystals)	Phaneritic (Visible crystals)	Pegmatitic (Very large crystals)	Porphyritic (Visible crystals in aphanetic groundmass)
Ultramafic	**Olivine**			Komatiite	Dunite		
Ultramafic	**Olivine + Pyroxene**			Komatiite	Peridotite		
Ultramafic	**Pyroxene**			Komatiite	Pyroxenite		
Mafic	**Ca-Plagioclase, Olivine, Pyroxene** (Amphibole, Biotite)	Scoria		Basalt	Gabbro		Basalt Porphyry
Intermediate	**Na-Plagioclase, Amphibole, Biotite** (Quartz, Olivine, Pyroxene)	Volcanic Ash	Tuff	Andesite	Diorite		Andesite Porhyry
Felsic	**Orthoclase, Quartz, Biotite Muscovite** (Na-Plagioclase, Amphibole, Pyroxene)	Obsidian Pumice	Tuff	Rhyolite	Granite	Granite Pegmatite	Rhyolite Porphyry

microscopic examination can the minerals olivine, pyroxene and Ca-plagioclase be observed in basalt.

INTERMEDIATE: At intermediate temperatures (600-900°C) olivine and pyroxene no longer crystallize and a different mineral association dominated by amphibole, biotite and Na-plagioclase begins to crystallize. Intrusive rocks of intermediate composition with visible, roughly equally-sized crystals (e.g., **diorite**) appear as a mixture of light and dark mineral grains and often have a salt and pepper appearance (light gray with black components). Extrusive intermediate rocks with microscopic crystals (e.g., **andesite**) have a smooth dull surface and are medium to dark gray in color.

FELSIC: After the temperature of a magma has cooled below 600°C, most ions in the original magma are now part of solid mineral grains. The remaining liquid is rich in silica (SiO_2) and relatively large, hard to place ions such as potassium (K^+). Rocks which form in the final cooling stages of a magma are composed primarily of orthoclase feldspar, muscovite and quartz. A good rule of thumb is that if orthoclase is visible in the rock (e.g., **granite**) then it belongs to the felsic category. Visible orthoclase usually, but not always, imparts a pink or red color to the rock, but some potassium feldspar can appear white or light peach in color and positive identification of this mineral with a hand lens is essential. Fine grained felsic rocks (e.g., **rhyolite**) are almost always pink or red in color.

2.2. Texture

The texture of an igneous rock is determined by its surface appearance. Texture is a description of the size, shape and arrangement of mineral grains observed in a rock. These properties are directly related to the cooling history of the molten rock. Molten rock can cool intrusively below the Earth's surface, extrusively at the Earth's surface, or by a combination of both intrusive and extrusive cooling modes. If a lava cools at the surface it will do so quickly and the mineral grains in the rock will be microscopic or sometimes even nonexistent as in the case of volcanic glass. An igneous rock composed of microscopic crystals is said to have an **aphanitic** texture. An igneous rock containing no crystals whatsoever is said to have a **glassy** texture. Intrusive magmas will take longer to cool because internal temperatures are higher and surface layers of earth will act as insulation to prevent rapid heat loss. Rocks cooled underground will contain mineral grains large enough to be seen with the naked eye. These rocks are said to have **phaneritic** textures. If the crystals are unusually large (say centimetres across), the texture is considered to be **pegmatitic**. Occasionally a magma/lava will have a more complex cooling history that will involve a combination of two cooling modes and a hybrid of textural characteristics. These rocks are said to have **porphyritic** textures. These textures are discussed further below and are illustrated in Figure 2.2.

2.2-1. Extrusive\Volcanic Textures

GLASSY TEXTURE (Figure 2.2-a)**:** A glassy texture occurs when a magma is cooled suddenly before any chemical bonds have had a chance to form. At the high temperatures associated with magmas, ions are in constant motion and cannot form bonds. During normal cooling processes ions begin to bond together as the temperature decreases and mineral structures are allowed to grow. A magma may be cooled so quickly that ions become instantaneously frozen before they have had a chance to bond. Under these conditions a glassy texture will result. Glassy textures are commonly produced when magma is extruded into sea water or suddenly blasted out of a volcanic vent.

Rocks with a glassy texture may look like glass as in the case of **obsidian** or they may have a dull surface which is riddled with small holes or vesicles. When bubbles of gas erupt from the semi- solid surface of a hardening rock, minute craters are left behind called **vesicles**. Vesicles are characteristic of **scoria** and **pumice**. Pumice is so filled with air holes that it can float in water. Scoria is characterized by larger, less numerous vesicles than pumice because it is the product of a more mafic lava which contained less trapped gas. It also has a higher specific gravity than pumice and is therefore "heavier".

Tuffs and **welded tuffs** are produced when pyroclastic ash is blasted out of a volcanic vent and fused into rock upon settling back to Earth. Welded tuffs got their name because of their characteristic layering caused by compression-induced flattening of semi-molten components.

APHANITIC TEXTURE (Figure 2.2-b)**:** Magmas which are extruded from volcanoes as lava flows, cool rapidly at the Earth's surface, yet more slowly than if they had been violently exploded into the atmosphere or injected into ocean waters. These lavas cool slowly enough for microscopic minerals to form but too quickly for these minerals to grow large enough to be seen with the naked eye or even with a 10X hand lens. The surface of the rock will be smooth and uniform in color (normally gray, pink or black). The minerals only become visible if thin transparent slices of rock (called thin-sections) are examined under a microscope (you may see some of these during a lab lecture). **Rhyolite, andesite** and **basalt** are the basic rock types characterized by aphanitic texture.

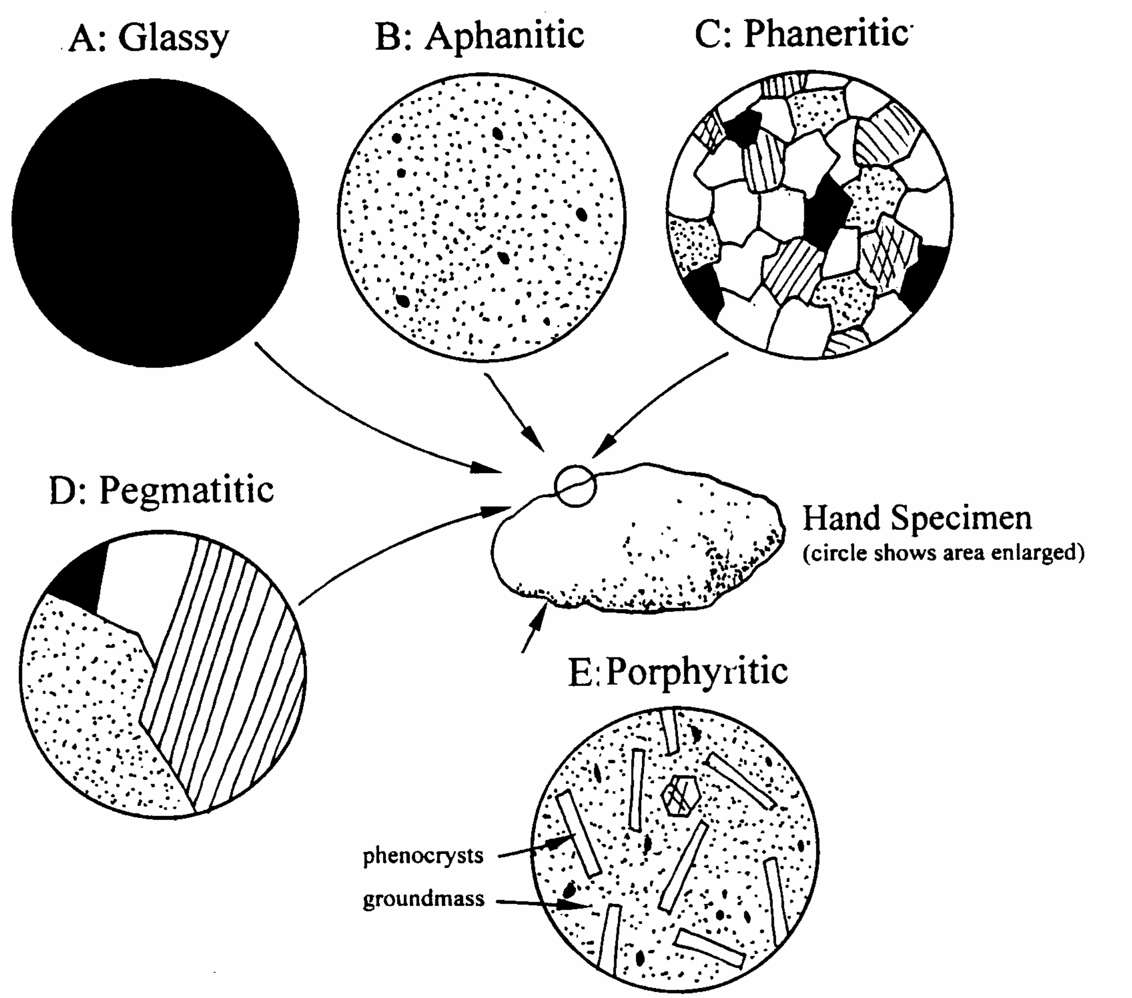


Figure 2.2. Schematic illustrations of igneous textures that you will observe using a 10X hand lens. The field of view for all of the textures is the same (about 1 cm across). (A): glassy texture (e.g., obsidian); (B): aphanitic texture (e.g., basalt); (C): phaneritic texture (e.g., granite); (D): pegmatitic texture (e.g., granite pegmatite); (E): porphyritic texture (e.g., basalt porphyry).

2.2-2. Intrusive/Plutonic Textures

PHANERITIC TEXTURE (Figure 2.2-c): Intrusively cooled rocks contain mineral grains which are visible to the naked eye and appear as an interlocking mass of roughly equidimensional crystals. The characteristic appearance of a granite tombstone is typical of a phaneritic texture. The overall color of the rock is variable and will depend on the association of minerals present. The individual types of minerals which compose the rock can be identified easily with a 10X hand lens. **Granite, diorite** and **gabbro** are rocks with a phaneritic texture which correspond, respectively, to magmas of felsic, intermediate and mafic compositions.

PEGMATITIC TEXTURE (Figure 2.2-d): Pegmatites contain large interlocking crystals and result from very slow cooling. They are usually of felsic composition (e.g **granite pegmatite**). Because magmas cool over an infinite variety of speeds, rocks will exist which are intermediate between the phaneritic and pegmatitic texture. Use your thumb as a guide to distinguish the two. In a true pegmatite all of the crystals will be about the size of your thumb or larger.

2.2-3. Combination Textures

PORPHYRITIC TEXTURES: The porphyritic texture is produced by a change in the cooling speed of the magma. In porphyritic rocks the cooling process consists of an initial slow phase during which the largest crystals are formed and a later, more rapid phase which results in smaller crystal growth. The resulting rock will contain large crystals from the early cooling phase surrounded by smaller crystals which can be either visible or microscopic in size. The larger crystals produced during the slow cooling phase of the magma are called **phenocrysts** and the smaller mass of crystals surrounding these is called the **groundmass**. (Figure 2.2-e).

The porphyritic texture is perhaps one of the most difficult to recognize because the surface appearance of these rocks is so variable. This is largely the result of the formation of these rocks. The texture occurs when a magma that has begun to cool intrusively is suddenly extruded onto the Earth's surface through a volcanic eruption. The phenocrysts from the early slow cooling phase become surrounded by a groundmass of microscopic crystals. The slow cooling phase can produce phenocrysts of any size from barely visible to as large as your thumb. The key is that these phenocrysts, no matter what size, are surrounded by the smooth aphanitic rock texture which has no visible crystals. The porphyritic texture can be compared to islands in a smooth sea or chocolate chips in a cookie. Typical rocks with this texture include **rhyolite porphyry, andesite porphyry** and **basalt porphyry.**

2.3. Identification of Igneous Rocks

Igneous rock classification depends on a visual estimate of a rock's texture, overall crystal size(s) and mineral composition. Table 2.1 will help you identify the rock names of the specimens in your tray. To use this chart, first determine the texture of the unknown rock, then identify the minerals which compose it. Rock names are itemized down the right hand side of the diagram. Until you get used to identifying minerals with your hand lens, you may need to heavily rely on color as a key to composition. The **color index** of minerals is a semi-quantitative tool in identifying igneous rock composition. Pink or red rocks are generally felsic (BEWARE of chemical weathering!), gray rocks will be intermediate and black rocks will likely be mafic. Ultramafic rocks range in color from light green (dunite) to black (pyroxenite). After you have determined the texture and composition of your rock, find the intersection of the column and row and read the rock name. Identification of finely crystalline minerals must in most cases be done with a hand lens. Quartz looks like a clear or milky grain of glass and can usually be distinguished from feldspar by its vitreous luster. Don't forget what you learned about minerals from the first part of this course.

2.4 Exercises

Check with your lab instructor to determine which of the optional exercises (if any) that you are responsible for in this lab component of GY 111. Regardless of these exercises, all students should be able to identify the igneous rocks like those provided in the rock tray, their textures, compositional differences (Table 2.1), mode of formation etc. For the exam, you should be able to identify the following attributes of each igneous rock specimen:

(a) their texture (phaneritic, aphanitic, glassy etc.)

(b) their mineral composition (quartz, feldspar, olivine etc.).

(c) whether they are plutonic or volcanic.

(d) their name.

Optional Exercises

You may wish to refer to your lecture notes and/or textbook for assistance in answering some of these questions.

1) What kind of igneous rocks would you expect to find on the Earth's surface near a shield volcano? How about a composite volcano?

2) How do hydrothermal fluids derived from subsurface magmas produce economical mineral deposits? (Your answer may need some library research).

3) How would igneous rocks formed in a dike differ from those formed in magma chambers?

4) What is the major requirement in order for a granite pegmatite to form?

5) How does a welded tuff differ from a crystal tuff and in what way(s) do they form?

6) Why did our human ancestors use obsidian to fashion arrow points? Why not use granite, a much harder substance?

7) Why does some basalt form columnar jointing when cooling?

8) Here's a question that might require a bit of reading. What is a "black smoker"? Where do they occur and why do they exist at all?

9) Draw a cross section of a shield volcano and of a composite volcano. Label all of the important components of these mountains, including those that occur below the Earth's surface.

10) If you walk along beaches in eastern Australia, you will find lots of fresh pumice all over the place. There are no volcanoes anywhere near this coastline. Where do you think it is coming from, and how does it get there? (Hint: the sea currents in this part of the world come from the east).

Notes