Lab 4: Volcanoes, Plutons, and Igneous Rocks

Introduction

Igneous rock forms when **magma** (molten rock) cools and **crystallizes**. **Volcanic eruptions** take place when magma reaches the surface before it solidifies. The magma flows onto the surface as **lava**, or **erupts** explosively as rapidly expanding gas propels bits of lava and rock outward. The rocks resulting from volcanic eruptions are called **extrusive**, or **volcanic** rocks. Volcanic rocks are named for *Vulcan*, the blacksmith god of Roman mythology, who was thought to be forging the tools of the gods inside active volcanoes. **Intrusive**, or **plutonic**, igneous rocks, on the other hand, form from magma that solidifies below the surface of the Earth. Plutonic rocks are named after *Pluto*, the Roman god of the underworld.

Igneous rocks are classified based upon their mineral **composition** *and* their mineral grain **texture**. This classification system is **interpretive**, because these characteristics imply something about the source of the magma and the conditions under which the rock formed.

A. Igneous Rock Composition

The mineralogy of an igneous rock is controlled by the chemical composition of its parent magma. 99% of the total bulk of most igneous rocks is made up of only eight elements:

- Silicon (Si)
- Oxygen (O)
- Magnesium (Mg)
- Iron (Fe)
- Sodium (Na)
- Aluminum (Al)
- Calcium (Ca)
- Potassium (K)

Most of these elements occur in the crystal structures of eight minerals, which constitute over 95% of the volume of all common igneous rocks. Therefore, these minerals are of paramount importance in the study of igneous rocks. Below is a list of the common igneous rock-forming minerals and their chemical formulas:

- Olivine — $(Mg,Fe)_2SiO_4$
- Calcium Plagioclase — $CaAl_2Si_2O_8$
- Sodium Plagioclase — $NaAlSi_3O_8$
- Pyroxene — Complex Ca-Mg-Fe-Al silicates
- Amphibole — Complex hydrous Na-Ca-Mg-Fe-Al silicates
- Biotite — $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$
- Orthoclase — $KAlSi_3O_8$
- Muscovite — $KAl_3AlSi_3O_{10}(OH)_2$
- Quartz — SiO_2

Table 4-1 lists the diagnostic properties of the common igneous rock-forming minerals.

Mineral	Properties
Olivine	Green to yellow-green; vitreous; small, equidimensional grains
Plagioclase	Usually white or gray; 2 cleavages at 90°; elongate grains; striations
Pyroxene	Black, greenish black, or brownish black; rather dull luster; blocky grains
Amphibole	Black with shiny, splintery appearance; two cleavages at 60° and 120°; elongate grains
Biotite	Shiny, black sheets; one perfect cleavage
Orthoclase	Usually white or pink; 2 cleavages at 90°; equidimensional grains
Muscovite	Shiny, silvery sheets; one perfect cleavage
Quartz	Colorless to gray; glassy with conchoidal fracture; irregular grains in intrusive rocks; equidimensional phenocrysts in extrusive rocks

Table 4-1. Diagnostic properties of the common igneous rock-forming minerals.

Most igneous rocks can be classified into three compositional groups, based on a particular assemblage of minerals:

(1) **Mafic** magma cools to produce dark-colored (or green) rocks that are composed of dense dark minerals that crystallize at high (e.g., 1000°C) temperatures.
(2) **Intermediate** magma cools to produce intermediate-color (or gray) rocks that are composed of the minerals that crystallize at mid-range (e.g., 800°C) temperatures.
(3) **Felsic** magma cools to produce light-colored (or orange) rocks that are composed of the light-colored, lower-density minerals that crystallize at comparatively low (e.g., 600°C) temperatures.

Bowen's Reaction Series

A magma crystallizes to solid rock by the **nucleation** and growth of various mineral crystals. Crystals nucleate when a magma cools below a specific temperature, but not all minerals crystallize at the same temperature. The order in which minerals crystallize out of a magma has been determined, and is expressed as **Bowen's reaction series** (Figure 4-1). Some minerals, such as olivine, are stable at high temperatures (1200°C) and crystallize first. Because minerals that crystallize at high temperatures have more space to grow, they tend to develop crystal faces. Minerals which are stable at lower temperatures, like quartz, crystallize during later stages of magma cooling. Because they must grow within spaces between early formed crystals, the lower-temperature minerals usually occur as irregular grains without well-defined crystal shapes. Therefore, the crystal faces of quartz are often difficult to see in igneous rocks.

The upper part of Bowen's reaction series has two reaction paths, **continuous** and **discontinuous**. If a magma cools at a slow rate, some minerals follow a series of **discontinuous reactions** to form the next lower-temperature mineral. For example, olivine crystallizes first, but as the temperature decreases, the olivine dissolves back into the melt and pyroxene crystals form. At these same temperatures plagioclase crystals also grow; however, they **continuously** react with the melt to form more sodium-rich compositions of plagioclase. A whole range of plagioclase minerals exist, ranging from those with 100% calcium to those with 100% sodium.

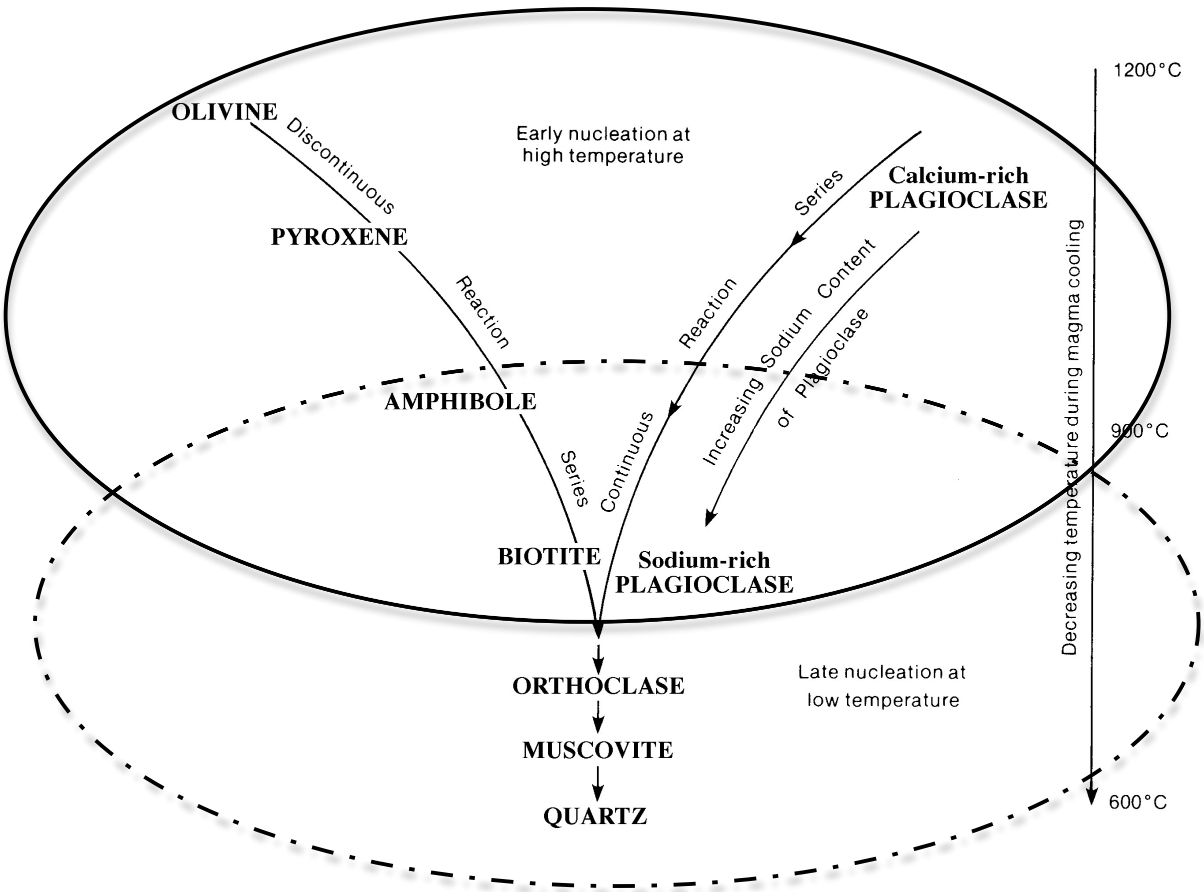


Figure 4-1: Bowen's reaction series, showing the sequence in which minerals crystallize within a cooling magma. The solid line defines minerals found in mafic rocks, the dashed line defines minerals found in felsic rocks and the overlap of the lines defines minerals found in intermediate rocks.

1. **Identify the eight common igneous rock-forming minerals (specimens M-1 through M-8).** You identified many of these minerals last week in lab. Refer to your mineral identification charts (Appendices A-1, A-2, and A-3) and the diagnostic properties of igneous rock-forming minerals (Table 4-1).

Specimen #	Mineral Name	Specimen #	Mineral Name
M-1		M-5	
M-2		M-6	
M-3		M-7	
M-4		M-8	

2. **Divide your mineral specimens (M-1 to M-8) into two piles: mafic minerals (those with dark or green colors), and felsic minerals (those with light or pink colors). List the minerals you have included in each group in the table for question 4.** *[One exception to this general rule is plagioclase. Plagioclase can be grouped with both felsic (Na-rich) and mafic (Ca-rich) minerals].*

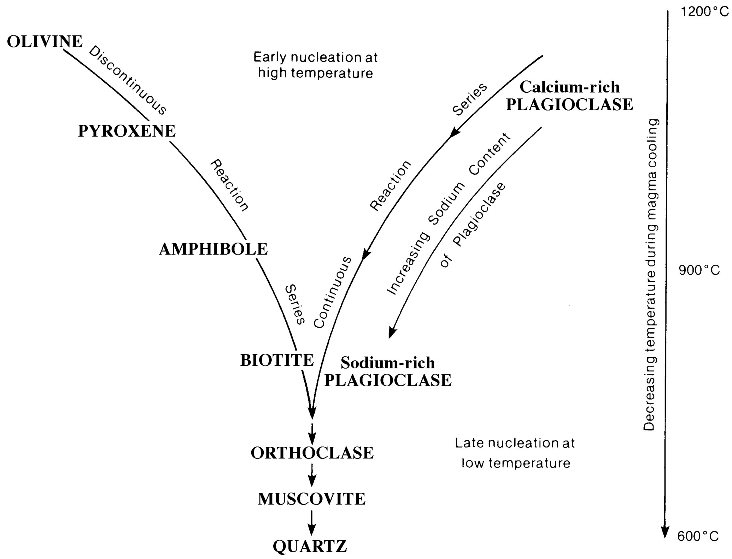
3. Examine the chemical formulas of the minerals you have divided into groups. **List the chemical elements unique to each group in the table after question 4.**

4. Use the mineral ID charts to examine the specific gravity of the minerals you have divided into groups. (Remember specific gravity is related to density.) **Calculate the average specific gravity for each mineral group in the table below.**

	Minerals	Common Chemical Elements	Average Specific Gravity
Mafic & Intermediate			
Felsic & Intermediate			

5. **What two chemical elements are found in all of these mineral samples?**

6. a. Determine where your minerals fit into Bowen's reaction series. **On the figure below label and circle the mafic and felsic minerals.** Note that where the circles overlap defines intermediate composition minerals.



6. b. Based on Bowen's Reaction Series, **which minerals might you expect to find in intermediate igneous rocks?**

7. Look at rock specimens R-1 and R-2. **Identify the minerals that are present in each sample. Are the samples mafic, intermediate, or felsic?**

Specimen #	Minerals Present	Mafic, Felsic, or Intermediate
R-1		
R-2		

8. **Identify the large mineral crystals in specimen R-3.**

9. Based on the color and/or mineral composition, **classify your 9 igneous rock samples (R-1 through R-9) as "mafic", "felsic", or "intermediate".** Write your answer on the Igneous Rock ID Chart (question 14) under "composition."

B. Igneous Rock Texture

Texture refers to the size, shape, and arrangement of the crystals or grains composing a rock. It has nothing to do with how a rock feels, just how it looks. The texture of a rock is a consequence of the physical and chemical conditions under which it formed, and, perhaps, some of the processes that have acted on the rock since that time.

Most igneous rocks have a **crystalline texture**, in which the various mineral crystals are interlocked with one another. This texture develops when crystals grow together as magma solidifies to form an igneous rock. The sequence in which minerals crystallize can often be determined from the texture of the rock. For example, the rock shown in Figure 4-2 is made of four minerals. A, B, and C are well-formed crystals, and grew during early magma cooling. D grew later, between crystals of B and C, and has an irregular shape. Crystals of A occur inside mineral B, but crystals of B are partly surrounded by C. Because included-crystals grow before their enclosing hosts, it follows that mineral A formed first, B second, C third, and D last.

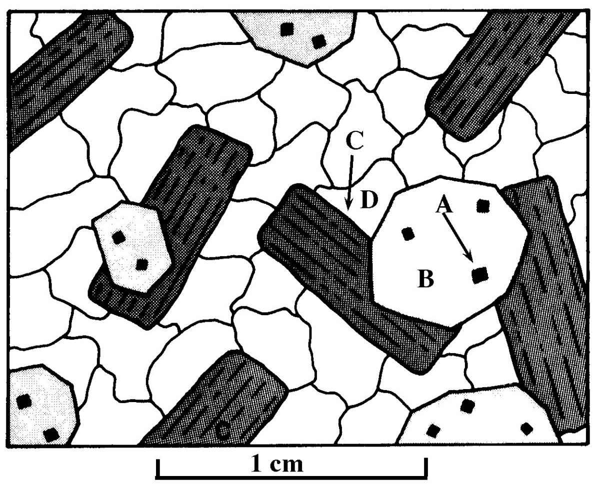


Figure 4-2: Drawing of an igneous rock texture composed of four different minerals (as seen under a microscope). The crystallization sequence of the rock is A to D. [From *Physical Geology* by R. Dallmeyer.]

The rate at which a magma cools has the greatest effect on the size of the crystals in an igneous rock. In general, the more slowly a magma cools, the larger the mineral crystals will be, because slow cooling provides more time for the chemical constituents to migrate to the growing mineral. The chemical composition also affects crystal size and other elements of the texture. For example, abundant water in magma allows chemical constituents to migrate more rapidly to growing minerals. The rapid expansion of gases during the eruption of a volcano also can have a profound effect on the texture of some volcanic rocks.

Most minerals grow approximately the same size when magmas crystallize at one depth within the Earth's crust, and the resulting rocks have an **equigranular texture**. We can differentiate between two types of equigranular texture: coarse-grained and fine-grained. Because intrusive magmas cool relatively slowly, they tend to form large crystals. Extrusive magmas, on the other hand, cool rapidly at the Earth's surface and form microscopic crystals. Because grain size is an important clue for determining the cooling history and environment in which a magma crystallized, igneous textures are divided into two major size categories:

(1) **Coarse-grained** (**phaneritic**): those that contain individual mineral grains that may be observed without the aid of a microscope (larger than 0.062 mm).
(2) **Fine-grained** (**aphanitic**): those that contain individual mineral grains too small to be observed without the aid of a microscope (smaller than 0.062 mm).

If a magma moves upward while it is crystallizing, the rates of cooling will change, and it is likely that resultant igneous rocks will contain minerals of different sizes. Minerals which crystallized and grew when the magma was deeper will likely be larger than those that grew during more rapid cooling at shallower depths. An igneous texture represented by two distinct grain sizes is rather common and defines what is termed a **porphyritic texture**. The larger mineral grains are called **phenocrysts**, and the smaller grains constitute the **matrix**, or **groundmass**. Depending on whether the magma ultimately cooled in the crust or at the surface, the groundmass can be coarse or fine-grained (Figure 4-3).

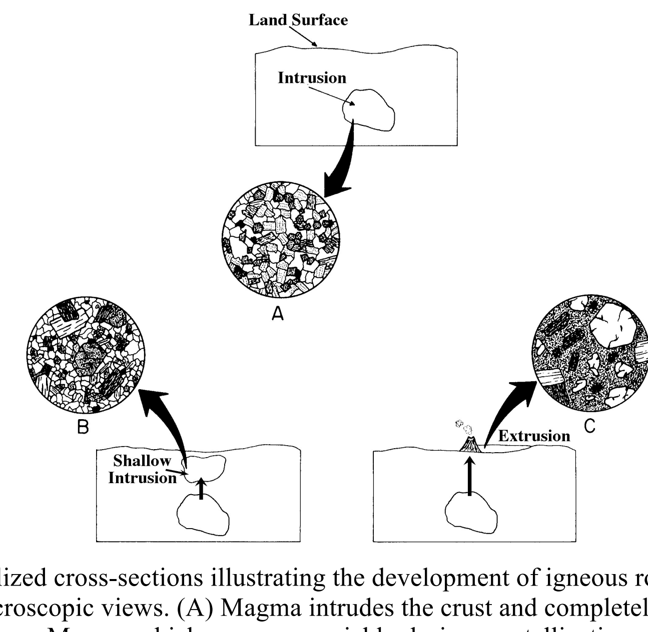


Figure 4-3: Generalized cross-sections illustrating the development of igneous rock textures. Insets are enlargements of microscopic views. (A) Magma intrudes the crust and completely crystallizes, resulting in an equigranular texture. Magma which moves up quickly during crystallization may have one of two possible cooling histories: (B) if magma completely crystallizes near the surface, resultant igneous rocks will contain phenocrysts of early-formed crystals in a coarse-grained matrix; (C) if magma is extruded onto the surface, resultant igneous rocks will have large phenocrysts of early-formed crystals in a fine-grained matrix.

Several unique igneous textures develop in association with volcanic eruptions. These textures include:

(1) **Glassy**: When magmas cool very rapidly at the Earth's surface there frequently is not sufficient time for atoms to combine, and minerals do not nucleate. These hardened magmas are noncrystalline solids and have a **glassy** texture.
(2) **Vesicular**: Magmas often contain a large number of gas bubbles. If extruded magma cools rapidly, some bubbles may not be able to escape. These trapped bubbles form holes which form a spongy or **vesicular** texture.
(3) **Fragmental**: Some magma is ejected into the atmosphere during volcanic eruptions. This magma usually solidifies as ash or larger volcanic fragments before falling back to the surface. Igneous rocks that form by consolidation of this debris typically have a **pyroclastic** or **fragmental** texture.

10. **Identify the textures of the following specimens** ("glassy", "fine-grained", "coarse grained", "porphyritic fine-grained", or "porphyritic coarse-grained"). **Interpret their rate of cooling** ("slow", "moderately fast", "very fast", or "two-stage"), and their **mode of origin** ("intrusive" or "extrusive").

Specimen #	**Texture**	**Rate of Cooling**	**Mode of Origin**
R-4			
R-5			
R-6			

11. **Briefly describe the cooling history of rock specimen R-7 during its formation**.

12. Rock specimens R-3 & R-8 are of the same composition but have different textures.

a. **Compositionally are they felsic, intermediate, or mafic? (circle one)**

b. **What is the texture of specimen R-8?**

c. **Based on the composition and texture, give specimen R-8 a name.**

13. **Describe the texture of the nine rock specimens on your Igneous Rock ID Chart (question 14) under "texture."** First determine if they are "coarse-grained", "finegrained", or "glassy". Then determine if they have any other special textures, such as "porphyritic", "vesicular", or "fragmental".

Identifying Igneous Rocks

An igneous rock may be classified by comparing its textural and mineralogical properties with the Igneous Rock Identification Chart (Appendix B-1). Be aware that igneous rock types are texturally and mineralogically gradational. Therefore, the subdivisions between rock types are somewhat arbitrary.

14. **Use the Igneous Rock Identification Chart (Appendix B-1) to name the nine rock specimens in your tray.**

Specimen #	Composition	Texture	Rock Name
R-1			
R-2			
R-3			
R-4			
R-5			
R-6			
R-7			
R-8			
R-9			

15. **What minerals would you expect to form as phenocrysts in a basalt?** (Hint: Consider magma composition and Bowen's reaction series). **Explain your answer**.

Appendix B-1: Igneous Rock Chart

Composition (Minerals present) → / **Texture** ↓		***Felsic*** Quartz Orthoclase Biotite Na-Plagioclase	***Intermediate*** Na-Plagioclase Amphibole Pyroxene Biotite	***Mafic*** Ca-Plagioclase Pyroxene Olivine
Coarse-grained*		**GRANITE**	**DIORITE**	**GABBRO**
Fine-grained*		**RHYOLITE**	**ANDESITE**	**BASALT**
Glassy		**OBSIDIAN**		
Vesicular		**PUMICE**	**SCORIA**	
Fragmental (pyroclastic)	Coarse	**VOLCANIC BRECCIA**		
	Fine	**TUFF**		

*Some igneous rocks have a porphyritic texture, which means it has mineral of at least two distinctive sizes. If a rock is predominantly fine-grained and mafic, it is a basalt. If phenocrysts (the larger mineral grains) are present in the fine-grained matrix, this rock is called a porphyritic basalt.

The **viscosity** of a lava (its resistance to flow) is closely related to its composition. Mafic magma is very fluid (has a low viscosity) relative to felsic magma. As a result, mafic lava travels a long way after it is erupted, whereas felsic lava tends to pile up near the place where they are erupted. Felsic lava also tends to have a much higher **volatile** (gas) content. A large gas content in lava tends to create a more explosive eruption. We will now consider two different volcanoes: Mt St Helens, Washington; and Kilauea, Hawaii. In order to successfully complete this exercise, you need to be able to understand and read topographic maps. Ask your TA for help if you have some difficulty reading the topographic maps. Here are a couple of important things that will help you read the maps:

- **Contour lines** are points of equal elevation. The **contour interval** is the elevation difference between contour lines. The contour lines that are close together indicate steep topography, and those that are far apart indicate flat topography.
- The **scale** of a map indicates horizontal distances represented on a map. Each map has its own scale, usually found at the bottom.

Mt St Helens, Washington (an example of a composite or stratovolcano)

16. a. **What is the scale of this map?**

    b. **What is the contour interval?**

    c. **What is the highest elevation around the crater?**

    d. **What is the elevation at Redrock Pass (in the southwest part of the map)?**

    e. **How far apart (in miles) are these two points on the map?**

The change in elevation divided by the horizontal distance between those two points is called the **slope**. Slope is commonly given in feet per mile.

17. **What is the approximate slope (in feet/mile) of the southwest side of Mt St Helens?**

Look at the volcanic rock from Mt St Helens.

18. a. **Overall, is it dark colored (mafic) or light colored (felsic)?**

    b. **What other features do you see in this rock?**

19. **a. What kind of eruption did Mt St Helens have in 1980?**

    b. **What evidence on the map supports this?**

c. **What characteristics of the lava likely contributed to this type of eruption?**

Kilauea, Hawaii *(an example of a shield volcano)*

20. a. **What is the scale of this map?**

b. **What is the contour interval?**

c. **What is the elevation of the volcano observatory on top of Kilauea?**

d. **What is the approximate elevation of the water tanks in the southwest corner of the map?**

e. **What is the horizontal distance (in miles) between these two points?**

21. **What is the slope (in feet/mile) of the southwest side of Kilauea?**

Look at the rock from Hawaii.

22. a. **Is it dark colored (mafic) or light colored (felsic)?**

b. **What other features do you see in this rock?**

23. **a. How would you describe most of the Hawaiian volcanic eruptions?**

b. **What characteristics of the lava contribute to this type of eruption?**

Volcano Comparison/Discussion

24. *Look at the photos of Mauna Loa, a volcano very similar to Kilauea, and of Mt. Rainier, a volcano very similar to Mt. St. Helens.* **How would you describe the slope of each volcano – steep and rugged, or gentle and fairly flat?** Hint: look at where the volcano meets the horizon, not at the foreground.

25. a. **Why are the slopes of Mt. St Helens and Kilauea so different?**

b. **How does the type of lava influence the slope?**

c. **How is the temperature of the lava related to the slope of the sides of a volcano?**

d. **How does the type of lava affect the eruption style of these volcanoes?**

26. **Complete the following chart using the information you have accumulated from above**. Use Mt. St Helens as the felsic composition and Kilauea as the mafic composition.

	Composite cone	**Shield volcano**
Example	Mt. St Helens	Kilauea
Slope		
Viscosity of lava		
Temperature of lava		
Volatile content		
Lava composition		
Eruption style		
Tectonic setting		

27. a. **How does the style of eruption influence where people live?**

b. **Is it 'safer' to live near a volcano that erupts the way Kilauea does, or a volcano that erupts in the same fashion Mt St Helens does? Why?**