Introduction
Igneous rocks comprise the bulk of the crust of the Earth. The processes that lead to the formation of igneous rocks have brought Earth’s water to the surface (as well as the atmosphere and the chemicals that make up all of organic life), produced most of its metallic ore deposits, and are responsible for some of our most spectacular scenery and dangerous hazards. They are the principal preserved responses to tectonic plate divergence and convergence, and as such constitute a record of those activities in the past. As such, it is in our interest to learn to recognize, to interpret, and to understand them.

Igneous rocks form when magma (molten rock material) freezes and solidifies. Volcanic eruptions take place when magma reaches the surface before it solidifies. The magma may flow onto the surface as fluid lava or it may erupt explosively as rapidly expanding gas propels bits of lava and rock outward. The rocks resulting from volcanic eruptions cool rapidly and are known as extrusive igneous rocks, because the magma was extruded from the Earth. Intrusive igneous rocks form from the magma that solidifies beneath the Earth’s surface after it has intruded into the pre-existing rocks.

Because igneous rocks form under diverse conditions, they differ widely in texture, mineral composition, and appearance.

Crystallization of Magma and Bowen’s Reaction Series
At high temperatures, a magma is completely liquid, but as the temperature drops, crystals begin to form. They don’t all form at once, however. At first, crystals of only one or two minerals begin to grow. As the temperature continues to drop, these early-formed crystals may grow to
become nicely shaped, they may react with the magma and be partially or wholly dissolved, or new minerals may begin to grow around them, preventing further growth. Continued crystallization increases the proportion of crystals and decreases the amount of liquid. Crystals grow up against one another and form an interlocking, crystalline network. Other minerals may crystallize with further temperature decreases; these will grow in the liquid remaining between earlier-formed crystals.

Because minerals form in a sequence, it is possible to figure out that sequence by carefully studying the textural relations in the rock. This kind of process was done by N.L. Bowen during the early part of the 20th century, but he carried it a giant step further by duplicating the crystallization process in the laboratory. He paid particular attention to reactions between minerals as indicated by textural relations. For example, he commonly found crystals of olivine surrounded by pyroxene (pyroxene is a family of minerals that includes augite) and concluded that olivine formed first, and then at a lower temperature, reacted with the liquid (magma) to form pyroxene. He called this a **discontinuous reaction**, because it results in the formation of a completely different mineral (pyroxene). As the pyroxene grows around the olivine, it sometimes prevents further reaction from taking place, and a partially reacted upon, rounded olivine is left surrounded by pyroxene.

Bowen also observed that plagioclase feldspars gradually changed their chemical composition as magma temperature decreased and plagioclase crystallized. He attributed this to a **continuous reaction** between the magma and the growing crystals of plagioclase: the first plagioclase crystal to form are rich in calcium, but as the temperature of the magma drops and plagioclase crystals grow, they continuously react with the remaining liquid, changing their chemical composition and becoming richer in sodium.

Bowen summarized his studies with a diagram, now called *Bowen’s Reaction Series*, which included all of the major rock-forming minerals of common igneous rocks. The **discontinuous**
reaction series contains all of the common iron-forming (ferro-magnesian) minerals. Plagioclase makes up the continuous reaction series. The three minerals at the bottom do not form by reaction with the first-formed crystals. They simply crystallize last, sometimes in the sequence in which they are listed and sometimes simultaneously.

The reaction series shows that, when a natural magma cools, certain minerals crystallize earlier and at higher temperatures than others. The common rock-forming minerals form in a regular sequence, with olivine and calcium-rich plagioclase at the top of the list, crystallizing at temperatures some 500-600ºC higher than quartz, which is at the bottom of the list. The crystallization temperatures of the plagioclase feldspars fall in the same range as the ferromagnesian minerals. Note, however, that the more calcium-rich plagioclases crystallize at higher temperatures than the less calcium- and more sodium-rich plagioclases. The most sodium-rich plagioclase crystallizes at the lowest temperature.

Where and How Magmas Form
Most volcanoes are associated with tectonic plate boundaries. What happens at plate boundaries that allows magmas to form? Are there simply cracks that open into a huge reservoir of magma? Not likely; although part of the Earth’s core is molten, the silicate magmas from which igneous rocks form are very different from the molten iron alloys in the core.

The most likely way for magmas to form is by partial melting of existing rocks. What would happen if a rock made of quartz, orthoclase, sodium plagioclase, biotite, and hornblende began to melt? We can use Bowen’s Reaction Series to predict the results. The minerals lowest in the series, such as quartz and orthoclase, melt at lower temperatures than minerals higher in the series. Imagine that the temperature got just high enough to melt the quartz and feldspar, but not high enough to melt the rest of the minerals. Because quartz and orthoclase are the main minerals in granite, the partial melt would have a felsic composition similar to that of granite. The liquid, because it is less dense than the surrounding rock, would migrate upward. Drops of liquid would eventually coalesce to form a body of magma, which would continue to move upward until it either erupted on the surface or crystallized below the surface.

At divergent plate boundaries (where plates move away from one another), hot, buoyant peridotite from the mantle rises and, because of its ultramafic composition, partially melts to form a mafic magma that is chemically similar to basalt or gabbro. The magma rises and intrudes into the surrounding lithosphere or is extruded onto the seafloor.

The process at convergent plate boundaries (where plates move toward one another) is more complex. When the down-going slab of lithosphere gets hot enough, water-rich fluids are released that trigger partial melting in both the slab and the overlying wedge of mantle. As the magma rises, high-temperature minerals such as olivine may crystallize and be left behind, and the magma may partially melt some of the rocks through which it passes. These and other complex processes yield abundant intermediate magma (chemically like andesite or diorite), which erupts at the surface, and felsic magma (chemically like granite or rhyolite), which is trapped below the surface to form large bodies of intrusive igneous rock.
Changes in Magmas
Like the magma formed at convergent plate boundaries, most magmas undergo some kind of change between the time they form and the time they solidify into rock. The changes may result from partially dissolving or melting the surrounding rock, from mixing with other magmas, or from processes within the magma itself.

As an example of a process within the magma, consider what might happen when a gabbroic magma crystallizes. According to Bowen’s Reaction Series, olivine is the first mineral of the discontinuous series to crystallize. Olivine is denser than the magma, so if there are no currents within the magma the olivine crystals would sink and form a mush of olivine crystals and magma. This would leave a smaller amount of magma at the top of the magma chamber, and what is left would be depleted in the components of olivine (magnesium and iron). Should the magma rise, the olivine crystals would be left behind and the rising magma would be less mafic than the original one. Thus, two different igneous rocks would be formed: one from the olivine-rich mush left behind, and the other from the rising magma.

Texture
Texture refers to the size, shape, and arrangement of the crystals or grains composing the rock. 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 a magma solidifies to form an igneous rock.

The rate at which a magma cools has the greatest effect on the sizes of the crystal 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 of the magma also affects crystal size and other elements of texture. For example, abundant water in magma allows chemical constituents to migrate more rapidly to growing mineral crystals. And rapid expansion of gases during the eruption of a volcano has a profound effect on the texture of some volcanic rocks.

Textures Based on Crystal Size
Glassy: A rock with glassy texture is made of glass and has few or no crystals. An example is obsidian. Some igneous rocks are partly crystals or partly glass.

Obsidian is simple to identify due to its vitreous (or glassy) luster and its conchoidal fracture. As with the microcrystalline silicate chalcedony, this fracture produces natural edges that can be sharper than any knife or metal blade. This property made obsidian (and chalcedony rocks like flint or jasper) a favorite among stone-age peoples for fashioning tools such as axes, knives and spearheads. This sample of banded obsidian has a chemical composition similar to rhyolite, but obsidian contains no mineral crystals because it solidified before any ordered crystals could form.
**Fine-grained** (or **Aphanitic**): An igneous rock (or a part of an igneous rock) with a fine-grained or aphanitic texture has crystals, but they are too small to recognized with the unaided eye. In practice, this means that the average dimension of the crystals is less than 1 millimeter.

This basalt is an example of a rock with a fine-grained, or aphanitic texture. The individual mineral crystals present here are too small to be seen with the naked eye and in most cases require a microscope to identify.

**Coarse-grained** (or **Phaneritic**): An igneous rock consisting mostly of crystals large enough to see without a hand lens (> 1 mm) has a coarse-grained or phaneritic texture.

A phaneritic, or coarse-grained crystalline texture.

In this sample of granite the large flesh-colored crystals are potassium feldspar (orthoclase), the white crystals are plagioclase, the gray translucent crystals are quartz, and the small black crystals are biotite.

**Pegmatitic**: Igneous rocks with exceptionally large crystals (> 2-3 centimeters) have a pegmatitic texture and are called **pegmatites**. These large crystals result from very slow cooling of water-rich magmas.

Pegmatites are very coarse crystalline intrusive rocks that typically represent small intrusions or the very last phase of an intrusive event. They are defined by their large crystals, typically larger than 2-3 cm (1 inch) which form because the magmas which cool to form pegmatites typically contain lots of excess water. Also, pegmatites often contain unusual minerals, or larger percentages of minerals that usually exist as trace minerals (such as the large root beer brown crystals of sphene shown here).
Porphyritic: Crystals of two different sizes are present in rocks with a porphyritic texture. The large crystals, or phenocrysts, are surrounded by many smaller crystals, collectively called the groundmass. The groundmass can be aphanitic or phaneritic, but the phenocrysts are typically coarse-grained. Both intrusive and extrusive igneous rocks can be porphyritic, but it is more typical of extrusive rocks.

Porphyritic texture in a sample of andesite. The groundmass of the rock has an aphanitic texture, but the rock also contains a number of large crystals, or phenocrysts. The long thin phenocrysts in this specimen are hornblende crystals.

A granodiorite porphyry. In this type of porphyry the groundmass is a phaneritic rock visible crystals of uniform size. The phenocrysts are also visible to the naked eye but are very large in relation to the groundmass. Some of the coffin-shaped orthoclase (potassium feldspar) crystals shown here are more than 1 inch wide.

Other Textures of Extrusive Igneous Rocks

Vesicular: As magma approaches and flows on the surface of the Earth, gases will evolve from the fluid (in much the same way as CO₂ evolves from soda or beer when you open the bottle). If the lava solidifies before the gas can escape, the resulting rock will contain numerous cavities, or vesicles, at the sites of the former gas bubbles, giving it a vesicular texture. Vesicles may vary from a few millimeters to several centimeters in diameter. This is relatively common in basaltic magmas; a vesicular basalt is commonly known as scoria.

A vesicular texture refers to a rock permeated by small bubbles. These vesicles were created by gas trapped in the rock when it solidified. Basaltic lava flows are commonly vesicular. Highly vesicular basalts are called scoria and can range in color from dark gray to black (if fresh) to brick red (typically older and oxidized. Scoria rocks may rarely appear vitreous.
**Pumice**: A lava containing a great deal of gas may froth out onto the surface, solidify very quickly, and form a rock with lots of very small vesicles. Pumice-type rocks are commonly glassy and are associated with obsidian flows.

Pumice could also be said to have a vesicular texture, but there are two primary differences between pumice and other vesicular volcanic rocks: (1) the rock matrix in pumice is entirely glassy, containing no minerals; (2) the volume of the bubbles makes up the bulk of the rock’s volume, so that pumice has an extremely low density (and usually will float in water). The thin glass walls of the bubbles are extremely thin, sharp and fragile, making this rock very popular as an abrasive agent for scraping calluses from your feet (since it will abrade skin but break before it cuts too deeply.

**Pyroclastic**: Volcanoes that erupt explosively expel lots of gas, bits of lava, and fragments of rocks and ash. The volcanically produced fragments, or *pyroclasts* (fire rocks), either are blown into the air before falling to the ground or are carried down the slopes of the volcano as a gas-charged surface flow. Settling to the ground while still hot, these materials can become fused or welded together to form a *pyroclastic* rock. Extrusive rocks with pyroclastic textures usually contain small bits of glass, mineral crystals, various sizes of rock fragments. The rocks may be soft and lightweight for their size and have a rather “open” texture, or they may be quite hard and dense, depending on the degree of compaction during the welding process. A *tuff* is a lightweight pyroclastic rock composed primarily of *welded ash*. If a tuff contains many large fragments of pre-existing rock it is called a *volcanic breccia*.

Volcanic tuff has a pyroclastic texture, representing a rock that is made up of broken fragments of existing rock thrown up by a violent eruption that are mixed in a matrix of volcanic ash. The pyroclastic texture of most tuffs is not this obvious. This sample shows excellent color contrast between the various angular clasts (red, orange, brown, etc.) and the compacted ash (light-colored). The composition of the ash is usually rhyolitic to andesitic and is commonly pink, gray or white but can even be green.

**Mineral Composition**
Relatively few minerals make up most igneous rocks. To correctly identify the rock, you must identify the major minerals contained within. This is fairly easy for coarse-grained rocks, but more difficult (though not impossible) for fine-grained rocks.

1. Most dark colored igneous rocks are rich in calcium-rich plagioclase (*anorthite*) and ferromagnesian minerals such as *augite*, *hornblende*, and *olivine*. These rocks are referred to as *mafic* rocks. *Ultramafic* rocks are usually composed entirely of ferromagnesian minerals.
2. Light-colored or **felsic** igneous rocks commonly contain potassium feldspar (*orthoclase*), sodium-rich plagioclase (*albite*), and *quartz*, along with minor amounts of other minerals.

3. **Intermediate** igneous rocks are neither light nor dark, and contain some light-colored minerals such as feldspar and quartz, and dark minerals such as hornblende and biotite.

4. Quartz, when found in igneous rocks, is vitreous (glassy), and typically colorless. It may appear rather gray in color due to the fact that you can see through it.

5. *Orthoclase* or potassium feldspar is usually pink. White or gray feldspars may be either potassium feldspar or plagioclase (if striations are present it is plagioclase).

6. Cleavage and general appearance can help to identify hornblende and augite. Hornblende cleavages do not intersect at 90° but augite cleavages do. Hornblende is typically elongate and splintery, while augite crystals tend to look blocky.

### Recognizing Minerals in Intrusive Igneous Rocks

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Properties</th>
</tr>
</thead>
</table>
| Orthoclase (*potassium feldspar*) | - Usually white or pink  
- 2 cleavages @ 90°  
- Euherdal crystals may be coffin-shaped |
| Plagioclase feldspar | - Chalky white in granite or diorite, but medium- to blue-gray in gabbro  
- 2 cleavages @ 90°  
- Striations may be visible in cleavage face |
| Quartz | - Colorless to gray in igneous rocks  
- Glassy with conchoidal fracture  
- Irregular crystals in intrusive rocks |
| Biotite | - Shiny and black  
- One perfect cleavage  
- Equidimensional flat crystals  
- Accessory mineral found only in felsic or intermediate rocks |
| Muscovite | - Shiny and silvery-white  
- One perfect cleavage  
- Flaky equidimensional crystals  
- Accessory mineral found only in felsic rocks |
| Hornblende (*amphibole*) | - Black and shiny  
- Two good cleavages at 56° and 124°  
- Euherdal, elongate (needle-like) crystals |
| Augite (*pyroxene*) | - Very dark green to black  
- Duller than hornblende or biotite  
- Two cleavages @ 90°  
- Blocky euherdal crystals  
- Found only in intermediate to mafic rocks, never in the presence of quartz |
| Olivine | - Light green to yellow green  
- Vitreous luster  
- Small equidimensional crystals  
- Found only in mafic rocks, never in the presence of quartz |
**Classification and Identification of Igneous Rocks**

Igneous rocks are classified by their texture and mineral content. The classification scheme lists common textures in the left-hand column and typical mineral composition in the top row. Although rock names occupy distinct spaces in the table, it should be understood that these divisions are artificial and that rock types are gradational with one another. To identify a rock, determine the texture and mineral content, and find the name in the “pigeonhole” that satisfies both. For example, a rock that is coarse grained, porphyritic, and contains quartz and potassium feldspar is a porphyritic granite.

<table>
<thead>
<tr>
<th>Texture</th>
<th>Pegmatitic</th>
<th>Phaneritic (coarse-grained)</th>
<th>Aphanitic (fine-grained)</th>
<th>Pyroclastic (clasts &lt; 2 mm)</th>
<th>Pyroclastic (clasts &gt; 2 mm)</th>
<th>Glassy and massive</th>
<th>Glassy and vesicular</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pegmatite</td>
<td>Granite pegmatite</td>
<td>Diorite pegmatite</td>
<td>Gabbro pegmatite</td>
<td>Peridotite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Granite</td>
<td>Diorite</td>
<td>Gabbro</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aphanitic granite</td>
<td>Porphyritic diorite</td>
<td>Porphyritic gabbro</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rhyolite</td>
<td>Andesite</td>
<td>Basalt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rhyolite porphyry</td>
<td>Andesite porphyry</td>
<td>Basalt porphyry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rhyolite tuff</td>
<td>Andesite tuff</td>
<td>Basalt tuff</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rhyolite breccia</td>
<td>Andesite breccia</td>
<td>Basalt breccia</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Mineral Composition**

- **Felsic**
  - >10% quartz
  - >50% feldspar w/ orthoclase > plagioclase
  - <15% biotite, muscovite, hornblende

- **Intermediate**
  - 0-10% quartz
  - 0-15% plagioclase
  - <50% hornblende (especially), augite or biotite

- **Mafic**
  - 20-85% Ca-Plagioclase (light-medium gray)
  - 15-50% augite
  - 0-35% olivine

- **Ultramafic**
  - Olivine ± pyroxene

**Percentage of ferromagnesian (dark-colored) minerals**
1. If crystals are not visible or are barely visible with a hand lens, and:
   a. The rock looks like glass, the texture is glassy.
   b. It is not glassy, but has a texture similar to fine or medium sandpaper, the texture probably is fine-grained.
   c. If the texture is fine-grained and vesicles are present, the texture is fine-grained and vesicular.
   d. The rock consists of fragments of glass, pumice, or other rocks, the texture is most likely pyroclastic.

2. If crystals are visible without a hand lens, and:
   a. Most crystals are larger than 3 centimeters, the texture is pegmatitic.
   b. Most crystals are smaller than 3 centimeters, the texture is coarse-grained.
   c. Crystals are of two sizes, the texture is porphyritic.

Next identify the major minerals. The important mineralogical criteria are:

1. Presence or absence of quartz (only the granites and rhyolites in column 2 have quartz);
2. The type of feldspar (whether orthoclase or plagioclase, and if plagioclase, whether sodium-rich or calcium-rich);
3. The proportions and kinds of dark-colored minerals (biotite / hornblende / augite / olivine).

Minerals in the groundmass of fine-grained rocks commonly cannot be identified; however, phenocrysts in such rocks can be helpful. According to the table, if quartz phenocrysts are present, the rock is rhyolite; if only hornblende phenocrysts are present, it is andesite; if only augite and olivine are present, it is basalt; and if feldspar phenocrysts are present, the feldspar must be identified on the basis of presence or absence of striations.