# Chapter 1

# Introduction to Igneous Petrology

## 1.1 Introduction

Igneous petrology is the study of magma and the rocks that solidify from magma. Thus igneous petrologists are concerned with the entire spectrum of processes that describe how magmas are produced and how they ascend through the mantle and crust, their mineralogical and geochemical evolution, and their eruption or emplacement to form igneous rocks. Igneous petrology requires a working knowledge of mineralogy. Readers who wish to review the characteristics of the major rock-forming igneous minerals will find a concise summary in Appendix 1. The appendix emphasizes the identification of rock-forming minerals in hand sample and in thin section. In addition, the appendix includes descriptions of minerals found in minor abundance but commonly occurring in igneous rocks, including accessory minerals that contain trace amounts of uranium and are important geochronometers.

Before geologists can understand the origin of igneous rocks, they must classify and describe them. This chapter introduces the classification of igneous rocks using the mineralogical classification system recommended by the International Union of Geological Sciences (IUGS) Subcommission on the Systematics of Igneous Rocks, which has the advantage that it is relatively simple and can be applied in the field. For rocks that are too fine-grained to name using this classification, a geochemical classification can be employed instead. The simplest of these, the total alkali versus silica classification, is introduced in this text.

Finally, this chapter introduces basic terminology that describes the textural and structural features of igneous rocks. Descriptions of igneous textures document crystal shape, size, and the arrangement of the various minerals, glass, and cavities in the rock. Igneous structures are larger-scale features that are the result of rock-forming processes. The textures and structures preserved in igneous rocks provide information about their evolution, emplacement, and crystallization, all of which are fundamental goals of igneous petrology.

## 1.2 The Scope of Igneous Petrology

All rocks ultimately derive from magmas, which solidify to form igneous rocks. Consider, for example, the history of a shale. Such a rock is now composed of clay minerals. These clay minerals may have formed by weathering of a sedimentary rock that contained rock fragments and mineral grains. These components in turn may have been produced by erosion of a granitic gneiss. Before it was metamorphosed, this gneiss may have been a granodiorite, which is an igneous rock formed by crystallizing magma. As this example illustrates, the study of igneous petrology forms a foundation from which to study metamorphic and sedimentary rocks.

Igneous petrology is the study of the classification, occurrence, composition, origin, and evolution of rocks formed from magmas. The discipline can be divided into two components: **igneous petrography**, which is the description and classification of igneous rocks; and **igneous petrogenesis**, which is the study of the origin and evolution of igneous rocks. There are many different ways to approach the study of igneous petrology. **Field geology** is very important to the study of igneous petrology because important information is contained in the field relationships between rock units, the structure of an igneous rock, and its texture and physical appearance. For example, volcanologists depend heavily on their field observations during an eruption, and on the distribution of ash, lava, and other volcanic ejecta formed as the result of the eruption, to model the processes that occurred within a volcano before and during an eruption. **Laboratory identification** of the minerals in a thin section of an igneous rock, along with the chemical composition and age of a rock, are important means of classifying and relating it to other rocks with which it is spatially associated.

Another important way to study igneous rocks is through geochemistry. **Major-element geochemistry** can determine whether a suite of rocks is related through a process such as magmatic differentiation or mixing. **Trace-element geochemistry** is used to identify the role various minerals may have played as either crystallizing phases or residual phases in a suite of rocks. **Isotope geochemistry**, which can involve both radiogenic and stable isotopes, can determine whether a suite of rocks formed from a single magma, or whether a more complex, multisource process was involved.

Because magmas that crystallize beneath Earth's surface are not observable and lavas erupted on the surface are hot and often dangerously explosive, geologists find it difficult to study the formation of igneous rocks directly. Therefore **experimental petrology** is an important aspect of igneous petrology in which the pressures and temperatures required for igneous rocks to form and evolve are reproduced in the laboratory. For many rocks, field and petrographic description does not provide conclusive proof of the process by which they formed. For these rocks, data gathered from experimental petrology are essential.

## 1.3 Classification of Igneous Rocks

One of the most tedious aspects of igneous petrography is the mastery of terminology. Innumerable, and often inscrutable, names have been applied to igneous rocks over the past few centuries as petrology grew in importance and sophistication. Much igneous terminology is arcane because in the early days of the science, petrologists did not have access to experimental data, phase diagrams, isotopic systems, or thermodynamic data and thus their work was mainly descriptive as opposed to quantitative. One way they described rocks was to name them. Among the more picturesque names is **charnockite**, which was named after the rock that formed the tombstone of Job Charnock, the founder of Calcutta (now Kolkata), India. Charnockite is a name given to an orthopyroxene-bearing granite, but there is no way to determine that from the origin of the name unless one was to desecrate Job Charnock's tombstone by sampling it for thin section and chemical analysis.

Unfortunately, like charnockite, most of the rock names that arose early in the development of igneous petrology do not provide much insight into the origin or evolution of the rock they describe. Many of the rock names based on type locality were given in the nineteenth or early twentieth century. Over time, geologists recognized the necessity of a more systematic rock classification scheme. In 1972, the IUGS Subcommission on the Systematics of Igneous Rocks published a rock classification system that has been widely adopted, and use of many of the old rock names has been abandoned (Streckeisen, 1976; LeMaitre et al., 1989; LeBas and Streckeisen, 1991).

There are two basic approaches to the naming of rocks. A rock can be classified either according to the minerals that make it up or by its chemical composition. The first approach has the benefit that geologists can name rocks in the field by identifying their mineralogy; however, it is not very helpful for classifying fine-grained rocks. Alternately, a chemical classification requires analytical data, and therefore is not useful in the field, but it does provide a means of naming fine-grained or glassy rocks. The compositions of most igneous rocks can be expressed in nine oxides: $SiO_2$, $TiO_2$, $Al_2O_3$, $Fe_2O_3$, FeO, MgO, CaO, $Na_2O$, and $K_2O$. These combine to form the major rock-forming igneous minerals, which include pyroxene, olivine, garnet, amphibole, mica, quartz, plagioclase, alkali feldspar, feldspathoid, magnetite, and ilmenite. Most rocks contain only a few of these minerals. The IUGS classification uses both mineralogical and chemical data, but emphasizes classification on the basis of mineralogy.

### 1.3.1 Preliminary Classification

Igneous rocks are divided into the general categories of **plutonic**, **hypabyssal**, and **volcanic** depending on their grain size. Plutonic rocks characteristically have coarse or medium grain sizes (>1 mm) and are inferred to have crystallized deep in the crust. Hypabyssal and volcanic rocks are fine-grained to glassy. Volcanic rocks crystallize at the surface and hypabyssal rocks crystallize at shallow depths, typically less than a kilometer. Because the grain size of an igneous rock is determined by the cooling rate of the magma and this is a function both of magma temperature and the ambient temperature of the rocks into which the magma was emplaced, grain size generally increases with depth but there is no specific depth associated with the transition from plutonic to hypabyssal rocks.

In addition to classification according to grain size, we can describe the general composition of a rock using the terms **felsic**, **mafic**, and **ultramafic**. Rocks rich in quartz, feldspars, or feldspathoids are light colored and are called *felsic*. The term *felsic* combines parts of the words **fel**dspars (and **fel**dspathoids) and **si**lica. Darker-colored rocks rich in ferromagnesian minerals are called *mafic*. The term *mafic* reflects the enrichment of these rocks in **ma**gnesium and iron (**F**e). Ultramafic rocks are essentially free of any felsic minerals.

### 1.3.2 IUGS Classification of Plutonic Rocks

Because plutonic rocks are relatively coarse-grained so that their constituent minerals can be easily identified, either in hand specimen or in thin section, they are the most straightforward group of igneous rocks to classify. The IUGS classification is based on the modal amounts of the common minerals, which are divided into five groups:

| | |
|---|---|
| Q | quartz |
| A | alkali feldspar, including albite with up to five mole percent anorthite ($<An_5$) |
| P | plagioclase with composition $An_5$ to $An_{100}$ |
| F | feldspathoids: nepheline, sodalite, analcite, leucite, cancrinite |
| M | mafic minerals: olivine, pyroxenes, amphiboles, micas, and opaque minerals, and accessory minerals such as zircon, apatite, sphene, allanite, garnet, and carbonate. |

Rocks containing less than 90 percent mafic minerals ($M<90$) are classified according to the amounts of Q, A, P, and F minerals they contain, whereas rocks containing more than 90 percent mafic minerals are classified according to the proportions of major mafic minerals. Felsic and mafic rocks typically have far less than 90 percent mafic minerals and ultramafic rocks far more.

Because rocks never contain both quartz and feldspathoids, felsic and mafic rocks can be classified in terms of three components, either QAP or FAP. Triangular plots of the three components are shown in Figure 1.1 along with the names assigned to rocks containing particular proportions of Q, A, P, and F minerals. However, some rocks are not uniquely defined by QAP or FAP alone. For example, both diorite and gabbro fall in the same portion of the QAP triangle. They are distinguished primarily on the basis of plagioclase composition: plagioclase in diorite is more sodic than $An_{50}$, whereas that in gabbro is more calcic. Because the IUGS classification does not consider the composition of the plagioclase, it cannot distinguish these two rock types. A third rock name is assigned to the gabbro/diorite portion of the QAP triangle: anorthosite. Anorthosite is a special name applied to rocks that contain more than 90 percent plagioclase. Because the IUGS classification is based only on the proportion of Q, A, P, and F minerals, it does not distinguish between rocks with only 10 percent ferromagnesian minerals and rocks with up to 90 percent ferromagnesian minerals. Therefore,

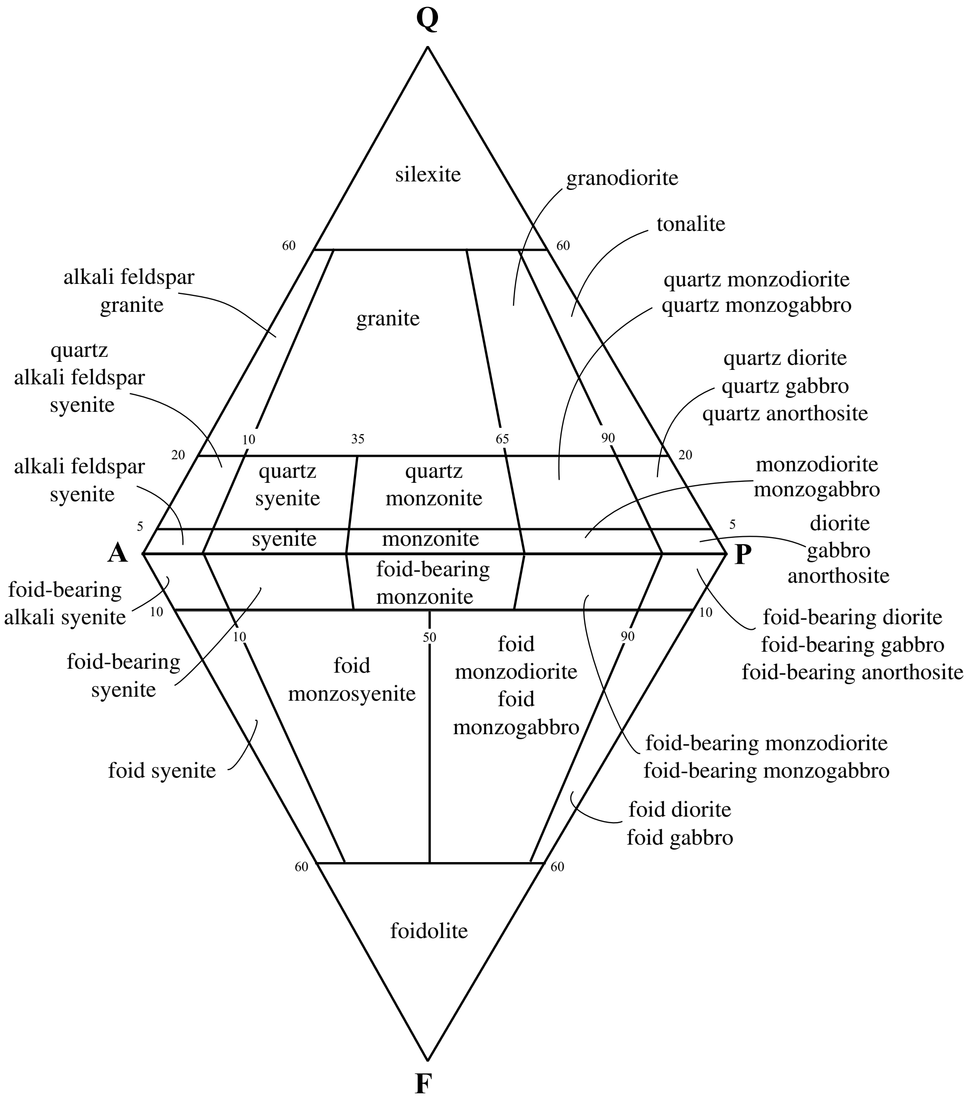


**Figure 1.1** IUGS classification of plutonic rocks based upon modal mineralogy. A = alkali feldspar, F = feldspathoid, P = plagioclase, Q = quartz. After Streckeisen (1976).

anorthosite occupies the same part of the triangle as do the diorites and gabbros that have considerably higher mafic mineral contents. This classification scheme can be further specified by adding the names of the major mafic minerals present, with the most abundant placed closest to the rock name. For example, a biotite-hornblende tonalite contains more hornblende than biotite.

Mafic rocks can be further subdivided according to the proportion of plagioclase, orthopyroxene, clinopyroxene, olivine, and hornblende they contain (Figure 1.2). Strictly speaking, the term *gabbro* applies to a rock consisting of augite and calcic plagioclase, although the term is also broadly applied to any rock consisting of calcic plagioclase and other ferromagnesian minerals. For example, troctolite, a rock with olivine + calcic plagioclase, and norite, a rock with orthopyroxene + calcic plagioclase, are included in the gabbro family. Though not shown in Figure 1.2, rocks consisting of calcic plagioclase and hornblende are, quite logically, called hornblende-gabbros. Most gabbroic rocks contain between 35 and 65 percent mafic minerals. If they contain less than this, the rock name may be prefixed by **leuco**-, meaning light. If they contain more than 65 percent mafic minerals, they may be prefixed by **mela**-, meaning dark.

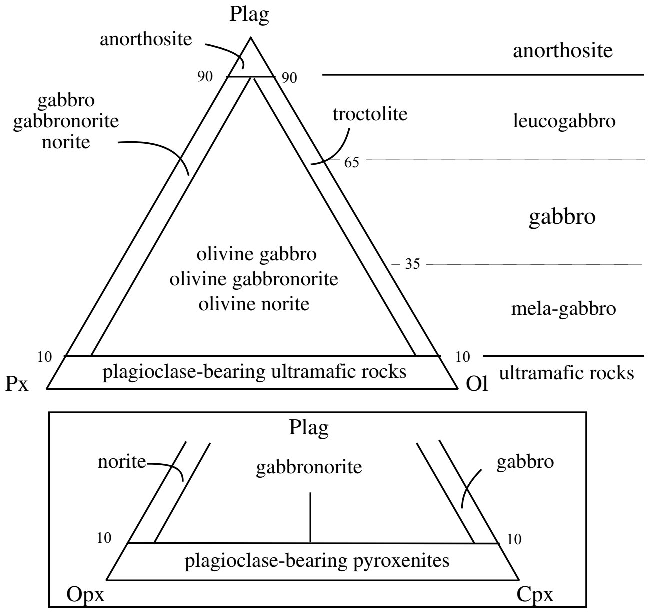


**Figure 1.2** IUGS classification of gabbroic rocks. Ol = olivine, Plag = plagioclase, Px = pyroxene. Inset shows classification with regards to the type of pyroxene. Opx = orthopyroxene, Cpx = augite. After Streckeisen (1976).

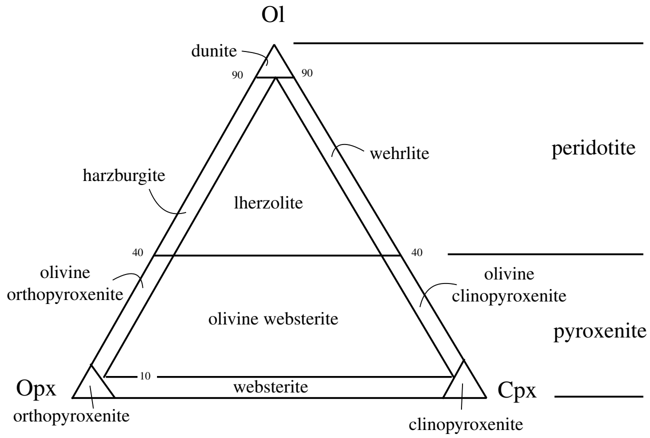


**Figure 1.3** IUGS classification of ultramafic rocks. Ol = olivine, Opx = orthopyroxene, Cpx = clinopyroxene. After Streckeisen (1976).

Ultramafic rocks contain little or no plagioclase and thus require their own classification scheme based on ferromagnesian mineral content. Ultramafic rocks containing more than 40 percent olivine are called peridotites, whereas ultramafic rocks containing more than 65 percent pyroxene are called pyroxenites (Figure 1.3). Peridotites and pyroxenites are further divided depending on the relative proportions of orthopyroxene, clinopyroxene, and olivine. The presence of other mineral phases can be used to further specify the name of the ultramafic rock; for instance, lherzolite that contains garnet is called garnet lherzolite.

Charnockites (orthopyroxene-bearing granitic rocks), lamprophyres (mafic and ultramafic rocks with mafic phenocrysts), carbonatites (igneous carbonate-rich rocks), and pyroclastic rocks have their own classification schemes (LeMaitre et al., 1989).

### 1.3.3 IUGS Classification of Volcanic and Hypabyssal Rocks

Whenever possible, the IUGS recommends that volcanic rocks be classified on the basis of modal mineralogy. The names for volcanic and hypabyssal rocks determined in this way are given in Figure 1.4. There are a few plutonic rock types for which there are no volcanic equivalents, such as anorthosite and ultramafic rocks. These plutonic rocks usually represent accumulations of crystals, and no liquid of that composition ever existed. The only ultramafic lava solidifies to form a rare rock called **komatiite**, which occurs almost exclusively in ancient Archean terrains. It is the volcanic equivalent of peridotite.

If the volcanic rocks are so fine-grained that minerals cannot be identified, then they must be classified on the basis of chemical composition. The IUGS has recommended that volcanic rocks be classified based upon their total alkali and silica contents (TAS) (LeBas et al., 1986) (Figure 1.5). The TAS diagram has as its x-axis the weight percent of $SiO_2$ of the rock, and as its y-axis the weight percent $Na_2O + K_2O$ of the rock. The diagram is then divided into fifteen fields. Classification using this chemical approach gives rock names that are typically consistent with the names based on the QAPF diagram.

## 1.4 Igneous Textures

Petrologists use textures and structures to interpret how igneous rocks crystallized. The terms *texture* and *structure* are nearly interchangeable, although **texture** of a rock refers to the small-scale appearance of the rock: the size, shape, and arrangement of its constituent phases,

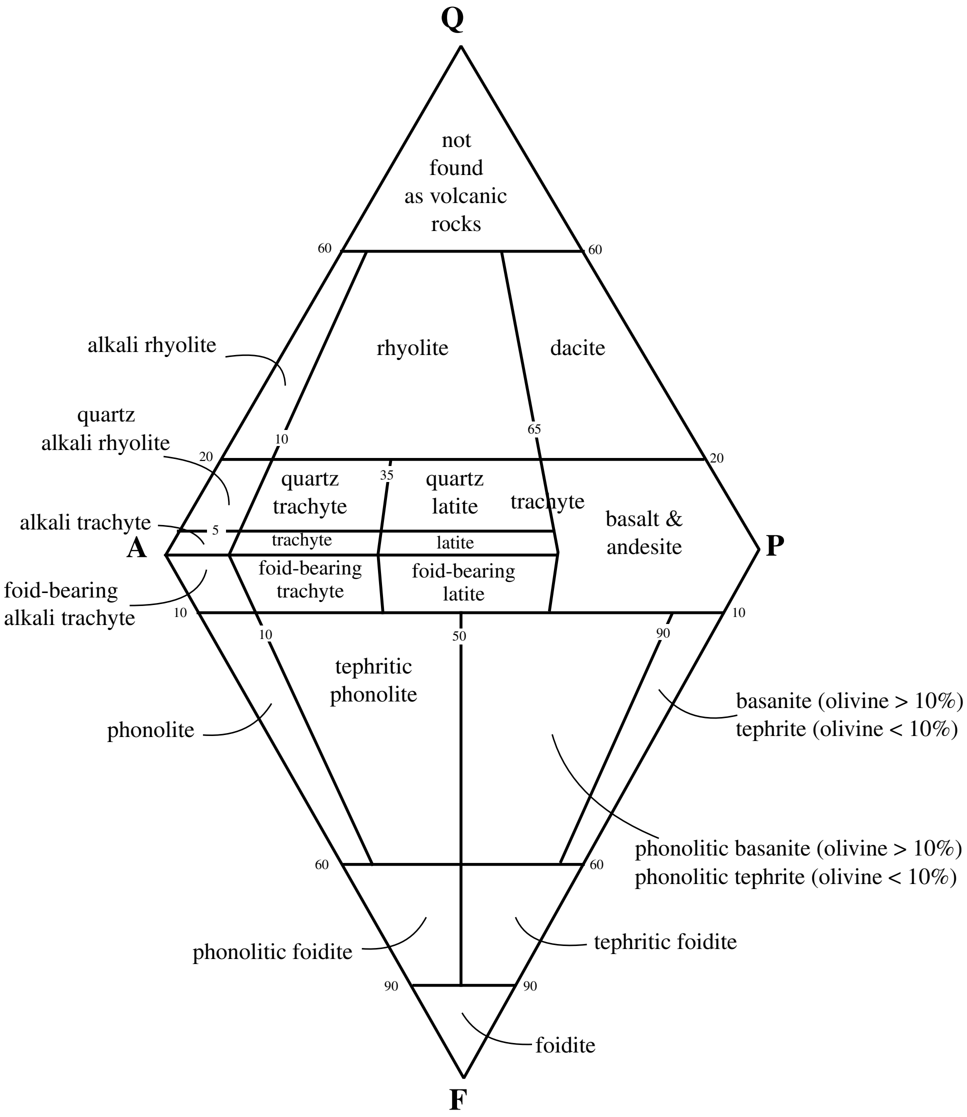


**Figure 1.4** IUGS classification of volcanic rock based on modal mineralogy. Abbreviations as in Figure 1.1. After Streckeisen (1980).

including minerals, glass, and cavities. The **structure** of a rock refers to larger-scale features recognizable in the field, such as banding, mineral zonation, or jointing. Textures may provide information about cooling and crystallization rates and the phase relations between minerals and magma at the time of crystallization. Structures indicate the processes active during the formation of rocks and the mechanisms of differentiation.

## 1.4.1 Crystal Size

Igneous textures, including the size and shape of minerals, provide information about the crystallization history of igneous rocks. The size of the crystals that form when a melt crystallizes involves a complex interaction between the rate at which crystals nucleate and the rate at which essential elements diffuse to the surface of the growing crystal. The rate at which elements move through a melt may not change much during cooling, but the rate of nucleation is strongly dependent on how close the melt is to the equilibrium crystallization temperature. No nucleation will occur at the equilibrium crystallization temperature because it requires some energy to nucleate a crystal. The melt has to be somewhat undercooled (i.e., cooled below the equilibrium crystallization temperature) before crystals can nucleate. The further the melt temperature is below the equilibrium crystallization temperature the faster the nucleation will be.

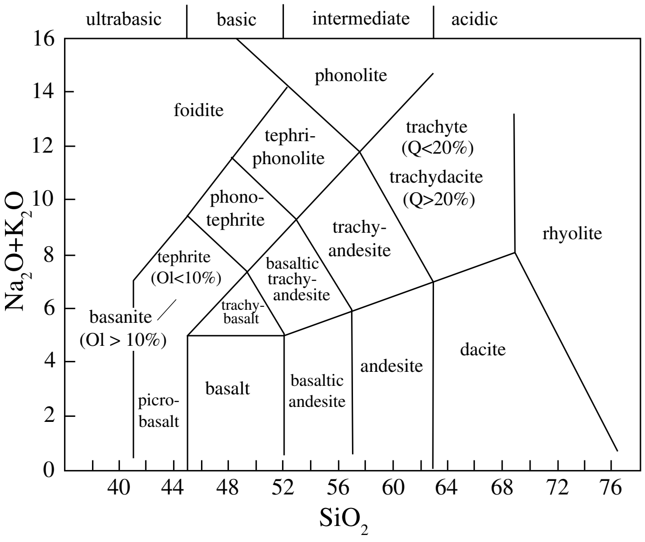


**Figure 1.5** IUGS classification of volcanic rocks based on chemical composition, in weight percent oxide. Q = quartz, Ol = olivine. After LeBas et al. (1986).

Consequently, one important variable that controls the size of minerals in an igneous rock is the cooling rate of the igneous magma. In a slowly cooled magma, which will form a plutonic rock, nucleation will be slow and nutrients will have ample time to migrate through the melt to grow large (up to centimeter-sized) crystals. Such a coarse-grained rock is said to be **phaneritic**. If a magma cools quickly, as in a hyperbyssal or a volcanic rock, then nucleation will be rapid and many nuclei will compete for resources, producing an **aphanitic**, or fine-grained rock. In some volcanic rocks, the magma cooled so rapidly that no nuclei at all could form and the resulting texture is **glassy**.

Another variable that varies grain size is the presence of volatile components or elements, such as $H_2O$ or F, that decrease the viscosity of the melt and, hence, enhance the ability of essential elements to reach the face of a growing crystal. Melts with an abundance of these elements may crystallize extremely coarse-grained crystals in the form of a pegmatite. These **pegmatites** may have grain sizes up to a meter or more.

## 1.4.2 Crystal Shape

Petrologists use the shape of crystals and how the various minerals are arranged in an igneous rock to decipher the crystallization history of a rock. A mineral growing in a melt will tend to have grain boundaries that are **euhedral**, that is, they are bounded by well-formed crystal faces. The thin section of nepheline basalt shown in Figure 1.6A is composed of euhedral crystals of augite and olivine contained in a fine-grained matrix. The textures shown in the thin section suggest that the augite and olivine began to crystallize from the melt and had grown to sizes of one to five millimeters before the lava erupted. The fine-grained matrix indicates that the melt in which the crystals were entrained chilled quickly and solidified as volcanic glass. A close examination of Figure 1.6A shows that the matrix is not all glass; a few extremely small grains of augite are also present. These probably nucleated shortly before the basalt erupted and solidified.

Crystals that are relatively large compared to the minerals composing the matrix of igneous rocks are called **phenocrysts**. In Figure 1.6A, the contrast in size between the phenocrysts and the matrix is obvious. However, few igneous rocks have a matrix so dominated by glass. More typically, the matrix will undergo some degree of crystallization. For example, the basalt shown in Figure 1.6B contains phenocrysts of equant olivine and elongate plagioclase in a matrix of finer-grained olivine, augite, plagioclase, and glass. Relations are similar in the andesite shown in Figure 1.6C, except the plagioclase in the andesite is stubbier than the plagioclase in the basalt. Phenocrysts of quartz may occur in highly siliceous melts, such as dacite and rhyolite (Figure 1.6D), and the presence of quartz phenocrysts is one way to identify these rocks in the field.

Many of the textures characteristic of volcanic rocks also help petrologists interpret plutonic rocks. The early crystallizing minerals form a matrix of interlocking euhedral grains, in a texture called **cumulate** texture. The minerals that formed later are constrained to grow in the interstices of these cumulus grains. These **postcumulus** grains are **anhedral**, which means they are not bounded by crystal faces. Examples of cumulate texture are shown in Figure 1.7A, a gabbro consisting of cumulus plagioclase and postcumulus augite, and in Figure 1.7B, a pyroxenite with cumulus orthopyroxene and postcumulus plagioclase. Some granitic rocks contain tabular plagioclase or potassium-feldspar; for example the granodiorite shown in Figure 1.7C contains distinctly tabular plagioclase. The plagioclase has the same stubby aspect ratio as plagioclase of similar composition in the volcanic rock shown

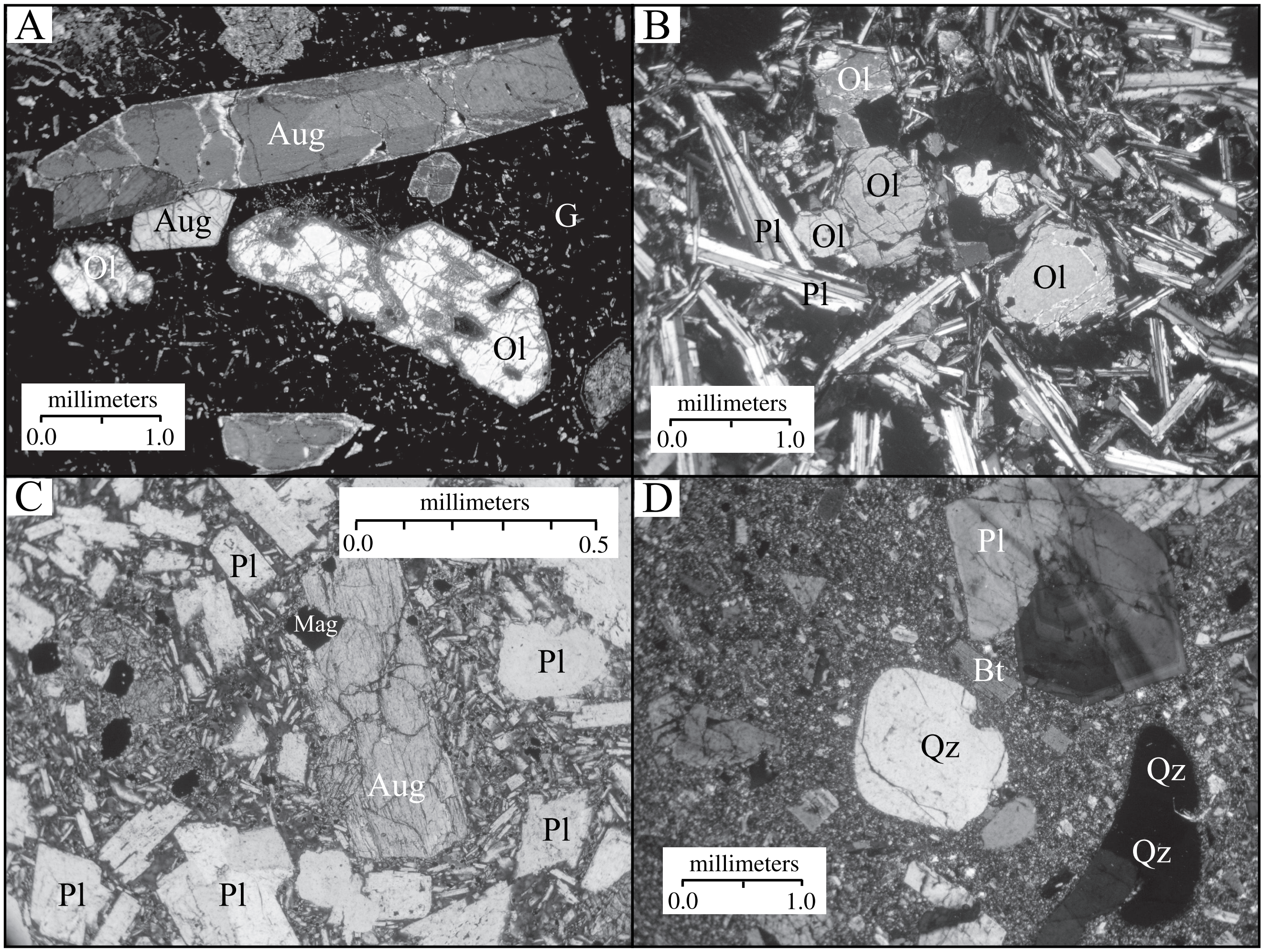


**Figure 1.6** Photomicrographs showing textures in volcanic rocks. (A) Glassy nepheline basalt containing phenocrysts of olivine (Ol), augite (Aug), and glass (G) erupted near the Kaiserstuhl, Southern Germany. Crossed polarized light (XPL). (B) Olivine tholeiite containing phenocrysts of olivine (Ol) and plagioclase (Pl) in a matrix of fine-grained olivine, augite, plagioclase, and glass from the Snake River Plain, Idaho, USA. XPL. (C) Andesite with phenocrysts of augite (Aug) plagioclase (Pl) and magnetite (Mag) in matrix of fine-grained plagioclase, augite, and glass from Soufriere volcano, St. Vincent. Plane polarized light (PPL). (D) Dacite consisting of quartz (Qz), plagioclase (Pl), and biotite (Bt) in a matrix of quartz, plagioclase, and glass. XPL.

in Figure 1.6C. The concentric zoning in this plagioclase records changes in composition as plagioclase grain grows in the granodioritic melt.

In some plutonic rocks, the magma solidifies after relatively coarse-grained minerals have formed, making a rock called a **porphyry**. This rock has a texture that is characterized by euhedral grains dispersed in a finer-grained matrix (Figure 1.7D). A porphyritic texture tells a geologist that the rock underwent a complex cooling history. First, it cooled slowly, during which time the phenocrysts grew, followed by sudden cooling that caused the rapid solidification of the rest of the melt.

## 1.5 Igneous Structures

Igneous rocks exhibit a wide variety of forms. Mafic volcanic rocks occur mostly as **flows**; felsic volcanic rocks may also form flows, but also commonly form **pyroclastic** rocks, or rocks fragmented while still hot. Hypabyssal rocks may form as **lava domes**, **dikes**, or **sills**, and plutonic rocks occur as plutons and batholiths, as well as dikes and sills.

### 1.5.1 Structures in Volcanic Flows

Lava flows may range in thickness from less than a meter to more than ten meters. Mafic lava flows are often divided

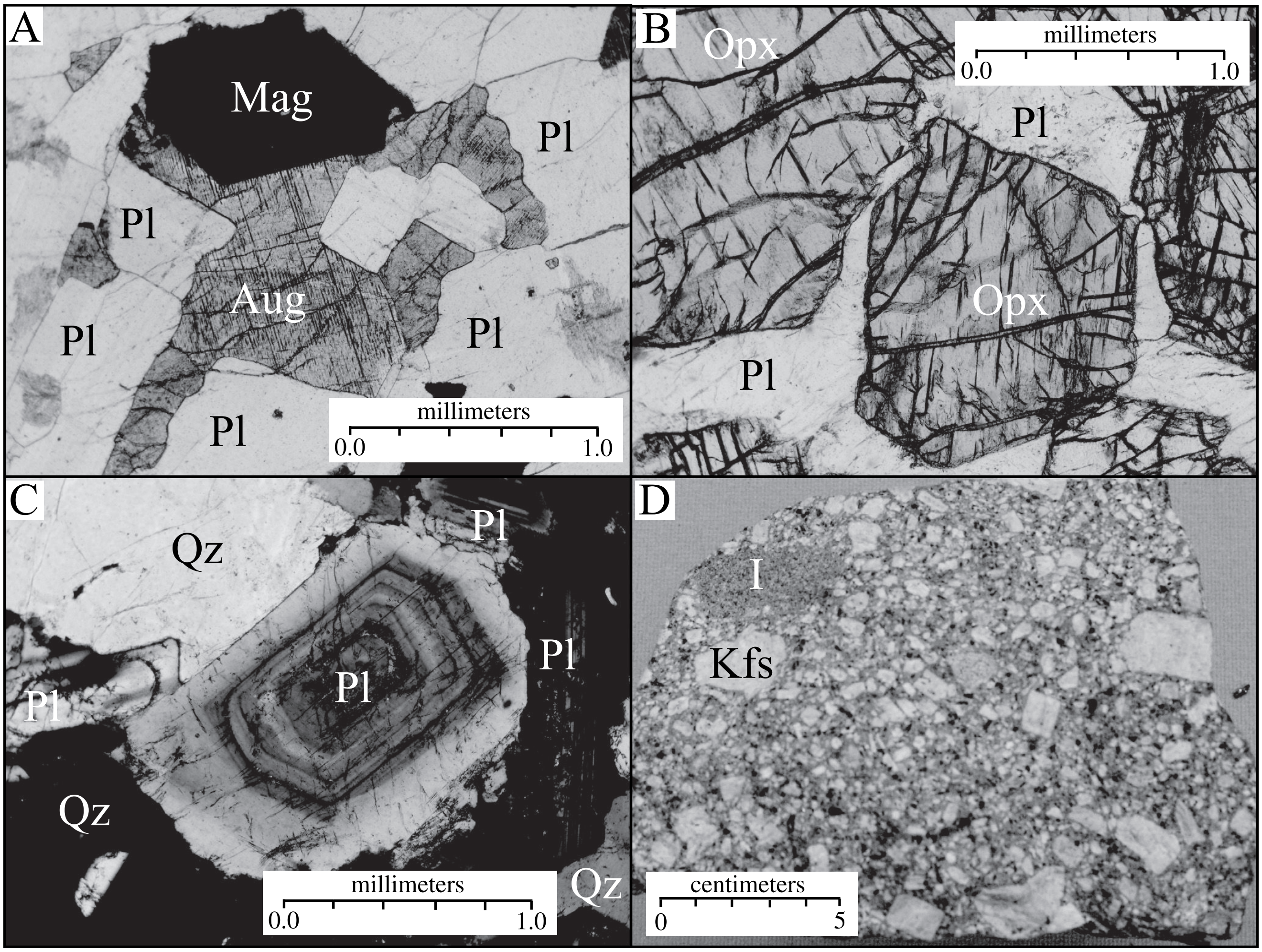


**Figure 1.7** Photomicrographs showing textures in plutonic igneous rocks. (A) Plane-polarized light (PPL) photomicrograph showing euhedral (i.e., cumulus) plagioclase (Pl) and magnetite (Mag) surrounded by anhedral (i.e., postcumulus) augite (Aug). Gabbro from the Skaergaard intrusion, Greenland. (B) Photomicrograph in PPL showing euhedral orthopyroxene (Opx) and anhedral plagioclase (P) in a feldspathic pyroxenite from the Stillwater intrusion, Montana, USA. (C) Photomicrograph in crossed polarized light (XPL) showing compositionally zoned, euhedral plagioclase (Pl) surrounded by anhedral quartz (Qz). Biotite-hornblende granodiorite from Blue Mountains, Oregon, USA. Field of view for all photomicrographs is 2.5 mm. (D) Photograph of a granite porphyry dike containing phenocrysts of K-feldspar (Kfs) in a fine grained matrix of K-feldspar, plagioclase, quartz, biotite, and hornblende. The rock also contains an inclusion (I), which is interpreted as an autolith composed of chilled material from the margin of the dike. Willow Creek pass, Colorado, USA.

into two types: blocky lava is known as *aa* (Figure 1.8A), and a massive lava with a ropey surface is called *pahoehoe* (Figure 1.8B). Pahoehoe texture forms on relatively hot lavas but as the lava cools, the surface breaks apart, making aa. These names are etymologically Hawaiian; abundant lava flows in Hawaii allowed native Hawaiians ample time to develop a terminology comparing the textures of the flows. In cross-section, many flows, particularly those that ponded before completely crystallizing, show **columnar jointing** (Figure 1.8C). Columnar jointing forms by contraction that cracks the rock as heat from the flow dissipates to the ground surface. The vertically oriented columns, which are typically hexagonal in cross-section, are commonly relatively wide at the base of the flow and more narrow at the top.

Where basalts erupt or flow into water, they form **pillows** (Figure 1.8D). The magma that contacts water is chilled and quenches, forming a distinctive lobate, or

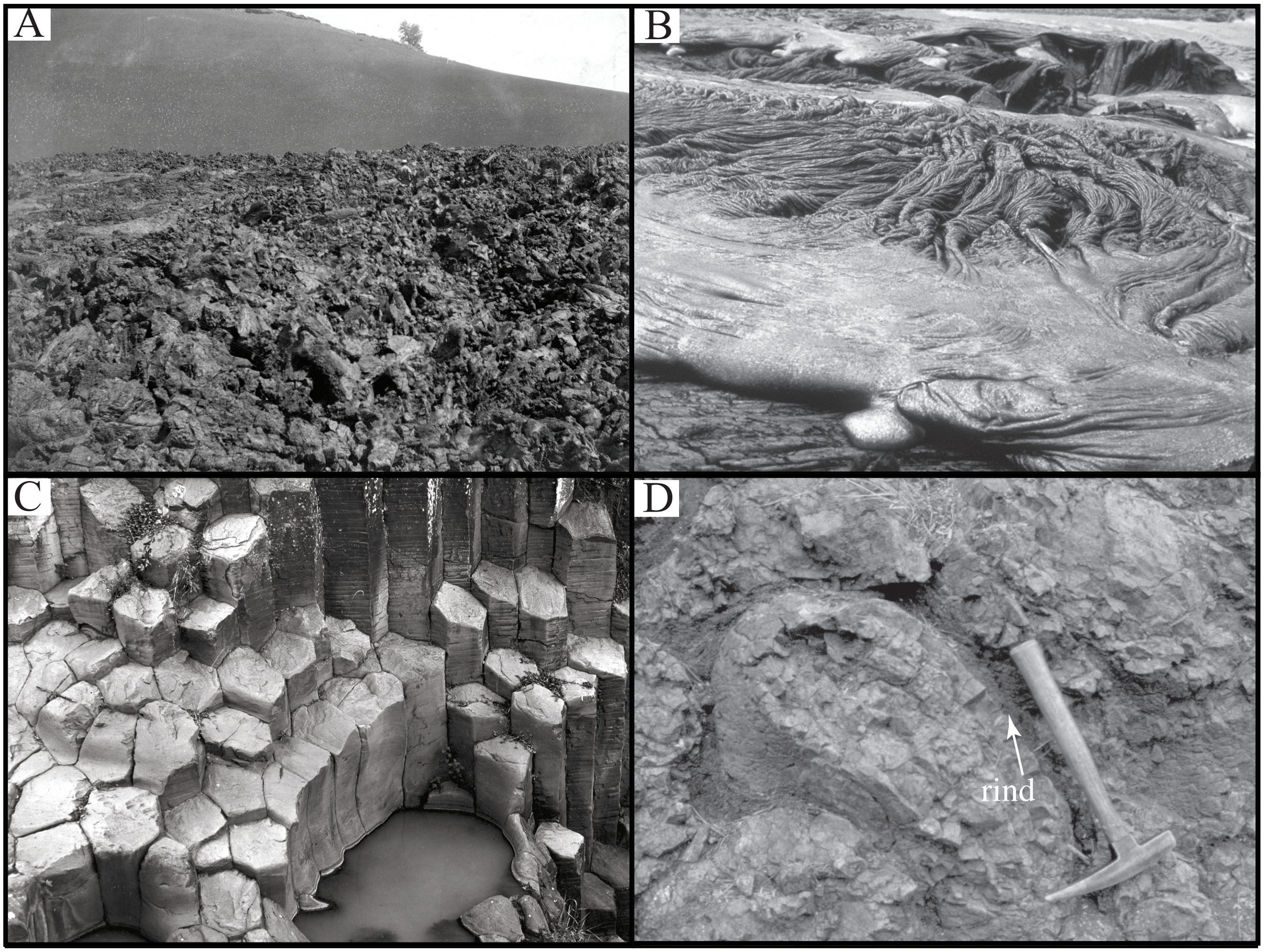


**Figure 1.8** Structures of volcanic rocks. (A) Blocky or aa lava flow in Snake River Plain, Idaho, USA. United States Geologic Survey photo library I.C. 738. (B) Ropey or pahoehoe lava from 1972–74 eruption of Kilauea volcano, Hawaii, USA. United States Geological Survey photo library HVO 221ct. (C) Columnar jointing in basalt, San Miguel Regla, Hidalgo, Mexico. United States Geologic Survey photo library Fries, C.4. (D) Pillow in basalt from Curaçao, Netherlands Antilles. Note the rind on the pillow.

"pillow," shape. As lava continues to flow, it breaks the solidified crust of the initial pillow to form another lobe. A pillow basalt is constructed of hundreds of these nested lobes. In cross-section, the pillows have a rounded top and a tail that points downward. Pillow basalts are diagnostic of subaqueous volcanism and because they are well preserved in the geologic record, they allow geologists to identify underwater eruptions up to billions of years old.

Commonly, gas bubbles exsolved from the magma gather at the top of a flow. Solidification of the melt will produce a rock pocked by holes from these exsolved gas bubbles. The holes are called **vesicles**, and they are key evidence of lava flows because gas bubbles are unlikely in hyperbyssal rocks. Vesicles are also important markers of the top of a flow, something that may be difficult to recognize in complexly deformed volcanic rocks.

### 1.5.2 Structures in Pyroclastic Deposits

Pyroclastic deposits are classified according to two factors: the size of the fragments within the deposit and the relative abundance of glass, crystals, and rock fragments (Figure 1.9). Fragments larger than thirty-two millimeters in diameter are called either *bombs* or *blocks*. **Bombs** are clots of magma that were partly or entirely plastic when erupted. Shapes of bombs are controlled by the initial fluidity of the magma, length and velocity of flight through the air, and deformation on impact. **Blocks** are erupted fragments of solid rock. Solid or liquid materials

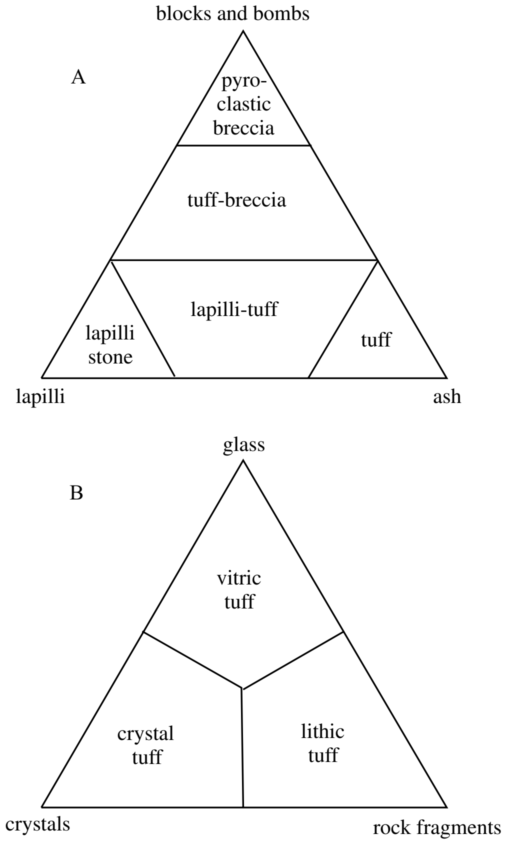


**Figure 1.9** Classification of pyroclastic rocks. After (A) Fisher (1966) and (B) Pettijohn (1975).

between four and thirty-two millimeters in size at the time of eruption are called **lapilli**. Finely spun glass threads are called *Pele's hair*; *accretionary lapilli* are spheroidal, concentrically layered pellets formed by accretion of ash and dust by condensed moisture in eruption clouds. **Ash** (Figure 1.10A) is incoherent ejecta less than four millimeters in diameter and may be vitric, crystal, or lithic ash depending on the proportion of glass, crystals, or rock fragments. **Pumice** and **scoria** are ejecta of melt that have a porosity of 30 to 80 percent. Scoria is andesitic or basaltic in composition, whereas pumice has intermediate to siliceous composition. Because the vesicles in pumice are isolated, pumice may have a density less than that of water and can float. **Tuff** is consolidated volcanic ash. The crystal-vitric tuff shown in Figure 1.10B contains both glassy material – ash and pumice – and crystals of quartz. The vitric tuff in Figure 1.10C contains pumice fragments flattened by the weight of the overlying pyroclastic material.

Pyroclastic deposits are also classified by their areal extent and their structure, and give geologists information on the eruption process. One type of pyroclastic deposit is a **pyroclastic fall** deposit that forms from pyroclastic material that falls directly out of the sky. Because of their mode of formation, pyroclastic fall deposits mantle topography with a uniform thickness of ash over a local area. Over large areas, pyroclastic fall deposits show systematic decreases in thickness and grain size away from the source. An isopach map can show the location of the vent, the wind direction, and the height of the eruption column. We can define two end members of a spectrum of pyroclastic fall deposits. In a **strombolian** eruption, the eruption column is low (1–3 km) and the fragments accumulate around the vent, forming the cone. This type of eruption is named after Stromboli, a volcano north of Sicily that has had frequent, rather quiet eruptions since historical times. In a **plinian** eruption, the eruption column is high (20–50 km) and pumice and ash are spread as a thin sheet covering areas up to $10^6$ km$^2$ (Figure 1.11). This type of eruption is named after Pliny the Younger, who in 79 CE wrote elaborate letters describing the eruption of Vesuvius that destroyed Pompeii (and killed his uncle, Pliny the Elder). Plinian and strombolian deposits are generally coarse-grained and are produced by explosive exsolution of volatiles that blows apart the magma. If a vent is situated where water has ready access, the mechanism of explosion changes fundamentally. Magma is torn apart by exsolving gases and mixes with water. Rapid vaporization triggers a thermal explosion and further fragmentation. These **phreatomagmatic** explosions are more violent and produce fine-grained deposits composed of glassy ash or **hyaloclastite**.

Another type of pyroclastic deposit is a **pyroclastic flow deposit**. These deposits form from avalanches of pyroclastic fragments that move down topographic lows and fill depressions. Their movement is broadly analogous to other natural debris flows (e.g., rock flows and mud flows). The deposits are characterized by poorly sorted material with a continuum of sizes from large blocks to fine ash because there is little room and time for sorting in a fast-moving avalanche of closely packed particles. In contrast, air fall deposits are usually well sorted because during transport through the high atmosphere the particles are sorted according to size and density. Because pyroclastic flows are gravity controlled, they infill topographic lows instead of mantling topography. As with air fall deposits,

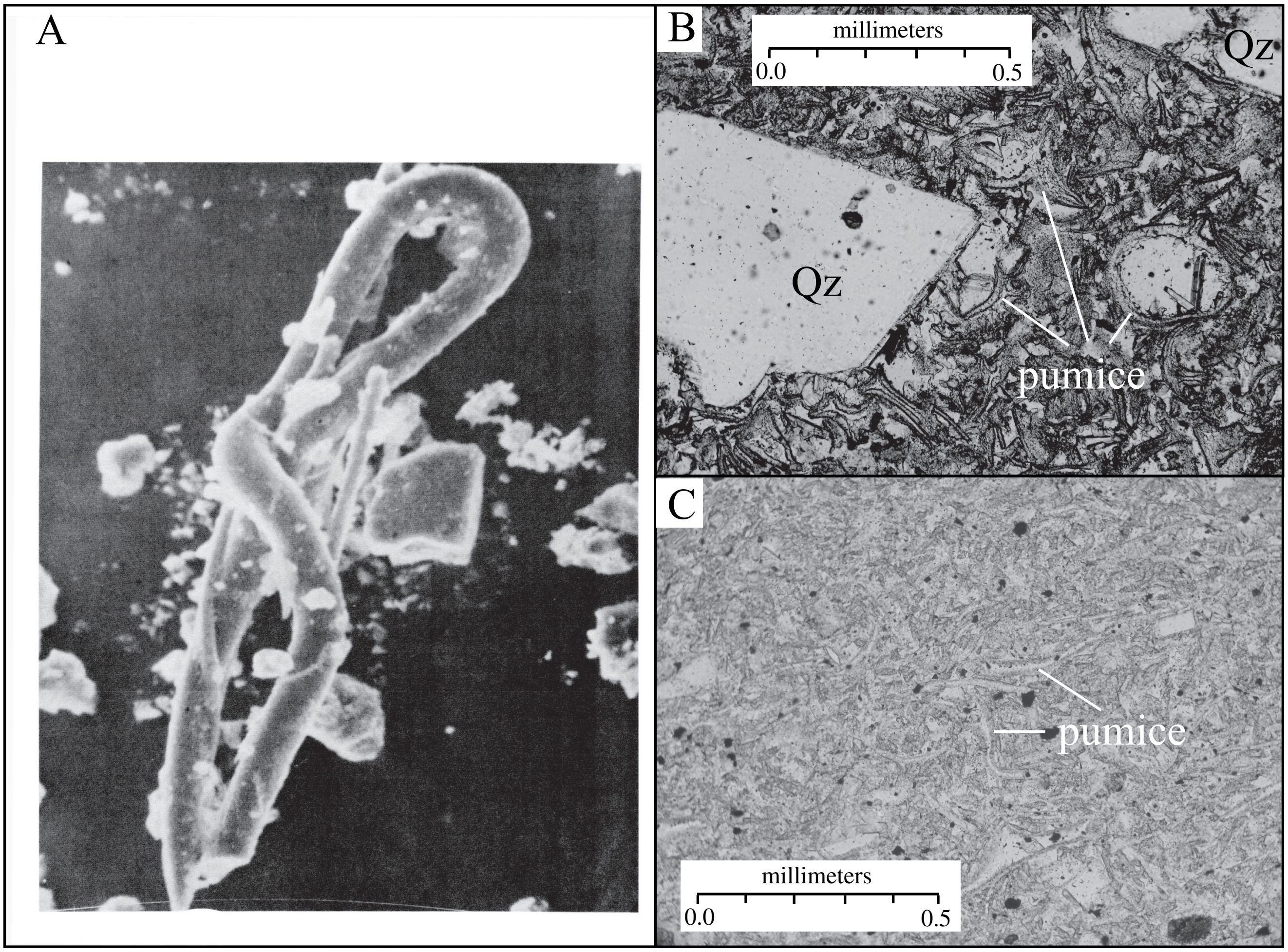


**Figure 1.10** Photomicrographs of pyroclastic rocks. (A) Ash from Mount Saint Helens collected in Laramie, Wyoming after the May 18, 1980 eruption. Length of the glass strand is 200 μm. (B) Crystal vitric tuff showing crystals and crystal fragments of quartz (Qz) in a matrix of pumice. PPL, FOV = 1.25 mm. Bandolier, New Mexico, USA. (C) Vitric tuff showing pumice fragments more compressed than those in Figure 1.9a. Lava Creek Tuff, Yellowstone, Idaho, USA. PPL, FOV = 1.25 mm.

pyroclastic flows vary by several orders of magnitude in their volume and dispersal.

Pyroclastic flow deposits may also form when a growing lava dome collapses(Figure 1.12). Growing lava domes are unstable and commonly break up to form landslides. If the melt is close to water saturation at the time the landslide forms, sudden decompression of the underlying magma could lead to explosion, which triggers an avalanche of hot blocks, ash, and gas. These deposits are typically monolithologic. Transported individual blocks can reach tens of meters in diameter. The pyroclastic flow deposits of Mont Pelée that formed on the island of Martinique in 1902 originated by collapse of a lava dome.

If the temperature of emplacement is sufficiently hot, pyroclastic deposits sometimes undergo processes of **welding** after deposition (Figure 1.11C). Welding occurs when particles are fused together by solid-state diffusion at particle contacts. For rhyolitic glass the minimum temperature for welding is 625°C at 1 atm. and 590°C at 10 atm. If the glass is sufficiently ductile (i.e., hot), the pumice and ash particles deform as they weld under the weight of the overlying deposit. The end result is a rock in which all porosity is removed and pumices are deformed in streaks or **fiamme**.

### 1.5.3 Structures in Hypabyssal Rocks

Hypabyssal rocks are rocks that crystallized at shallow depths. Magmas emplaced near the surface cool relatively quickly, and hypabyssal rocks are, therefore, typically fine-grained but lack evidence that they ever erupted on

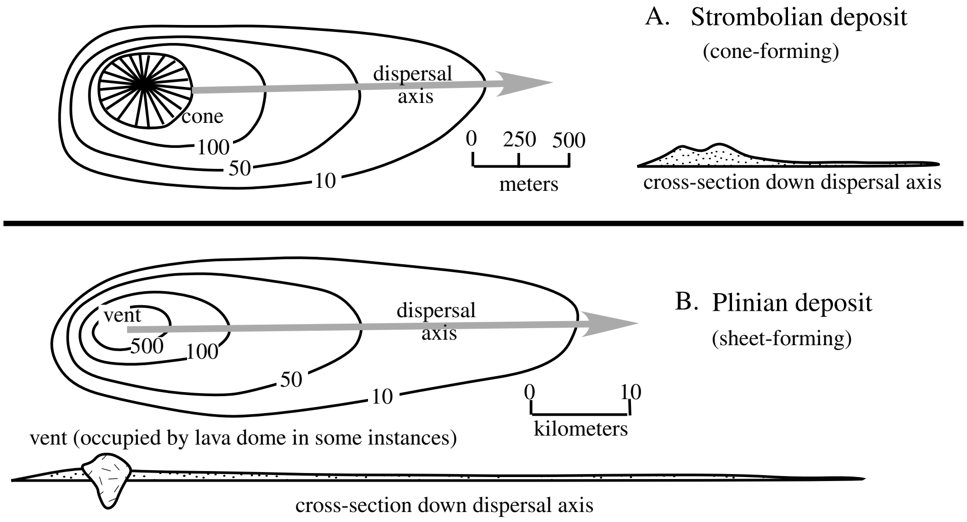
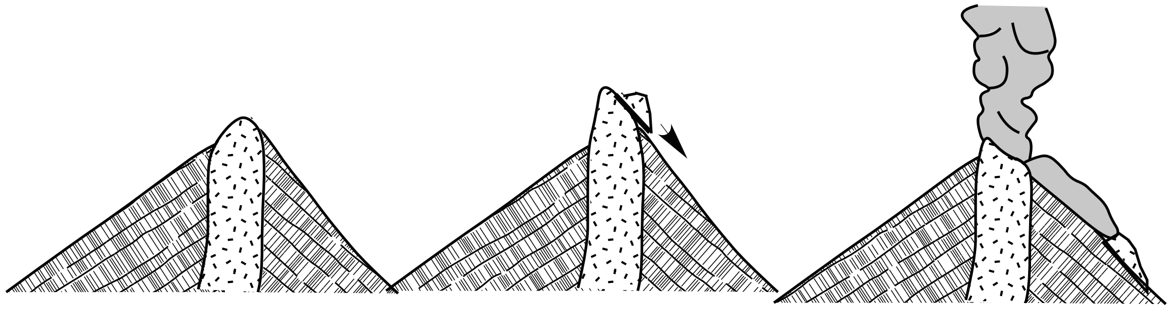


**Figure 1.11** Sketch showing the relative scale of aerial distribution of pyroclastic air fall deposits from strombolian and plinian eruptions.


1) Extrusion of lava dome

2) Lava dome becomes unstable and top slides off

3) Decompression causes explosions in underlying magma.

**Figure 1.12** Diagram of the formation of a pyroclastic flow deposit by the collapse of a lava dome.

the surface. Examples of hypabyssal rocks include **lava domes**, **volcanic necks**, **dikes**, and **sills**.

*Lava domes* include both hypabyssal and eruptive classes of igneous structures. They form from highly viscous lava that forms bulging, dome-shaped bodies that may be several hundred meters high (Figure 1.13). The surface of the dome may be made of fragmented lava (much like aa) that erupted on the surface of the dome but didn't manage to flow far. Beneath the surface, the dome consists of magma that shallowly solidified and was pushed into the domal shape by magma intruding from below.

Some volcanoes erupt easily eroded, fragmented rocks. As such, the volcano itself may not survive as a topographic feature. As the volcanic edifice erodes away, the vent of the volcano, which is made of rock that is more resistant to erosion, may remain. This irregularly shaped spire of hypabyssal rock is called a *volcanic neck* (Figure 1.14). Volcanic necks are common features in some volcanic terrains.

**Dikes** are tabular bodies of igneous rock that form when magma solidifies within a subterranean fracture. Dikes can range from centimeters to kilometers in thickness, although the thickness of hypabyssal dikes tends to be on the order of meters. Dikes can form on a local scale during the eruption of single volcanoes. Some volcanic necks have dikes radiating out from them that may extend for more than ten kilometers (Figure 1.14). These

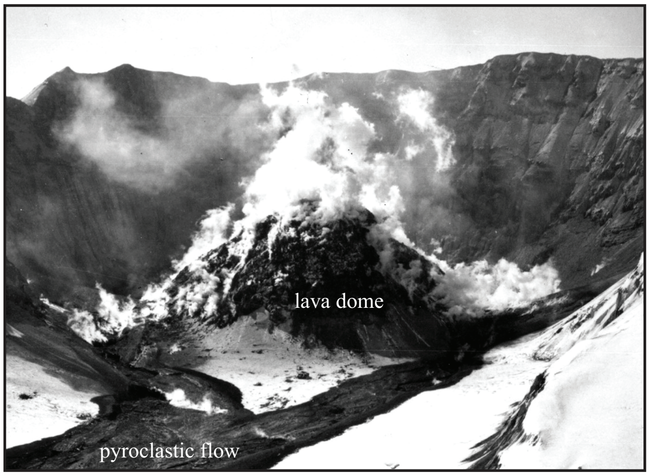


**Figure 1.13** Photo of a lava dome and pyroclastic flow within the caldera of Mount Saint Helens. The dome and flow occurred as part of the eruptive activity of March–April 1982. Photo by Richard Waitt. From the United States Geological Survey Earthquake Information Bulletin, 14, September–October 1982.

dikes indicate that, in addition to the eroded fragmental rocks, the fossil volcano erupted magma supplied by fissures now occupied by dikes.

When magma intrudes sedimentary rocks, they commonly parallel sedimentary bedding, rather than forcing fractures across bedding planes. Such intrusions are called **sills**. The term *sill* also applies to dikes that have intruded parallel to metamorphic layering in metamorphic rocks.

**Chilled margins** are a common, distinctive feature of hypabyssal sills and dikes. (Figure 1.15). When magmas are emplaced at fairly shallow depths, the ambient temperature is not very high and the magma on the margin of the dike or sill may chill very rapidly and be fine-grained. The fine-grained margins of the dike or sill insulate the magma in the interior of the dike or sill, allowing it to cool more slowly, becoming coarser grained.

When the crust fractures in an extensional tectonic environment, intrusion of magma into the resulting faults produces a **dike swarm**. A dike swarm consists of many dikes with similar orientation and chemistry that extend over tens to hundreds of kilometers. Dike swarms are best exposed in Precambrian terrains (Map 1.1) where erosion has stripped away the sedimentary cover. The compositions, dates, and orientations of Precambrian dike swarms may be used to reconstruct Precambrian continental configurations.

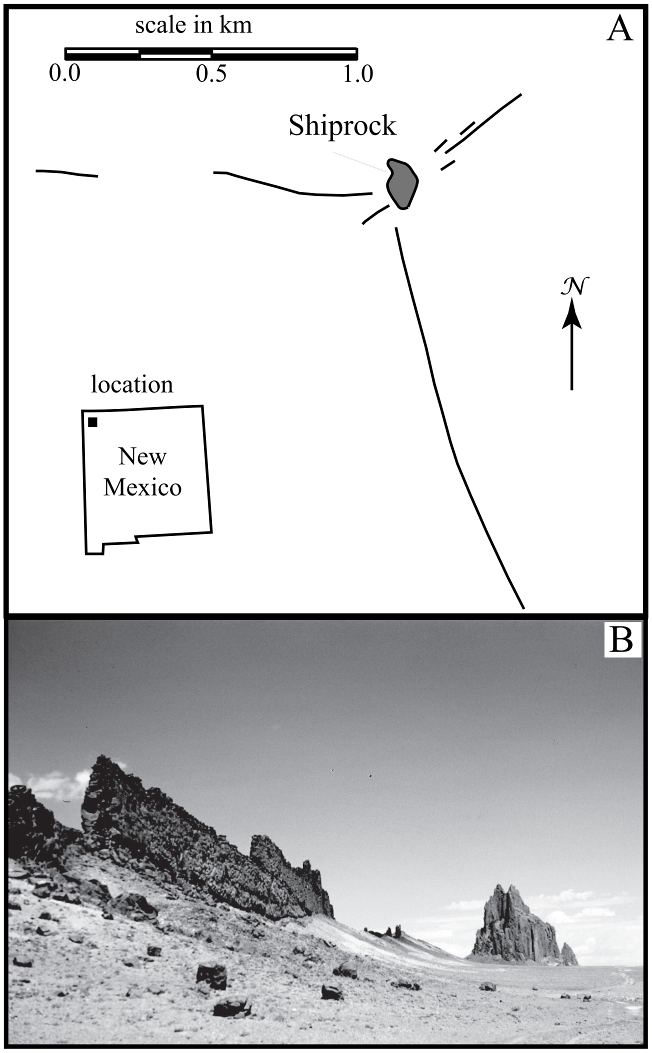


**Figure 1.14** (A) Geologic sketch map of Shiprock in New Mexico, USA, showing dikes (linear features) radiating out of a volcanic neck (irregular gray shape). The volcanic neck, called Shiprock, is about 600 meters high. (B) View of Shiprock and dikes from the southeast. Photo from the United States Geological Survey photo library, McKee, 1007ct.

### 1.5.4 Structures in Plutonic Rocks

Plutonic rocks occur as irregularly shaped bodies known as **plutons.** A pluton larger than forty $mi^2$ in outcrop is called a **batholith**, although large batholiths are composed of many individual plutons. For example, the Sierra Nevada batholith, which is exposed over an area of about 600 x

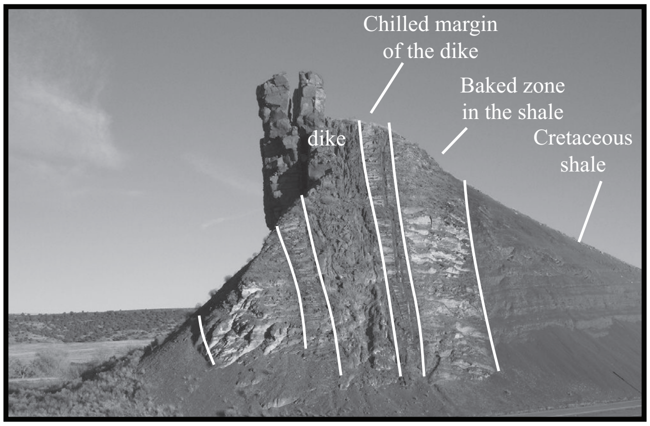
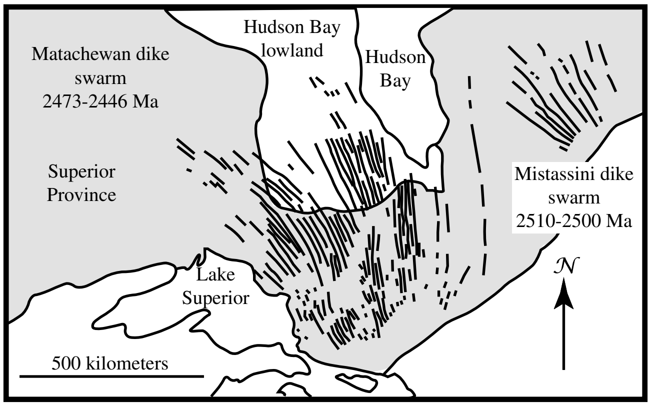


**Figure 1.15** Photo of chilled Tertiary dike intruding and baking adjacent Cretaceous sedimentary rocks, southern Colorado, USA. Photo by Eric Erslev.



**Map 1.1** Geologic map of the Matachewan and Mistassini dike swarms in the southern portion of the Canadian Shield. Dikes in the Hudson Bay lowland are mapped aeromagnetically. Modified after Buchan et al. (2007).

200 km in eastern California, consists of hundreds of separate plutons that were emplaced over a time period that ranges over most of the Mesozoic, though the bulk of the batholith was emplaced throughout the Cretaceous. The term *batholith* is usually applied to granitic rocks. Large plutons composed of mafic rocks are more commonly referred to as *intrusions*.

Plutons emplaced in shallow environments may preserve chilled margins, although those intruded deeper in the crust may not. Igneous intrusions commonly contain blocks of exotic rock that range from centimeters to kilometers in size. In some occurrences, the inclusions are fragments plucked off the country rock during the intrusion of the magma or that foundered into the magma from the roof of the intrusion. Such fragments of country rock are called **xenoliths** (Figure 1.16A); the term *xeno-* means foreign. In some plutons, inclusions consist of pieces of a slightly older intrusion that was clearly part of the same magma sequence as the host rock. These types of enclaves are called **autoliths** (Figure 1.16B). If it is unclear whether the inclusion is related to the host rock, the term **enclave** can be used.

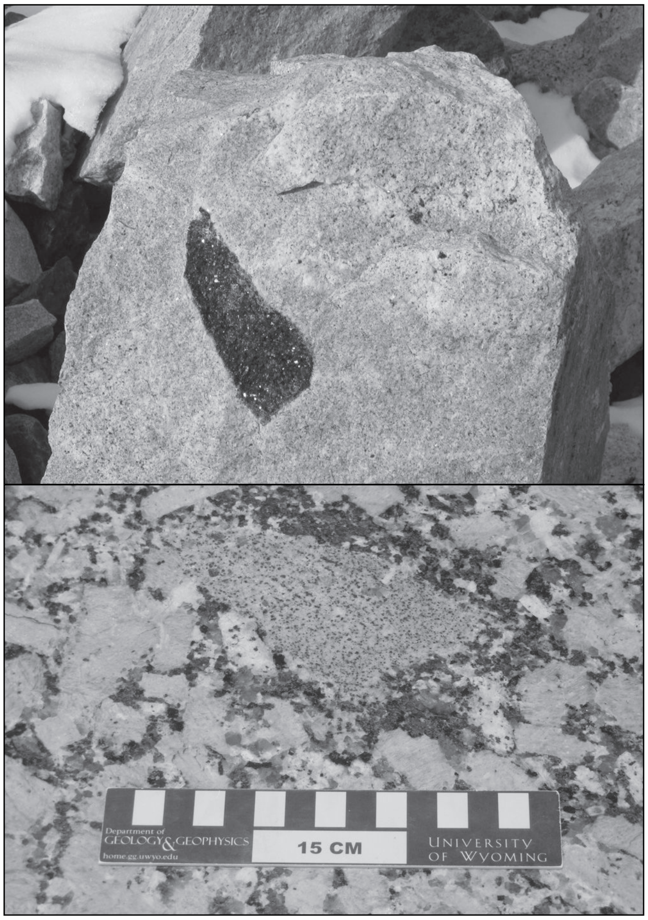


**Figure 1.16** (A) Biotite-rich xenolith in granodiorite dike cutting the Laramie anorthosite complex, Wyoming, USA. (B) Fine-grained granodiorite autolith in granite, floor of main terminal building, Denver International Airport.

Dikes are also present in plutonic rocks, although because they were emplaced at relatively great depth (and hence relatively high temperatures), they seldom show chilled margins. Because dikes in plutonic environments tend to be emplaced into a relatively warm environment, they may also be as coarse-grained as the rocks they intrude, unlike hypabyssal dikes.

## Summary

- Igneous rocks form by solidification of magma, either on Earth's surface (extrusive or volcanic rocks), near the surface (hypabyssal rocks), or at depth (plutonic rocks).
- Igneous rocks are classified either on the basis of the proportions of quartz, feldspars, and mafic minerals or by their geochemical composition.
- The texture and structures preserved in igneous rocks allow geologists to interpret the environment in which the rocks formed.

## Questions and Problems

**Problem 1.1.** Determine the rock names for coarse-grained rock samples with the following proportions of alkali feldspar, plagioclase, and quartz.

| | A | B | C |
|---|---|---|---|
| Alkali feldspar | 0.55 | 0.37 | 0.1 |
| Plagioclase | 0.22 | 0.36 | 0.49 |
| Quartz | 0.23 | 0.27 | 0.41 |

**Problem 1.2.** Determine the rock names for coarse-grained rock samples with the following mineral proportions.

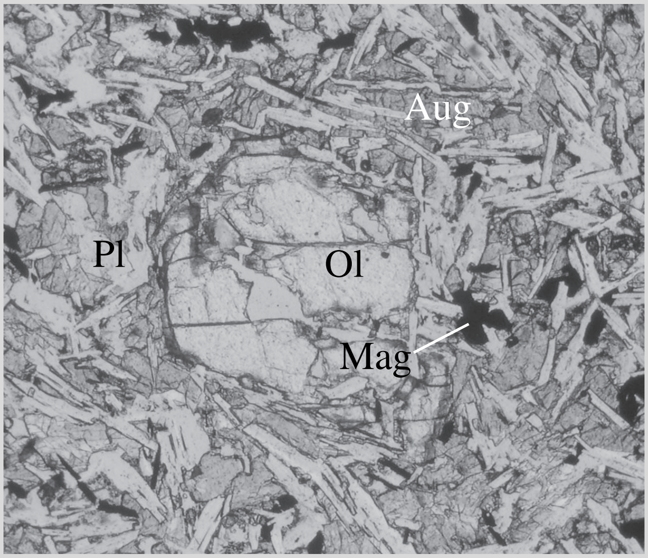
| | A | B | C |
|---|---|---|---|
| Alkalifeldspar | 15 | 3 | 0 |
| Plagioclase | 46 | 64 | 92 |
| Quartz | 21 | 2 | 3 |
| Biotite | 3 | 5 | 0 |
| Hornblende | 13 | 15 | 5 |

**Problem 1.3.** A coarse-grained rock sample consists of 15 percent plagioclase, 35 percent augite, and 50 percent enstatite. What is the name of this rock according to the IUGS classification?

**Problem 1.4.** Determine the rock names for volcanic rock samples with the following compositions:

| | A | B | C |
|---|---|---|---|
| $SiO_2$ | 54.7 | 70.97 | 60.06 |
| $TiO_2$ | 1.71 | 0.33 | 0.83 |
| $Al_2O_3$ | 16.34 | 13.72 | 16.51 |
| FeO* | 11.58 | 3.11 | 7.68 |
| MnO | 0.24 | 0.06 | 0.17 |
| MgO | 2.36 | 0.32 | 0.38 |
| CaO | 6.75 | 1.5 | 3.14 |
| $Na_2O$ | 4.14 | 3.67 | 4.57 |
| $K_2O$ | 1.47 | 5.22 | 5.58 |
| $P_2O_5$ | 0.71 | 0.06 | 0.25 |

**Problem 1.5.** Figure P1.1 is a photomicrograph of a trachyandesite with augite (Aug), magnetite (Mag), olivine (Ol), and plagioclase (Pl). Determine the order in which these minerals crystallized and explain your reasoning.



## Further Reading

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