# 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 rockforming 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. 2

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## 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., 2002; LeBas and Streckeisen, 1991).

There are two basic approaches to the naming of rocks. A rock can be classified either according to the minerals

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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<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, FeO, MgO, CaO, Na<sub>2</sub>O, and K<sub>2</sub>O. 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 in part 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, the general composition of a rock can be described 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 **feldspars** (and **feldspathoids**) and **silica**. Darker-colored rocks rich in ferromagnesian minerals are called *mafic*. The term *mafic* reflects the enrichment of these rocks in **magnesium** and iron (Fe). 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 abundance of the common minerals in volume percent (modal mineralogy, or **mode**), which are divided into five groups:

- Q quartz
- A alkali feldspar, including albite with up to five mole percent anorthite (<An<sub>5</sub>)
- P plagioclase with composition An<sub>5</sub> to An<sub>100</sub>
- 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<sub>50</sub>, 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,

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**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, Pl = plagioclase, Px = pyroxene. Inset shows classification with regards to the type of pyroxene. 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 60 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., 2002).

#### 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



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

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<sub>2</sub> of the rock, and as its y-axis the weight percent Na<sub>2</sub>O + K<sub>2</sub>O 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, 5

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**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, variations in mineral abundances, 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. One of the major controls on grain size is the rate of nucleation, which in turn 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.

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**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 affects 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

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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

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**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 grew 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 finergrained 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

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**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 (Pl) 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 *pahoe-hoe* (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 crosssection, 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

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**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 hypabyssal 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