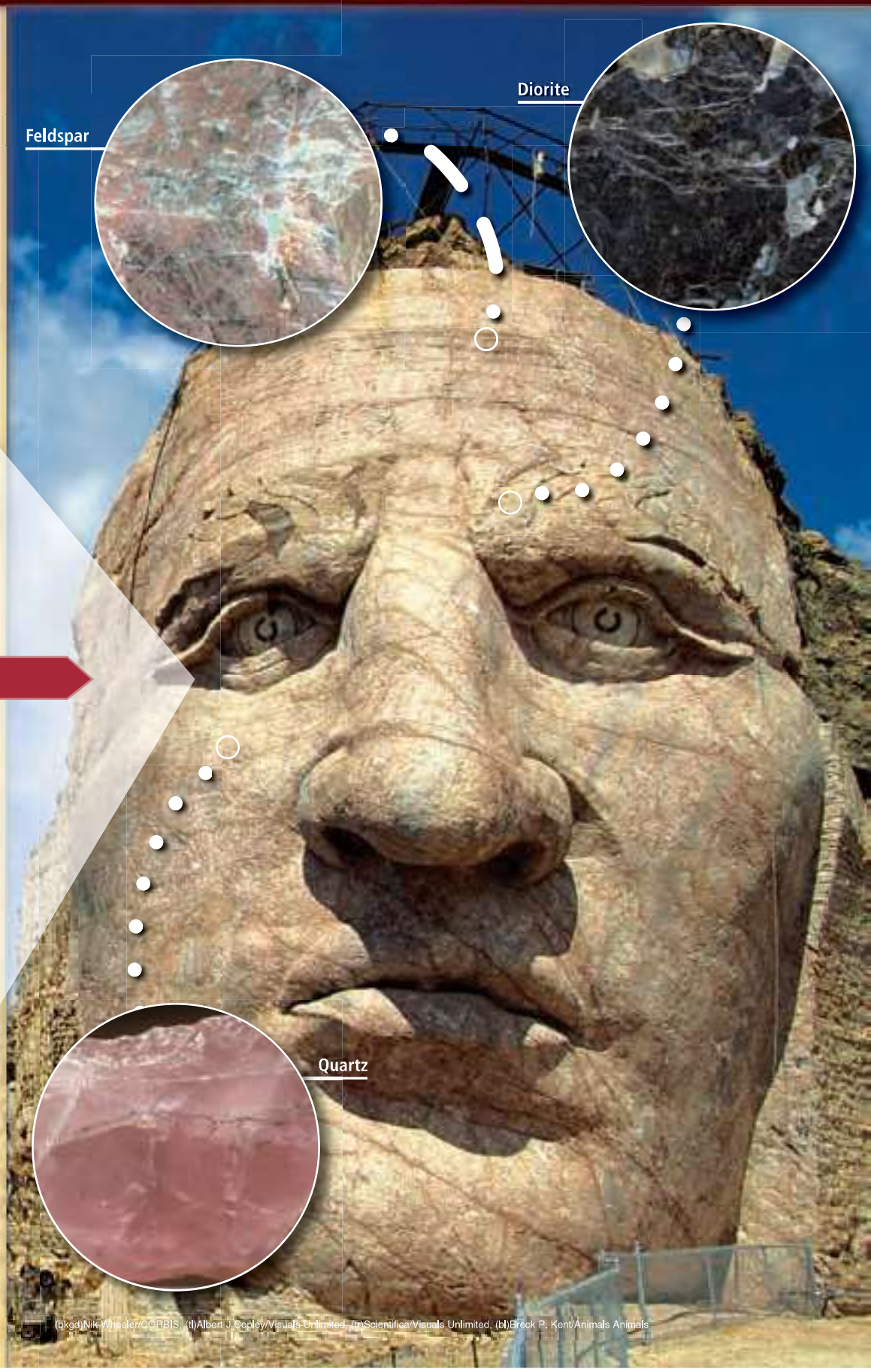
CHAPTER 5

Igneous Rocks



BIG Idea **Igneous rocks were the first rocks to form as Earth cooled from a molten mass to the crystalline rocks of the early crust.**

5.1 What are igneous rocks?

MAIN Idea Igneous rocks are the rocks that form when molten material cools and crystallizes.

5.2 Classification of Igneous Rocks

MAIN Idea Classification of igneous rocks is based on mineral composition, crystal size, and texture.

GeoFacts

- In the monument pictured here, Crazy Horse's head is over 26 m tall.
- The monument, located in South Dakota, was started in 1948 and is still a work in progress. The next component created will be his arm, which will measure more than 70 m.
- When completed, the monument will be more than 170 m tall and 195 m long. Nearly 10,000,000 metric tons of rock have already been blasted away.

(bkgd)Nik Wheeler/CORBIS, (tl)Albert J. Copley/Visuals Unlimited, (m)Scientifica/Visuals Unlimited, (bl)Breck P. Kent/Animals Animals

Start-Up Activities

LAUNCH Lab

How are minerals identified?

Igneous rocks are composed of different types of minerals. It is often possible to identify the different minerals in a sample of rock.

Procedure

1. Read and complete the lab safety form.
2. Examine a **sample of granite** from a distance of about 1 m. Record your observations.
3. Use a **magnifying lens** or **microscope** to observe the granite sample. Record your observations.

Analysis

1. **Illustrate** what you saw through the magnifying glass or microscope. Include a scale for your drawing.
2. **List** the different minerals that you observed in your sample.
3. **Describe** the sizes and shapes of the mineral crystals.
4. **Describe** any evidence that suggests that these crystals formed from molten rock.

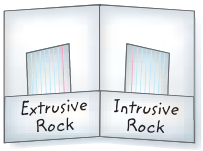
FOLDABLES™ Study Organizer

Types of Igneous Rocks Make this Foldable to compare intrusive and extrusive igneous rock.

STEP 1 Fold the bottom of a horizontal sheet of paper up about 3 cm.

STEP 2 Fold in half.

STEP 3 Unfold once, and dot with glue or staple to make two pockets. Label as shown.



FOLDABLES **Use this Foldable with Section 5.1.** As you read this section, use index cards or quarter sheets of paper to summarize how each type of rock forms and give examples.

Earth Science online

Visit glencoe.com to

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  - Interactive Time Lines
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Section 5.1

Objectives

- **Summarize** igneous rock formation.
- **Describe** the composition of magma.
- **Identify** the factors that affect how rocks melt and crystallize.

Review Vocabulary

silicate: mineral that contains silicon and oxygen, and usually one or more other elements

New Vocabulary

lava
igneous rock
partial melting
Bowen's reaction series
fractional crystallization

What are igneous rocks?

MAIN Idea **Igneous rocks are the rocks that form when molten material cools and crystallizes.**

Real-World Reading Link At any given point in time, igneous rocks are forming somewhere on Earth. The location and the conditions that are present determine the types of igneous rocks that form.

Igneous Rock Formation

If you live near an active volcano, you can literally watch igneous rocks form. A hot, molten mass of rock can solidify into solid rock overnight. As you read in Chapter 4, magma is molten rock below Earth's surface. **Lava** is magma that flows out onto Earth's surface. **Igneous rocks** form when lava or magma cools and minerals crystallize.

In the laboratory, most rocks must be heated to temperatures of 800°C to 1200°C before they melt. In nature, these temperatures are present in the upper mantle and lower crust. Where does this heat come from? Scientists theorize that the remaining energy from Earth's molten formation and the heat generated from the decay of radioactive elements are the sources of Earth's thermal energy.

Composition of magma The type of igneous rock that forms depends on the composition of the magma. Magma is often a slushy mix of molten rock, dissolved gases, and mineral crystals. The common elements present in magma are the same major elements that are in Earth's crust: oxygen (O), silicon (Si), aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), potassium (K), and sodium (Na). Of all the compounds present in magma, silica is the most abundant and has the greatest effect on magma characteristics. As summarized in **Table 5.1,** magma is classified as basaltic, andesitic, or rhyolitic, based on the amount of silica it contains. Silica content affects melting temperature and impacts how quickly magma flows.

Concepts in Motion

Table 5.1 Types of Magma

Interactive Table To explore more about magma composition, visit glencoe.com.

Group	Silica Content	Example Location
Basaltic	42–52%	Hawaiian Islands
Andesitic	52–66%	Cascade Mountains, Andes Mountains
Rhyolitic	more than 66%	Yellowstone National Park

Once magma is free of the overlying pressure of the rock layers around it, dissolved gases are able to escape into the atmosphere. Thus, the chemical composition of lava is slightly different from the chemical composition of the magma from which it developed.

Magma formation Magma can be formed either by melting of Earth's crust or by melting within the mantle. The four main factors involved in the formation of magma are temperature, pressure, water content, and the mineral content of the crust or mantle. Temperature generally increases with depth in Earth's crust. This temperature increase, known as the geothermal gradient, is plotted in **Figure 5.1.** Oil-well drillers and miners, such as those shown in **Figure 5.2,** have firsthand experience with the geothermal gradient. Temperatures encountered when drilling deep oil wells can exceed 200°C.

Pressure also increases with depth. This is a result of the weight of overlying rock. Laboratory experiments show that as pressure on a rock increases, its melting point also increases. Thus, a rock that melts at 1100°C at Earth's surface will melt at 1400°C at a depth of 100 km.

The third factor that affects the formation of magma is water content. Rocks and minerals often contain small percentages of water, which changes the melting point of the rocks. As water content increases, the melting point decreases.

Reading Check **List** the main factors involved in magma formation.

Mineral content In order to better understand how the types of elements and compounds present give magma its overall character, it is helpful to discuss this fourth factor in more detail. Different minerals have different melting points. For example, rocks such as basalt, which are formed of olivine, calcium feldspar, and pyroxene (pi RAHK seen), melt at higher temperatures than rocks such as granite, which contain quartz and potassium feldspar. Granite has a melting point that is lower than basalt's melting point because granite contains more water and minerals that melt at lower temperatures. In general, rocks that are rich in iron and magnesium melt at higher temperatures than rocks that contain higher levels of silicon.

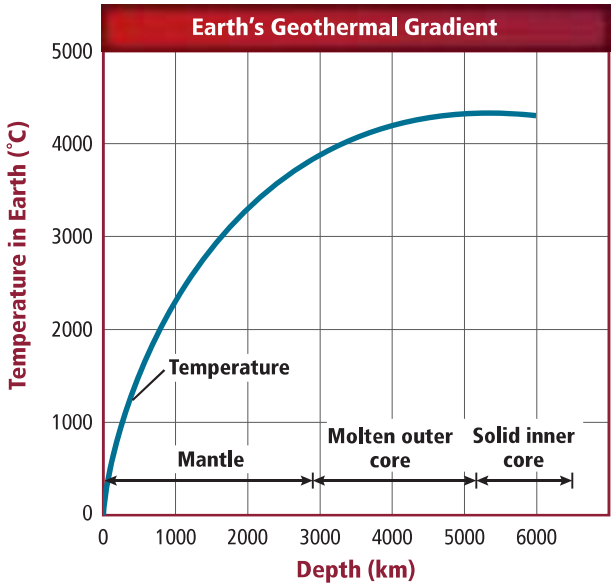


Figure 5.1 The average geothermal gradient in the crust is about 25°C/km, but scientists think that it drops sharply in the mantle to as low as 1°C/km.

Figure 5.2 The temperature of Earth's upper crust increases with depth by about 30°C for each 1 km. At a depth of 3 km, this drill bit will encounter rock that is close to the temperature of boiling water.

Lowell Georgia/CORBIS

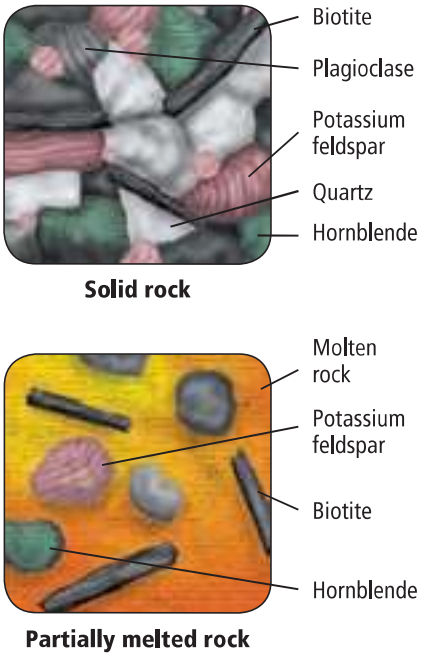


Figure 5.3 As the temperature increases in an area, minerals begin to melt.
Determine *What can you suggest about the melting temperature of quartz based on this diagram?*

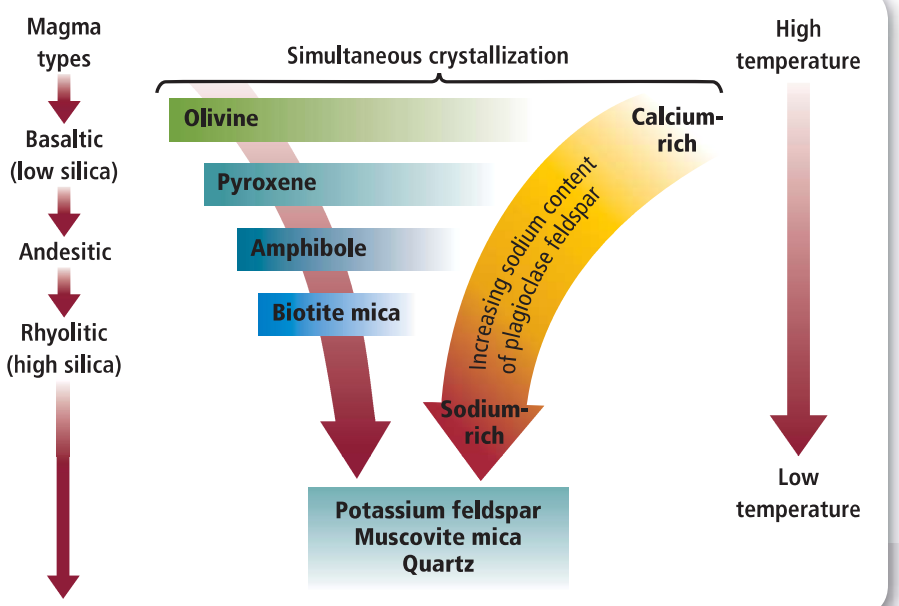
Partial melting Suppose you froze melted candle wax and water in an ice cube tray. If you took the tray out of the freezer and left it at room temperature, the ice would melt, but the candle wax would not. This is because the two substances have different melting points. Rocks melt in a similar way because the minerals they contain have different melting points. Not all parts of a rock melt at the same temperature. This explains why magma is often a slushy mix of crystals and molten rock. The process whereby some minerals melt at relatively low temperatures while other minerals remain solid is called **partial melting.** Partial melting is illustrated in **Figure 5.3.** As each group of minerals melts, different elements are added to the magma mixture thereby changing its composition. If temperatures are not high enough to melt the entire rock, the resulting magma will have a different composition than that of the original rock. This is one way in which different types of igneous rocks form.

Reading Check **Summarize** the formation of magma that has a different chemical composition from the original rock.

Bowen's Reaction Series

In the early 1900s, Canadian geologist N. L. Bowen demonstrated that as magma cools and crystallizes, minerals form in predictable patterns in a process now known as the **Bowen's reaction series.** **Figure 5.4** illustrates the relationship between cooling magma and the formation of minerals that make up igneous rock. Bowen discovered two main patterns, or branches, of crystallization. The right-hand branch is characterized by a continuous, gradual change of mineral compositions in the feldspar group. An abrupt change of mineral type in the iron-magnesium groups characterizes the left-hand branch.

Figure 5.4 On the left side of Bowen's reaction series, minerals rich in iron and magnesium change abruptly as the temperature of the magma decreases.
Compare *How does this compare to the feldspars on the right side of the diagram?*



Iron-rich minerals The left branch of Bowen's reaction series represents the iron-rich minerals. These minerals undergo abrupt changes as magma cools and crystallizes. For example, olivine is the first mineral to crystallize when magma that is rich in iron and magnesium begins to cool. When the temperature decreases enough for a completely new mineral, pyroxene, to form, the olivine that previously formed reacts with the magma and is converted to pyroxene. As the temperature decreases further, similar reactions produce the minerals amphibole and biotite mica.

Feldspars In Bowen's reaction series, the right branch represents the plagioclase feldspars, which undergo a continuous change of composition. As magma cools, the first feldspars to form are rich in calcium. As cooling continues, these feldspars react with magma, and their calcium-rich compositions change to sodium-rich compositions. In some instances, such as when magma cools rapidly, the calcium-rich cores are unable to react completely with the magma. The result is a zoned crystal, as shown in **Figure 5.5.**

Fractional Crystallization

When magma cools, it crystallizes in the reverse order of partial melting. That is, the first minerals that crystallize from magma are the last minerals that melted during partial melting. This process, called **fractional crystallization,** is similar to partial melting in that the composition of magma can change. In this case, however, early formed crystals are removed from the magma and cannot react with it. As minerals form and their elements are removed from the remaining magma, it becomes concentrated in silica.

Figure 5.5 When magma cools quickly, a feldspar crystal might not have time to react completely with the magma and might retain a calcium-rich core. The result is a crystal with distinct calcium-rich and sodium-rich zones.

FOLDABLES
Incorporate information from this section into your Foldable.

MiniLab

Compare Igneous Rocks

How do igneous rocks differ? Igneous rocks have many different characteristics. Color and crystal size are some of the features that differentiate igneous rocks.

Procedure

1. Read and complete the lab safety form.
2. Obtain a set of **igneous rock samples** from your teacher.
3. Carefully observe the following characteristics of each rock: overall color, crystal size, and, if possible, mineral composition.
4. Design a data table to record your observations.

Analysis

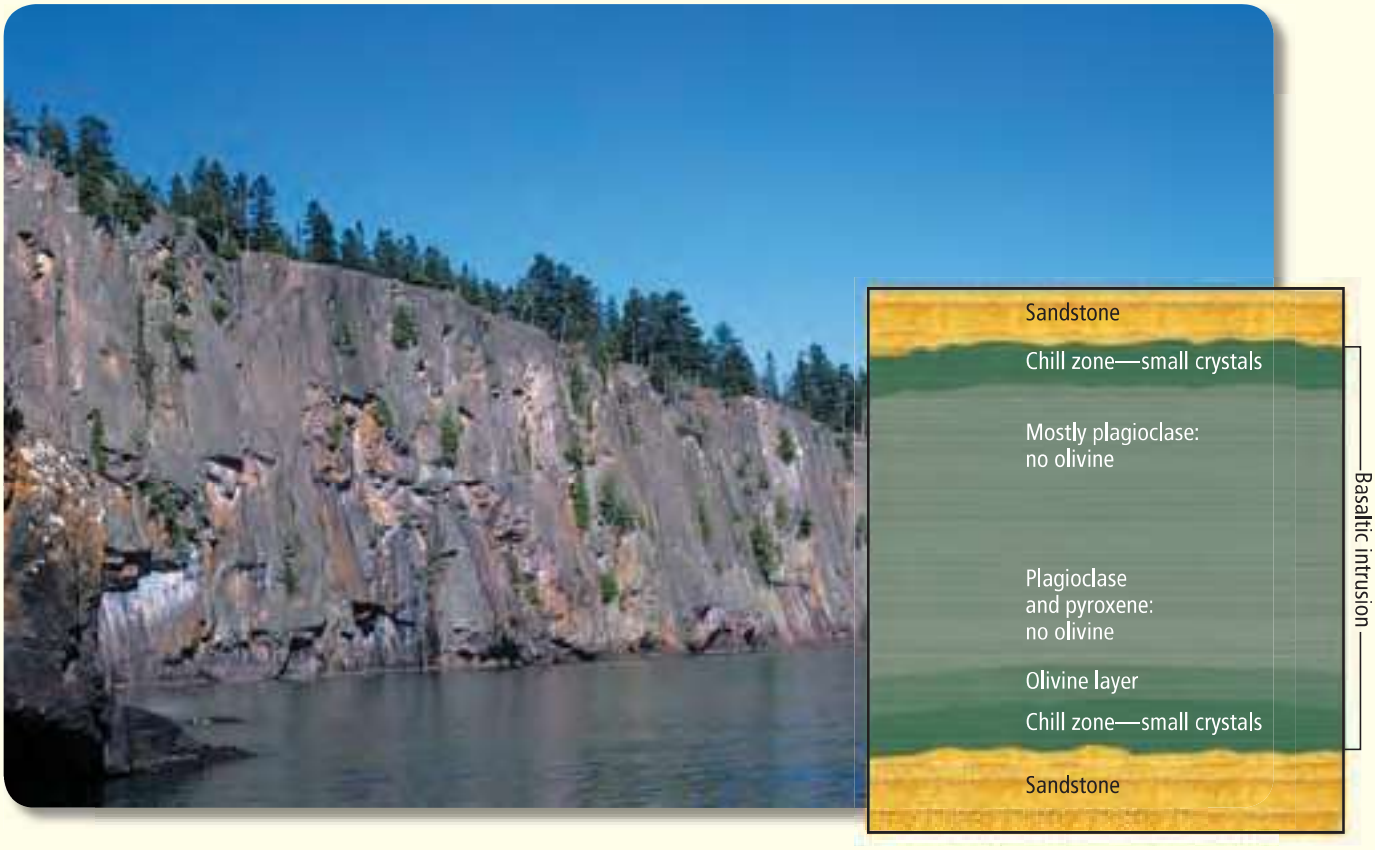
1. **Classify** your samples as either basaltic, andesitic, or rhyolitic. [Hint: The more silica in the rock, the lighter it is in color.]
2. **Compare and contrast** your samples using the data from the data table. How do they differ? What characteristics do each of the groups share?
3. **Speculate** in which order the samples crystallized. [Hint: Use Bowen's reaction series as a guide.]

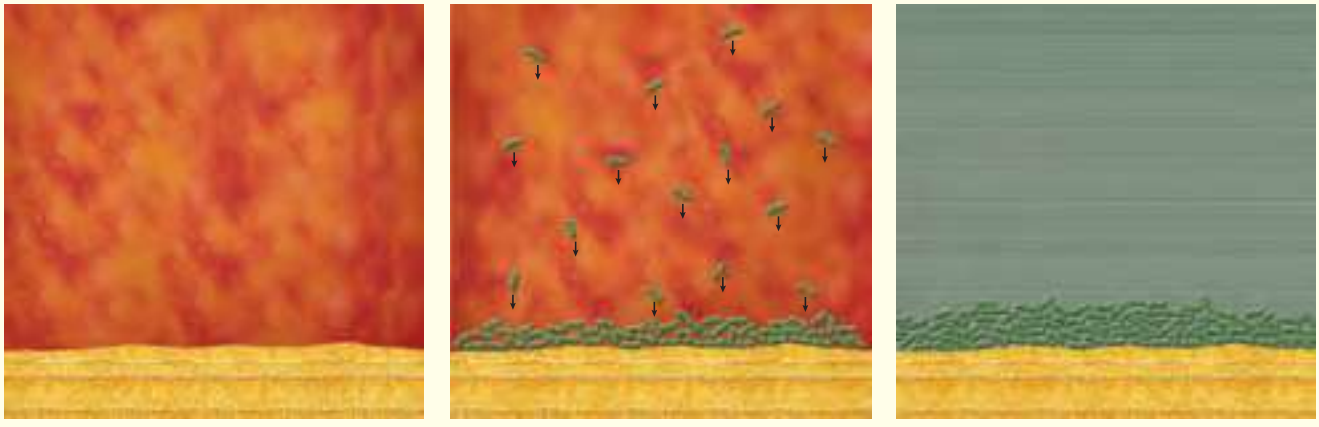
(t)Marli Miller/Visuals Unlimited, (b)Wally Eberhart/Visuals Unlimited

NATIONAL GEOGRAPHIC

Visualizing Fractional Crystallization and Crystal Settling

Figure 5.6 The Palisade Sill in the Hudson River valley of New York is a classic example of fractional crystallization and crystal settling. In the basaltic intrusion, small crystals formed in the chill zone as the outer areas of the intrusion cooled more quickly than the interior.





As magma in an intrusion begins to cool, crystals form and settle to the bottom. This layering of crystals is fractional crystallization.

Concepts in MOtion

To explore more about the Palisade Sill, visit glencoe.com.

Earth Science Online

Breck P. Kent/Animals Animals

As is often the case with scientific inquiry, the discovery of Bowen's reaction series led to more questions. For example, if olivine converts to pyroxene during cooling, why is olivine found in rock? Geologists hypothesize that, under certain conditions, newly formed crystals are separated from magma, and the chemical reactions between the magma and the minerals stop. This can occur when crystals settle to the bottom of the magma body, and when liquid magma is squeezed from the crystal mush to form two distinct igneous bodies with different compositions. **Figure 5.6** illustrates this process and the concept of fractional crystallization with an example from the Hudson River valley in New York. This is one way in which the magmas listed in **Table 5.1** are formed.

As fractional crystallization continues and more magma is separated from the crystals, the magma becomes more concentrated in silica, aluminum, and potassium. This is why last two minerals to form are potassium feldspar and quartz. Potassium feldspar is one of the most common feldspars in Earth's crust. Quartz often occurs in veins, as shown in **Figure 5.7,** because it crystallizes while the last liquid portion of magma is squeezed into rock fractures.

Figure 5.7 These quartz veins represent the last remnants of a magma body that cooled and crystallized.

Section 5.1 Assessment

Section Summary

- Magma consists of molten rock, dissolved gases, and mineral crystals.
- Magma is classified as basaltic, andesitic, or rhyolitic, based on the amount of silica it contains.
- Different minerals melt and crystallize at different temperatures.
- Bowen's reaction series defines the order in which minerals crystallize from magma.

Understand Main Ideas

1. MAIN Idea **Predict** the appearance of an igneous rock that formed as magma cooled quickly and then more slowly.
2. **List** the eight major elements present in most magmas. Include the chemical symbol of each element.
3. **Summarize** the factors that affect the formation of magma.
4. **Compare and contrast** magma and lava.

Think Critically

5. **Predict** If the temperature increases toward the center of Earth, why does the inner core become solid?
6. **Infer** the silica content of magma derived from partial melting of an igneous rock. Would it be higher, lower, or about the same as the rock itself? Explain.

WRITING in Earth Science

7. A local rock collector claims that she has found the first example of pyroxene and sodium-rich feldspar in the same rock. Write a commentary about her claim for publication in a rock collector society newsletter.

Douglas P. Wilson; Frank Lane Picture Agency/CORBIS

Section 5.2

Objectives

- **Classify** different types and textures of igneous rocks.
- **Recognize** the effects of cooling rates on the grain sizes in igneous rocks.
- **Describe** some uses of igneous rocks.

Review Vocabulary

fractional crystallization: a sequential process during which early formed crystals are removed from the melt and do not react with the remaining magma.

New Vocabulary

intrusive rock
extrusive rock
basaltic rock
granitic rock
texture
porphyritic texture
vesicular texture
pegmatite
kimberlite

Classification of Igneous Rocks

MAIN Idea **Classification of igneous rocks is based on mineral composition, crystal size, and texture.**

Real-World Reading Link Many statues, floors, buildings, and countertops have something in common. Many of them are made of the popular rock type granite—one of the most abundant rocks in Earth's crust.

Mineral Composition of Igneous Rocks

Igneous rocks are broadly classified as intrusive or extrusive. When magma cools and crystallizes below Earth's surface, **intrusive rocks** form. If the magma is injected into the surrounding rock, it is called an igneous intrusion. Crystals of intrusive rocks are generally large enough to see without magnification. Magma that cools and crystallizes on Earth's surface forms **extrusive rocks.** These are sometimes referred to as lava flows or flood basalts. The crystals that form in these rocks are small and difficult to see without magnification. Geologists classify these rocks by their mineral compositions. In addition, physical properties such as grain size and texture serve as clues for the identification of various igneous rocks.

Igneous rocks are classified according to their mineral compositions. **Basaltic rocks,** such as gabbro, are dark-colored, have lower silica contents, and contain mostly plagioclase and pyroxene. **Granitic rocks,** such as granite, are light-colored, have high silica contents, and contain mostly quartz, potassium feldspar, and plagioclase feldspar. Rocks that have a composition of minerals that is somewhere in between basaltic and granitic are called intermediate rocks. They consist mostly of plagioclase feldspar and hornblende. Diorite is a good example of an intermediate rock. **Figure 5.8** shows examples from these three main compositional groups of igneous rocks. A fourth category, called ultrabasic, contains the rock peridotite. These rocks contain only iron-rich minerals such as olivine and pyroxene and are always dark. **Figure 5.9** summarizes igneous rock identification.

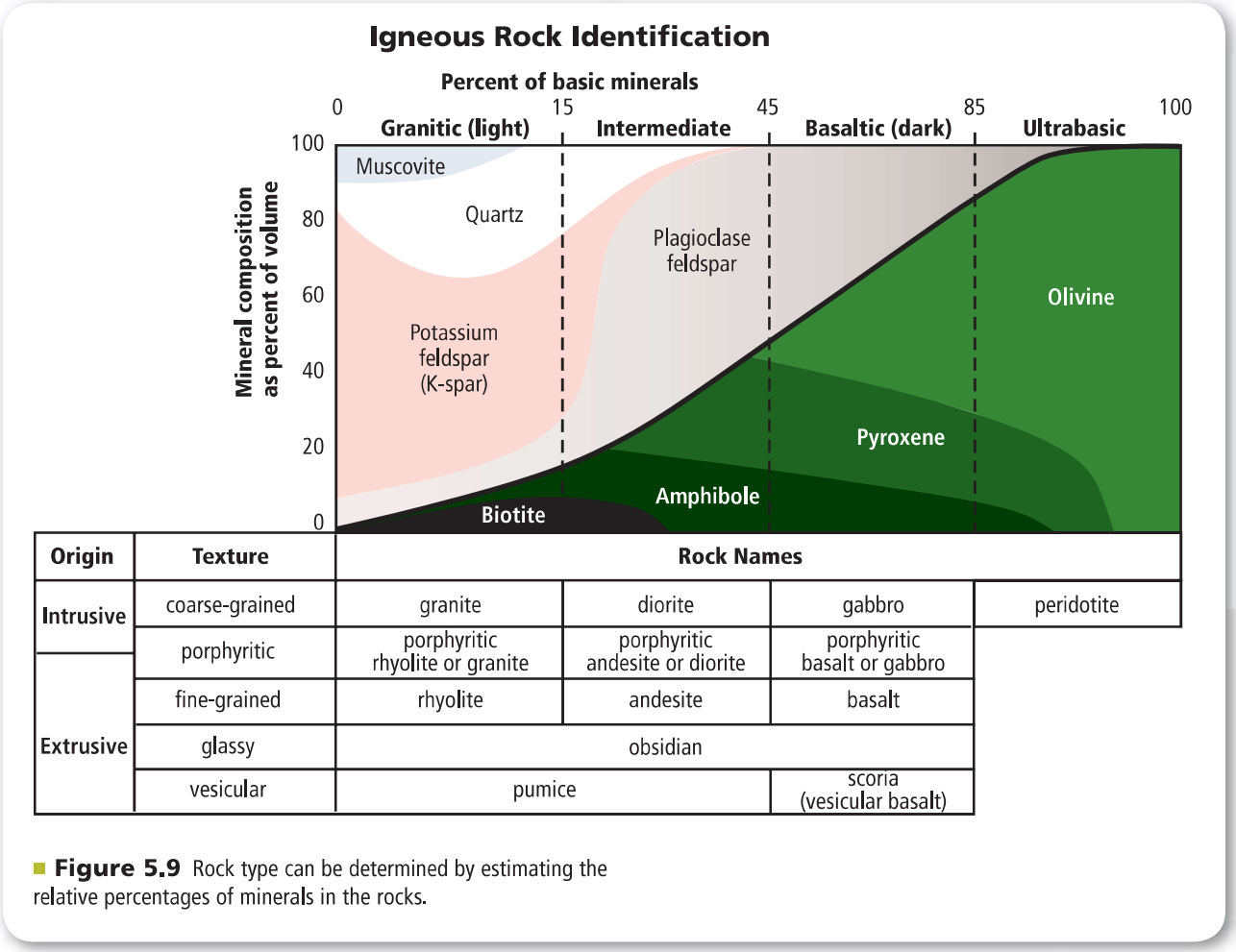
Figure 5.8 Differences in magma composition can be observed in the rocks that form when the magma cools and crystallizes.
Observe *Describe the differences you see in these rocks.*

Gabbro

Granite

Diorite

(l)Wally Eberhart/Visuals Unlimited, (c)E.R. Degginger/Photo Researchers, (r)Albert Copley/Visuals Unlimited



Origin	Texture	Rock Names			
Intrusive	coarse-grained	granite	diorite	gabbro	peridotite
	porphyritic	porphyritic rhyolite or granite	porphyritic andesite or diorite	porphyritic basalt or gabbro	
Extrusive	fine-grained	rhyolite	andesite	basalt	
	glassy	obsidian			
	vesicular	pumice		scoria (vesicular basalt)	

Figure 5.9 Rock type can be determined by estimating the relative percentages of minerals in the rocks.

Texture

In addition to differences in their mineral compositions, igneous rocks differ in the sizes of their grains or crystals. **Texture** refers to the size, shape, and distribution of the crystals or grains that make up a rock. For example, as shown in **Figure 5.10,** the texture of rhyolite can be described as fine-grained, while granite can be described as coarse-grained. The difference in crystal size can be explained by the fact that one rock is extrusive and the other is intrusive.

Figure 5.10 Rhyolite, granite, and obsidian have different textures because they formed in different ways.

Rhyolite

Granite

Obsidian

(l)Wally Eberhart/Visuals Unlimited, (c)Breck P. Kent/Animals Animals, (r)Breck P. Kent/Animals Animals

Porphyry

Vesicular basalt

Pumice

Figure 5.11 Rock textures provide information about a rock's formation. Evidence of the rate of cooling and the presence or absence of dissolved gases is preserved in the rocks shown here.

Crystal size and cooling rates When lava flows on Earth's surface, it cools quickly and there is not enough time for large crystals to form. The resulting extrusive igneous rocks, such as basalt, which is shown in **Figure 5.10,** have crystals so small that they are difficult to see without magnification. Sometimes, cooling occurs so quickly that crystals do not form at all. The result is volcanic glass, such as obsidian, also shown in **Figure 5.10.** In contrast, when magma cools slowly beneath Earth's surface, there is sufficient time for large crystals to form. Thus, intrusive igneous rocks, such as granite, diorite, and gabbro, can have crystals larger than 1 cm.

Porphyritic rocks Look at the textures of the rocks shown in **Figure 5.11.** The top photo shows a rock with two different crystal sizes. This rock has a **porphyritic** (por fuh RIH tihk) **texture,** which is characterized by large, well-formed crystals surrounded by finer-grained crystals of the same mineral or different minerals.

What causes minerals to form both large and small crystals in the same rock? Porphyritic textures indicate a complex cooling history during which a slowly cooling magma suddenly began cooling rapidly. Imagine a magma body cooling slowly, deep in Earth's crust. As it cools, the first crystals to form grow large. If this magma were to be suddenly moved higher in the crust, or if it erupted onto Earth's surface, the remaining magma would cool quickly and form smaller crystals.

Vesicular rocks Magma contains dissolved gases that escape when the pressure on the magma lessens. If the lava is thick enough to prevent the gas bubbles from escaping, holes called vesicles are left behind. The rock that forms looks spongy. This spongy appearance is called **vesicular texture.** Pumice and vesicular basalt are examples shown in **Figure 5.11.**

Reading Check **Explain** what causes holes to form in igneous rocks.

Thin Sections

It is usually easier to observe the sizes of mineral grains than it is to identify the mineral. To identify minerals, geologists examine samples that are called thin sections. A thin section is a slice of rock, generally 2 cm × 4 cm and only 0.03 mm thick. Because it is so thin, light is able to pass through it.

(t)Albert J. Copley/Visuals Unlimited, (c)Jerome Wyckoff/Animals Animals, (b)Breck P. Kent/Animals Animals

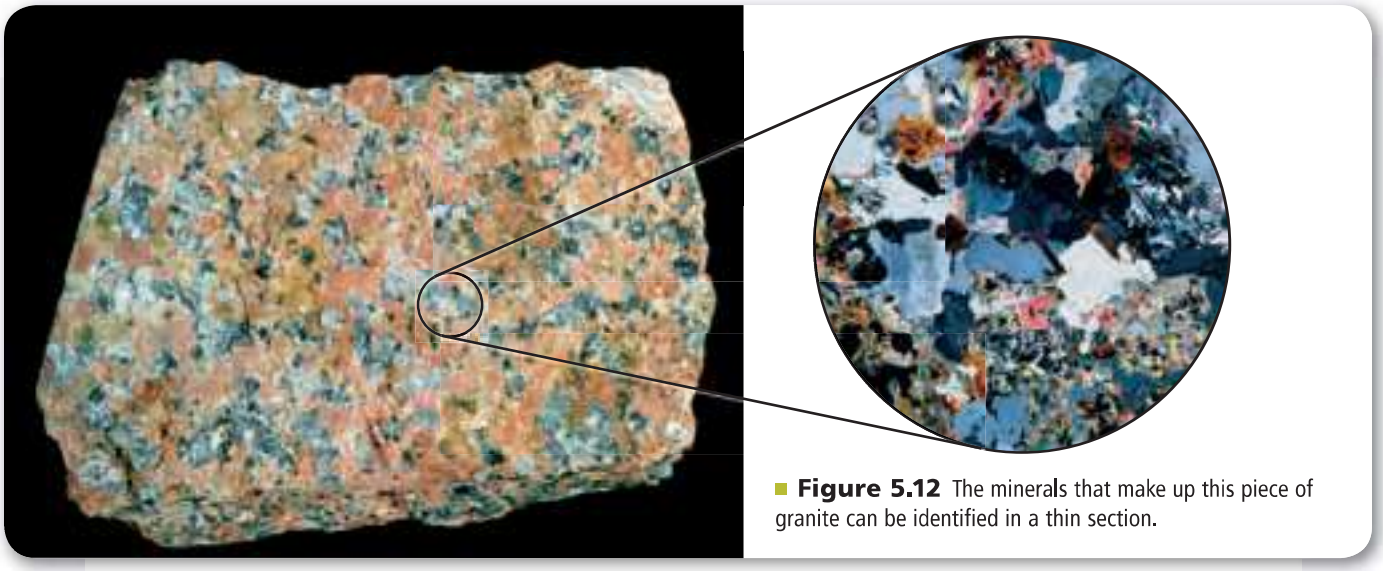


Figure 5.12 The minerals that make up this piece of granite can be identified in a thin section.

When viewed through a special microscope, called a petrographic microscope, mineral grains exhibit distinct properties. These properties allow geologists to identify the minerals present in the rock. For example, feldspar grains often show a distinct banding called twinning. Quartz grains might appear wavy as the microscope stage is rotated. Calcite crystals become dark, or extinguish, as the stage is rotated. **Figure 5.12** shows the appearance of a thin section of granite under a petrographic microscope.

Igneous Rocks as Resources

The cooling and crystallization history of igneous rocks sometimes results in the formation of unusual but useful minerals. These minerals can be used in many fields, including construction, energy production, and jewelry making. Some of these uses are described in the following paragraphs.

Veins As you learned in Chapter 4, ores are minerals that contain a useful material that can be mined for a profit. Valuable ore deposits often occur within igneous intrusions. At other times, ore minerals are found in the rocks surrounding intrusions. These types of deposits sometimes occur as veins. Recall from Bowen's reaction series that the fluid left during magma crystallization contains high levels of silica and water. This fluid also contains any leftover elements that were not incorporated into the common igneous minerals. Some important metallic elements that are not included in common minerals are gold, silver, lead, and copper. These elements, along with the dissolved silica, are released at the end of magma crystallization in a hot, mineral-rich fluid that fills cracks and voids in the surrounding rock. This fluid solidifies to form metal-rich quartz veins, such as the gold-bearing veins in the Sierra Nevada. An example of gold formed in a quartz vein is shown in **Figure 5.13.**

Reading Check **Explain** why veins have high amounts of quartz.

Figure 5.13 Gold and quartz are extracted from mines together. The two are later separated.

Infer ***What can you determine from this photo about the melting temperature of gold?***

(tl)E. R. Degginger/Photo Researchers, (tr)Alfred Pasieka/Photo Researchers, (br)Breck P. Kent/Animals Animals

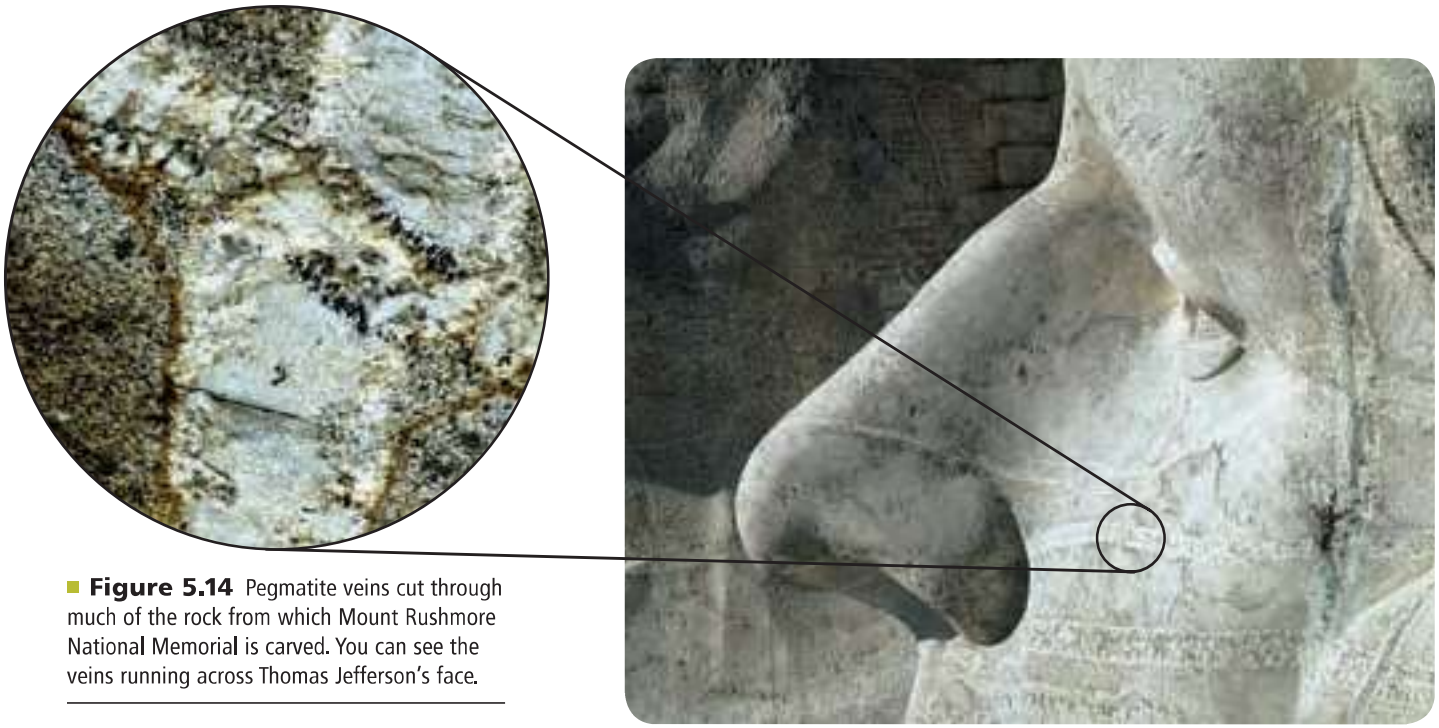


Figure 5.14 Pegmatite veins cut through much of the rock from which Mount Rushmore National Memorial is carved. You can see the veins running across Thomas Jefferson's face.

Pegmatites Vein deposits can contain other valuable resources in addition to metals. Veins of extremely large-grained minerals are called **pegmatites.** Ores of rare elements, such as lithium (Li) and beryllium (Be), form in pegmatites. In addition to ores, pegmatites can produce beautiful crystals. Because these veins fill cavities and fractures in rock, minerals grow into voids and retain their shapes. Some of the world's most beautiful minerals have been found in pegmatites. A famous pegmatite is the rock source for the Mount Rushmore National Memorial located near Keystone, South Dakota. A close-up view of President Thomas Jefferson, shown in **Figure 5.14,** reveals the huge mineral veins that run through the rock.

PROBLEM-SOLVING LAB

Interpret Scientific Illustrations

How do you estimate mineral composition? Igneous rocks are classified by their mineral compositions. In this activity, you will use the thin section in **Figure 5.12** to estimate the different percentages of minerals in the sample.

Analysis

1. Design a method to estimate the percentages of the minerals in the rock sample shown in **Figure 5.12.**
2. Make a data table that lists the minerals and their estimated percentages.

Think Critically

3. **Interpret Figure 5.9** to determine where in the chart this rock sample fits.
4. **Compare** your estimates of the percentages of minerals in the rock with those of your classmates. Why do the estimates vary? What are some possible sources of error?
5. **Propose** a method to improve the accuracy of your estimate.

(l)W. K. Fletcher/Photo Researchers, (r)Dave Bartruff/CORBIS

Kimberlites Diamond is a valuable mineral found in rare, ultrabasic rocks known as **kimberlites,** named after Kimberly, South Africa, where the intrusions were first identified. These unusual rocks are a variety of peridotite. They most likely form deep in the crust or in the mantle at depths of 150 to 300 km, because diamond and other minerals present in kimberlites can form only under very high pressure.

Geologists hypothesize that kimberlite magma is intruded rapidly upward toward Earth's surface, forming long, narrow, pipelike structures. These structures extend many kilometers into the crust, but they are only 100 to 300 m in diameter. Most of the world's diamonds come from South African mines, such as the one shown in **Figure 5.15.** Many kimberlites have been discovered in the United States, but diamonds have been found only in Arkansas and Colorado. The diamond mine in Colorado is the only diamond mine currently in operation in the United States.

Igneous rocks in construction Igneous rocks have several characteristics that make them especially useful as building materials. The interlocking grain textures of igneous rocks make them strong. In addition, many of the minerals present in igneous rocks are resistant to weathering. Granite is among the most durable of igneous rocks. You have probably seen many items, such as countertops, floors, and statues, made from the wide variety of granite that has formed on Earth.

Figure 5.15 Diamonds are mined from kimberlite in mines like this one in Richtersveld, Northern Cape, South Africa.

Section 5.2 Assessment

Section Summary

- Classification of igneous rocks is based on three main characteristics.
- The rate of cooling determines crystal size.
- Ores often occur in pegmatites. Diamonds occur in kimberlites.
- Some igneous rocks are used as building materials because of their strength, durability, and beauty.

Understand Main Ideas

1. MAIN Idea **Infer** why obsidian, which is black or red in color, can have a granitic composition.
2. **Describe** the three major compositional groups of igneous rocks.
3. **Apply** what you know about cooling rates to explain differences in crystal sizes.
4. **Distinguish** between andesite and diorite using two physical properties of igneous rocks.

Think Critically

5. **Speculate** why there are almost no extrusive ultrabasic rocks in Earth's crust.
6. **Determine** whether quartz or plagioclase feldspar is more likely to form a well-shaped crystal in an igneous rock. Explain.

MATH in Earth Science

7. A granite slab has a density of 2.7 g/cm^3. What is the mass of a 2-cm-thick countertop that is 0.6 m $\times$ 2.5 m? How many grams is this?

(t)Koos van der Lende/age fotoStock, (b)Ken Lucas/Visuals Unlimited

Moon Rocks

During each of the six Apollo missions, lunar rocks were collected with the hope of providing information about the Moon's origin, history, and environment. How do moon rocks compare with rocks on Earth?

Moon rock types Between 1969 and 1972, astronauts collected approximately 380 kg of lunar rocks. The 2415 individual pieces range in size from a grain of sand to a basketball.

Generally, moon rocks vary in color from gray to black to white to green. Some rocks are glassy, some are hard, and others are fragile. Analysis of the rocks has revealed at least three different rock types on the Moon. Basaltic rocks formed from lava flows and volcanic ash that reached the surface through cracks and fissures caused by meteorite impacts. Breccias formed when meteorites shattered rocks and then fused the pieces together with the heat generated by the impact. Pristine rock is rock that has not been hit by meteorites. Pristine rock is commonly composed of calcium-rich plagioclase feldspar and is gray in color.

Moon rock composition Moon rocks are unique in two ways. First, they contain no water and are not oxidized. Considering how much iron is contained in the rocks, this is a sharp contrast to weathered and rusty iron-bearing rocks on Earth. Second, the surfaces of some moon rocks are covered with tiny pockmarks called zap pits. These are caused by micrometeoroids that impact the rocks on the Moon's surface. Zap pits do not occur on Earth rocks because friction from Earth's atmosphere causes tiny meteoroids to burn up long before they reach Earth's surface.

Moon rock classification Scientists use the same categories for classifying lunar rocks as they use for igneous rocks on Earth.

This scientist is studying a piece of basalt that was collected from the lunar surface during the *Apollo 15* mission.

Based on mineral composition, scientists named a new class of moon rocks called KREEP rocks. These contain high amounts of potassium (K), rare Earth elements (REE), and phosphorus (P). These rocks are more radioactive and higher in thorium than Earth rocks.

Moon rock research Lunar rock research continues at the Johnson Space Center in Houston, Texas. The rocks are protected in stainless steel vaults in a dry nitrogen atmosphere to keep them moisture- and rust-free. Scientists continue to pose questions about these rocks as they study the Moon's origin and history.

WRITING in Earth Science

Lunar Rock Game Use resources to design a game that involves the collection and analysis of lunar rocks by scientists. Trade games with classmates to increase your understanding of lunar rocks.

Roger Ressmeyer/CORBIS

GEOLAB

DESIGN YOUR OWN: MODEL CRYSTAL FORMATION

Background: The rate at which magma cools affects the grain size of the resulting igneous rock. Observing the crystallization of magma is difficult because molten rock is very hot and the crystallization process is sometimes very slow. Other materials, however, crystallize at lower temperatures. These materials can be used to model crystal formation.

Question: *How do minerals crystallize from magma?*

Materials

clean, plastic petri dishes
saturated alum solution
200-mL glass beaker
magnifying lens
dark-colored construction paper
thermometer
paper towels
water
hot plate

Safety Precautions

WARNING: ***The alum solution can cause skin irritation and will be hot when it is first poured into the petri dishes. If splattering occurs, wash skin with cold water.***

Procedure

1. Read and complete the lab safety form.
2. As a group, plan how you will change the cooling rate of a hot solution poured into a petri dish. Each group member should choose a petri dish in a predetermined location to observe during the investigation. Make sure your teacher approves your plan before you begin.
3. Place a piece of dark-colored construction paper on a level surface where it will not be disturbed. Be sure to put the paper in all of the predetermined locations. Place the petri dishes on top of the paper.
4. Using the glass beaker, obtain about 150 mL of saturated alum solution from your teacher. The temperature should be about 95°C to 98°C, just below boiling temperature.
5. Carefully pour some of the solution into each petri dish so that it is half full. Use caution when pouring the hot liquid to avoid splatters and burns.

Matt Meadows

6. Every 5 min for 30 min, record your observations of your petri dish. Make drawings of any crystals that begin to form.

Analyze and Conclude

1. **Compare** your methods of cooling with those of other groups. Did some methods appear to work better than others? Explain.
2. **Examine** your alum crystals. What do the crystals look like? Are they all the same size? Do all the crystals have the same shape?
3. **Draw** the most common crystal shape in your science journal. Compare your drawings with those of other groups. Describe any patterns that you see.
4. **Deduce** what factors affected the size of the crystals in the different petri dishes. How do you know?
5. **Infer** why the crystals changed shape as they grew.
6. **Compare and contrast** this experiment with magma crystallization.
7. **Evaluate** the relationship between cooling rate and crystal formation.

SHARE YOUR DATA

Peer Review Visit glencoe.com and post a summary of your data. Compare and contrast your results with those of other students who have completed this lab.

CHAPTER 5

Study Guide

STUDY TO GO

Download quizzes, key terms, and flash cards from glencoe.com.

BIG Idea Igneous rocks were the first rocks to form as Earth cooled from a molten mass to the crystalline rocks of the early crust.

Section 5.1 What are igneous rocks?

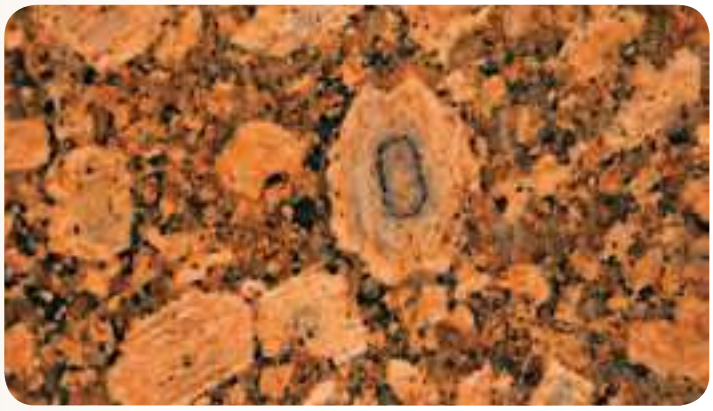
Vocabulary

- Bowen's reaction series (p. 114)
- fractional crystallization (p. 115)
- igneous rock (p. 112)
- lava (p. 112)
- partial melting (p. 114)

Key Concepts

MAIN Idea Igneous rocks are the rocks that form when molten material cools and crystallizes.

- Magma consists of molten rock, dissolved gases, and mineral crystals.
- Magma is classified as basaltic, andesitic, or rhyolitic, based on the amount of silica it contains.
- Different minerals melt and crystallize at different temperatures.
- Bowen's reaction series defines the order in which minerals crystallize from magma.



Section 5.2 Classification of Igneous Rocks

Vocabulary

- basaltic rock (p. 118)
- extrusive rock (p. 118)
- granitic rock (p. 118)
- intrusive rock (p. 118)
- kimberlite (p. 123)
- pegmatite (p. 122)
- porphyritic texture (p. 120)
- texture (p. 119)
- vesicular texture (p. 120)

Key Concepts

MAIN Idea Classification of igneous rocks is based on mineral composition, crystal size, and texture.

- Classification of igneous rocks is based on three main characteristics.
- The rate of cooling determines crystal size.
- Ores often occur in pegmatites. Diamonds occur in kimberlites.
- Some igneous rocks are used as building materials because of their strength, durability, and beauty.

(t)Marli Miller/Visuals Unlimited, (b)Albert J. Copley/Visuals Unlimited

Earth Science Online Vocabulary PuzzleMaker glencoe.com

CHAPTER 5 Assessment

Vocabulary Review

The sentences below are incorrect. Make each sentence correct by replacing the italicized word or phrase with a vocabulary term from the Study Guide.

1. Gases escape from *magma* as it flows out onto Earth's surface.
2. *Mohs scale of hardness* describes the order in which minerals crystallize.
3. *Lava* forms deep beneath Earth's crust.

Complete the sentences by filling in the blank with the correct vocabulary term from the Study Guide.

4. An igneous texture characterized by large crystals embedded in a fine-grained background is called a _____.
5. Igneous rocks that form under conditions of fast cooling are said to be _____.
6. Light-colored rocks with large crystals are said to be _____.

Understand Key Concepts

7. Which is the first mineral to form in cooling magma?
   A. quartz
   B. mica
   C. potassium feldspar
   D. olivine

Use the diagram below to answer Question 8.

8. Which process is occurring in the diagram?
   A. fractional separation
   B. crystal separation
   C. fractional crystallization
   D. partial melting

9. Which minerals are associated with the right-hand branch of Bowen's reaction series?
   A. olivine and pyroxene
   B. feldspars
   C. mica and feldspars
   D. quartz and biotite

10. Which magma type contains the greatest amount of silica?
    A. basaltic
    B. andesitic
    C. rhyolitic
    D. peridotic

11. Which does not affect the formation of magma?
    A. volume
    B. temperature
    C. pressure
    D. mineral composition

12. Which extrusive rock has the same composition as andesite?
    A. granite
    B. basalt
    C. obsidian
    D. diorite

Use the figure below to answer Question 13.

13. Which process formed this rock?
    A. slow cooling
    B. fast cooling
    C. very fast cooling
    D. slow, then fast cooling

14. Which type of ultrabasic rock sometimes contains diamonds?
    A. pegmatite
    B. kimberlite
    C. granite
    D. rhyolite

Breck P. Kent/Animals Animals

15. What effect does a fast cooling rate have on grain size in igneous rocks?
   A. It forms fine-grained crystals.
   B. It forms large-grained crystals.
   C. It forms light crystals.
   D. It forms dark crystals.

16. What term describes igneous rocks that crystallize inside Earth?
   A. magma
   B. intrusive
   C. lava
   D. extrusive

17. Which minerals are most common in granite?
   A. quartz and feldspar
   B. plagioclase feldspar and amphibole
   C. olivine and pyroxene
   D. quartz and olivine

Constructed Response

18. **List** some uses of igneous rocks in the construction industry.

19. **Explain** how and why the plagioclase feldspar in basaltic rocks differs from that in granitic rocks.

Use the photos below to answer Questions 20 and 21.

20. **Draw** a flowchart documenting the formation of the holes in this sample of vesicular basalt.

21. **Speculate** on the reasons that samples of pumice are able to float in water.

22. **Illustrate** how fractional crystallization changes the composition of magma, using the formation of iron-rich olivine to illustrate the point.

23. **Apply** the concepts of temperature and crystallization to explain why magma is often described as a slushy mixture of crystals and molten rock.

Use the table below to answer Questions 24 and 25.

Rock Composition

Mineral	Mineral Percentage			
	Rock 1	Rock 2	Rock 3	Rock 4
Quartz	5	35	0	0
Potassium feldspar	0	15	0	0
Plagioclase feldspar	55	25	0	55
Biotite	15	15	0	10
Amphibole	25	10	0	30
Pyroxene	0	0	40	5
Olivine	0	0	60	0

24. **Analyze** the data in the table, and explain which rock is most likely granite.

25. **Incorporate** Use the data for Rock 4 and the fact that it is fine-grained to determine the name of Rock 4.

Think Critically

26. **Compare** obsidian and granite to explain why granite is more easily carved into statues and monuments.

27. **Evaluate** this statement: It is possible for magma to have a higher silica content than the rock that forms from it.

28. **Apply** what you know about mineral hardness to explain why stainless steel knives do not harm granite cutting boards.

(t)Breck P. Kent/Animals Animals, (b)Jerome Wyckoff/Animals Animals

29. **Infer** Kimberlites are the source of most diamonds. Infer why scientists study kimberlites to learn more about Earth's mantle.

30. **Assess** Rocks generally consist of minerals. When molten rock is chilled rapidly, it becomes a glass. Volcanic glass is an extrusive igneous rock. Assess whether this rock contains minerals. Explain your answer. [Hint: Recall the definition of a mineral from Chapter 4.]

31. **Infer** why rocks that are composed of minerals that crystallize first according to Bowen's reaction series are unstable and break down quickly at Earth's surface.

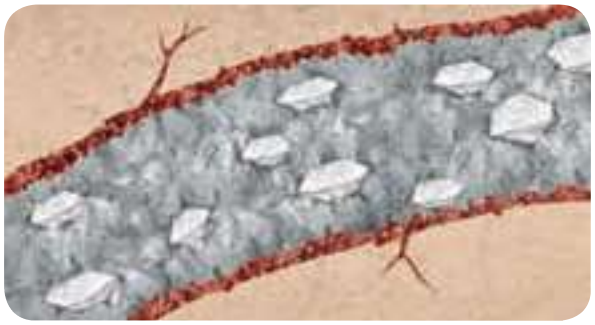
32. **Hypothesize** what the Palisade Sill would look like if the magma that formed it was granitic in composition.

Concept Mapping

33. Use the following terms to create a concept map showing the relationship among position in Earth's crust and mantle, crystal size, and rock type: *fast, slow, slowest, intrusive, extrusive, magma, lava, granite, rhyolite, basalt, gabbro, obsidian,* and *pumice.*

Challenge Question

Use the diagram below to answer Question 34.



34. **Determine** The diagram shows a cross section of the Leopard Lode, an igneous rock unit in Wyoming. Determine the formation history of this rock unit.

Additional Assessment

35. **WRITING in Earth Science** Building stone is expensive. Suppose you are selling kitchen countertops that look like granite, but consist of a less-expensive synthetic material. List the specific characteristics of granite that your customers would look for in the imitation granite.

Document–Based Questions

Data obtained from: Gerya, T.V., et al. 2003. Cold fingers in a hot magma: numerical modeling of country-rock diapirs in the Bushveld Complex, South Africa. *Geology* 31 (9): 753.

The Bushveld Complex is the world's largest layered intrusion. It was injected as a hot, dense basaltic magma between overlying volcanic and underlying sedimentary rocks. Modeling of this event indicates that finger-shaped bodies of heated, metamorphosed sedimentary rocks subsequently intruded the overlying igneous layers. The model assumed the igneous rock properties shown in the table.

Igneous Rock Properties

Rock Type	Density (kg/m^3)	T Solidus (°C)	T Liquidus (°C)
Granitic	2700 (solid) 2400 (molten)	675	925
Basaltic/ ultrabasic	3000 (solid) 2900 (molten)	950	1100

36. Compare and contrast the density of solid and molten rocks in this model.

37. Speculate about why the overlying rhyolitic rocks could not penetrate, or sink into, the basaltic magma.

38. Infer the meaning of the terms *liquidus* and *solidus.* At what temperature do the first crystals in granitic rocks melt?

Cumulative Review

39. What is a molecule? **(Chapter 3)**

40. Name a gemstone that consists of corundum. **(Chapter 4)**

Standardized Test Practice

Multiple Choice

Use the table below to answer Questions 1 and 2.

Characteristics of Rocks			
	Color	**Silica Content**	**Composition**
Rock A	light	high	quartz and feldspars
Rock B	dark	low	iron and magnesium

1. Rock A is most likely what kind of rock?
- **A.** felsic
- **B.** mafic
- **C.** ultramafic
- **D.** intermediate

2. Which type of rock is Rock B?
- **A.** granite
- **B.** diorite
- **C.** gabbro
- **D.** pegmatite

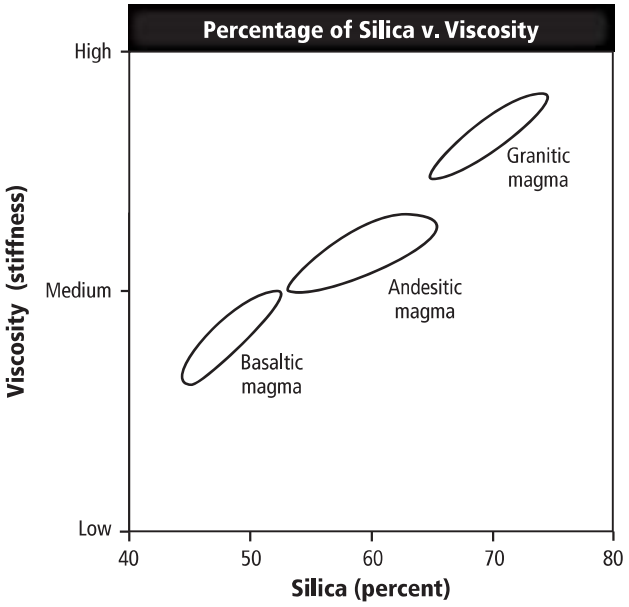
3. Which is most abundant in magma and has the greatest effect on its characteristics?
- **A.** O
- **B.** Ca
- **C.** Al
- **D.** SiO_2

4. Which process describes how different minerals form at different rates?
- **A.** partial melting
- **B.** Bowen's reaction series
- **C.** fractional crystallization
- **D.** geothermal gradient

5. Which is NOT a feature used for identifying minerals?
- **A.** hardness
- **B.** color
- **C.** density
- **D.** volume

6. Which is distorted on a Mercator projection map?
- **A.** shapes of the landmasses
- **B.** areas of the landmasses
- **C.** latitude lines
- **D.** longitude lines

Use the graph below to answer Questions 7 and 8.



7. What relationship can be inferred from the graph?
- **A.** Magmas that have more silica are more viscous.
- **B.** Magmas that have less silica are more viscous.
- **C.** Magmas always have low viscosity.
- **D.** There is no relationship between silica content and viscosity.

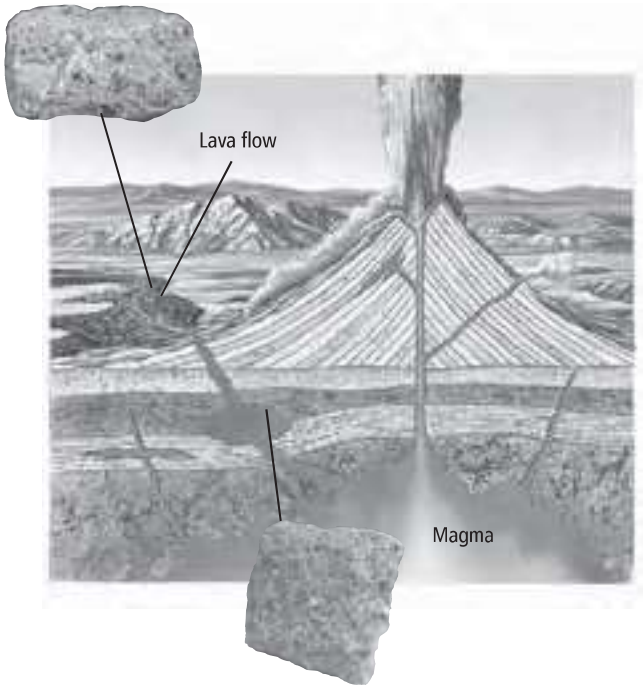
8. Which is a true statement about granitic magma?
- **A.** Granitic magma is heavier than the other two types of magma.
- **B.** Granitic magma is lighter than the other two types of magma.
- **C.** Granitic magma flows more quickly than the other two types of magma.
- **D.** Granitic magma flows more slowly than the other two types of magma.

9. Which is a combination of two or more components that retain their identities?
- **A.** chemical
- **B.** solution
- **C.** mixture
- **D.** element

10. Which is the lightest of all atoms?
- **A.** uranium atom
- **B.** oxygen atom
- **C.** carbon atom
- **D.** hydrogen atom

Short Answer

Use the picture below to answer Questions 11–13.



11. Name the type of igneous rock located at the bottom of the picture, and state a common example of that type of rock and explain how this rock is formed.

12. Name the type of igneous rock located at the top of the picture and state a common example of that type of rock and explain how this type of rock is formed.

13. Contrast the formation of the two types of igneous rock.

14. What does it mean to say that minerals are naturally occurring and inorganic?

15. Why are some minerals classified as gems?

16. Why are both latitude and longitude lines necessary when identifying a location?

Reading for Comprehension

Marianas Island Research

Billowing ash plumes, molten sulfur droplets, feisty shrimp feasting on fish killed by noxious gases, and red lava jetting from a vent are all part of the action recently filmed at an underwater volcano in the western Pacific Ocean. The images are the first ever direct observations of an active, submarine-arc volcano. Unlike volcanic activity at mid-ocean ridges, island-arc volcanoes can remain fixed over their magma sources for thousands of years, allowing them to sometimes grow above water level and become islands. The new studies at the Marianas Islands are giving scientists a firsthand look into this formation process. The volcano has been going through nearly constant low-level eruptions since at least 2004, when it was first observed, Embley says. It could potentially keep erupting for decades, giving scientists the opportunity to monitor its growth.

Article obtained from: Roach, J. "Deep-Sea Volcano Erupts on Film—A First" *National Geographic News.* 24 May 2006.

17. What are the benefits of the new studies at the Marianas Islands?

A. The studies give scientists a firsthand look into the formation process.
B. The studies reveal that the volcano could potentially keep erupting for decades.
C. The studies show life near the vent.
D. The studies are the first ever direct observations of an active submarine arc-volcano.

18. What can you infer from this passage?

A. Volcanoes constantly erupt at some level of intensity.
B. Volcanic activity occurs only at mid-ocean ridges.
C. Shrimp only eat fish killed by noxious gasses.
D. There are many active submarine volcanoes.

NEED EXTRA HELP?																
If You Missed Question . . .	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Review Section . . .	5.2	5.2	5.1	5.1	4.1	2.2	5.1	5.1	3.2	3.1	5.2	5.2	5.2	4.1	4.2	2.1