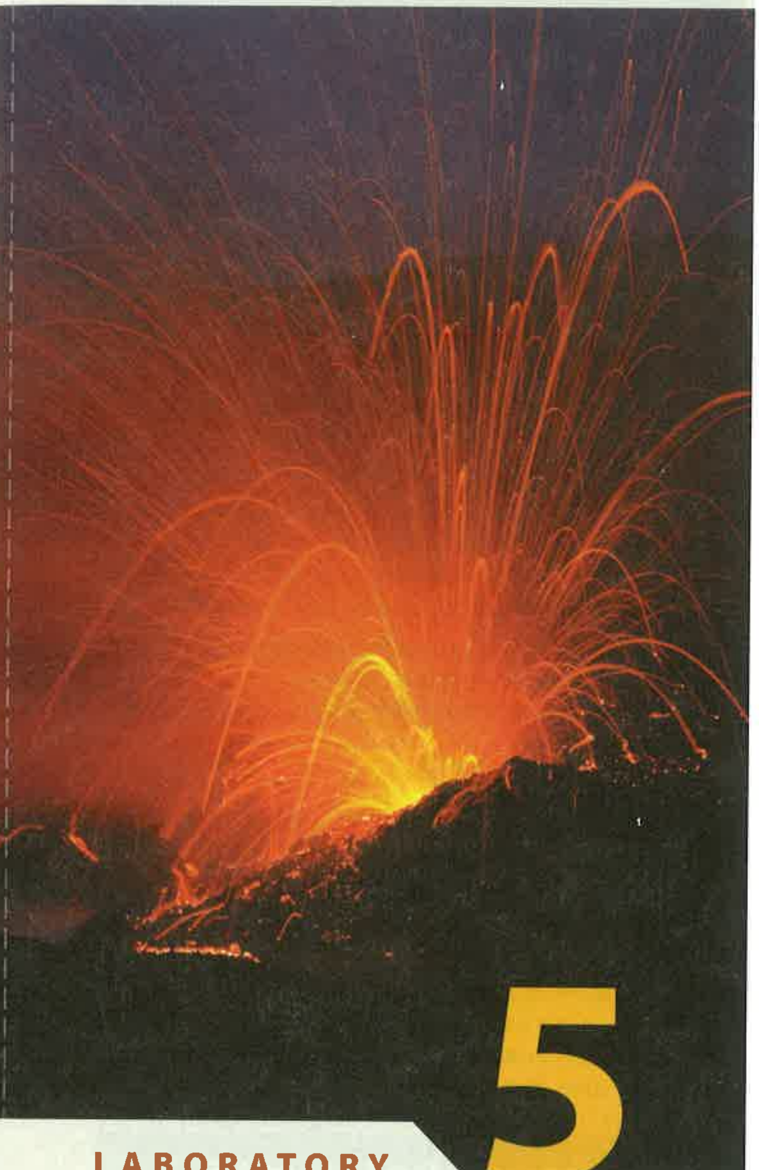

LABORATORY 5

Igneous Rocks and Processes

CONTRIBUTING AUTHORS

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Explosive volcanic eruptions like this one eject partially molten volcanic bombs that become rounded and cool as they fly through the air. (Superstock)

BIG IDEAS

Igneous rocks form wherever magma or lava cool to a solid state. The composition and texture of igneous rock samples, and the shapes of bodies of igneous rock, can be used to classify them and infer their origin. Lava and igneous rock-forming processes can be observed at volcanoes, which occur along lithospheric plate boundaries and hot spots, are linked to underground bodies of magma, and can pose hazards to humans.

FOCUS YOUR INQUIRY

THINK About It | What do igneous rocks look like? How can they be classified into groups?

THINK About It | What are igneous rocks composed of? How is composition used to classify and interpret igneous rocks?

THINK About It | What are igneous rock textures? How is texture used to classify and interpret igneous rocks?

THINK About It | How are rock composition and texture used to classify, name, and interpret igneous rocks?

THINK About It | How can the shapes of bodies of igneous rock be used to classify them and infer their origin?

Introduction

Right now, there are more than a hundred volcanoes erupting or threatening to erupt on continents and islands around the world. Some pose direct threats to humans. Others pose indirect threats, such as earthquakes and episodic melting of glaciers. In the oceans, deep under water and far from direct influence on humans, there are likely hundreds more volcanoes. The exact number is unknown, because they are erupting at places on the sea floor that humans rarely see.

Most of the world's volcanoes occur along its 260,000 kilometers of linear boundaries between lithospheric plates. The rest are largely associated with hot spots. All of the volcanoes overlie bodies of molten (hot, partly or completely melted) rock called **magma**, which is referred to as **lava** when it reaches Earth's surface at the volcanoes. In addition to their liquid rock portion, or *melt*, magma and lava contain dissolved gases (e.g., water, carbon dioxide, sulfur dioxide) and solid particles. The solid particles may be pieces of rock that have not yet melted and/or mineral crystals that may grow in size or abundance as the magma cools. **Igneous rocks** form when magma or lava cool to a solid state. The bodies of igneous rock may be as large as those in Yosemite Park, where bodies of magma cooled underground to form batholiths of igneous rock, tens of kilometers in diameter. They may be as small as centimeter-thick layers of volcanic ash, which is composed of microscopic fragments of igneous rock (mostly volcanic glass pulverized by an explosive volcanic eruption).

ACTIVITY

5.1 Igneous Rock Inquiry

THINK About It **What are igneous rocks composed of, and how can they be classified into groups?**

OBJECTIVE Analyze and describe samples of igneous rock, then infer how they can be classified into groups.

PROCEDURES

1. **Before you begin**, do not look up definitions and information. Use your current knowledge, and complete the worksheet with your current level of ability. Also, this is **what you will need** to do the activity:

   ____ Activity 5.1 Worksheet (p. 143) and pencil
   ____ optional: a set of igneous rock samples (obtained as directed by your instructor)

2. **Analyze the rocks, and complete the worksheet in a way that makes sense to you.**
3. **After you complete the worksheet**, be prepared to discuss your observations, interpretations, and inferences with others.

ACTIVITY

5.2 Minerals That Form Igneous Rocks

THINK About It **What are igneous rocks composed of? How is composition used to classify and interpret igneous rocks?**

OBJECTIVE Identify samples of eight minerals that form most igneous rocks and categorize them as mafic or felsic.

PROCEDURES

1. **Before you begin**, read Mafic and Felsic Rock-Forming Minerals below. Also, this is **what you will need:**

   ____ Activity 5.2 Worksheet (p. 144) and pencil
   ____ optional: a set of mineral samples (obtained as directed by your instructor)
   ____ optional: a set of mineral analysis tools (obtained as directed by your instructor)

2. **Then follow your instructor's directions** for completing the worksheet.

Mafic and Felsic Rock-Forming Minerals

There are eight silicate minerals that form most igneous rocks. This is because silicon and oxygen are the most common elements in magma and lava. The silicon and oxygen naturally forms silicon-oxygen tetrahedra, in which one silicon atom shares electrons with four oxygen atoms (**FIGURE 5.1**). This creates a silicon-oxygen tetrahedron (four-pointed pyramid) with four electrons too many, so each oxygen atom also shares an electron with another adjacent silicon atom. The simplest ratio of silicon to oxygen is 1:2, written SiO_2 and called **silica**.The mineral quartz is a crystalline form of pure silica. However, with the abundance of other chemicals in magma and lava, silicon-oxygen tetrahedra often bond with other kinds of metal atoms to make the other silicate minerals commonly found in igneous rocks. Although each one has its own unique properties that can be used to identify it, the minerals are also categorized into two chemical groups.

Felsic Minerals

The name *felsic* refers to feldspars (*fel-*) and other silica-rich (*-sic*) minerals. The common felsic minerals in igneous rocks are gray translucent *quartz*, light gray opaque *plagioclase feldspar*, pale-orange to pink opaque *potassium feldspar*, and glossy pale-brown to silvery-white *muscovite.* They are all light colored because their chemical composition lacks iron and magnesium.

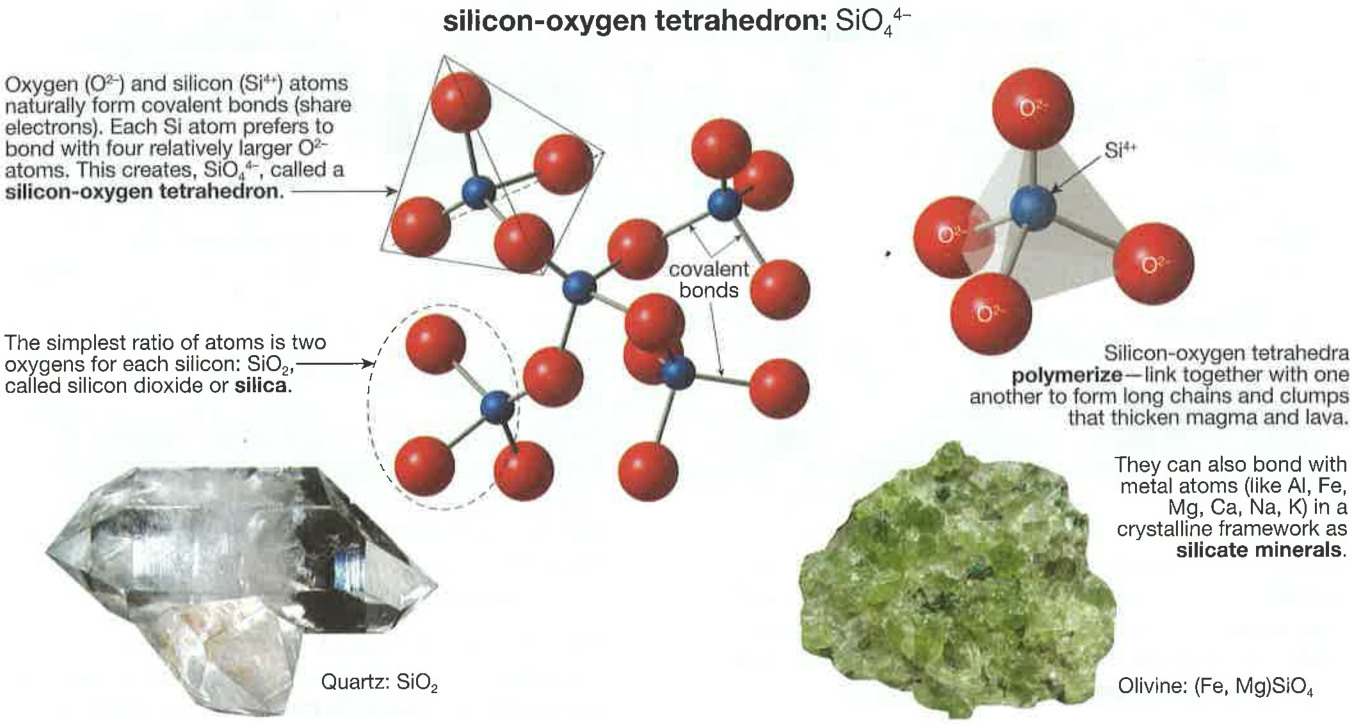


FIGURE 5.1 Silica and silicate minerals. Silicon (Si) and oxygen (O) are, by far, the most abundant chemical elements in magma, lava, and igneous rocks. They form silica (SiO_2), which thickens magma and lava (makes it more viscous) and bonds togther, alone (as quartz), or with metal atoms to make silicate minerals besides quartz in igneous rocks.

Mafic Minerals

The name *mafic* refers to minerals with magnesium (*ma-*) and iron (*-fic*) in their chemical formulas, so they are also called *ferromagnesian* minerals. They get their dark color from the abundant proportion of iron and magnesium in their chemical composition. The common mafic minerals in igneous rocks are glossy black *biotite*, dark gray to black *amphibole*, dark green to green-gray *pyroxene*, and olive-green *olivine*.

ACTIVITY 5.3 Estimate Rock Composition

THINK About It What are igneous rocks composed of? How is composition used to classify and interpret igneous rocks?

OBJECTIVE Determine the compositional group of an igneous rock using methods of visual estimation and point counting.

PROCEDURES

1. **Before you begin**, read about Composition of Igneous Rocks and How to Assign Rock Samples to Chemical Groups (p. 145). Also, this is **what you will need:**

   ____ Activity 5.3 Worksheet (p. 145) and pencil

2. **Then follow your instructor's directions** for completing the worksheet.

Composition of Igneous Rocks

Composition of a rock refers to what it is made of. *Chemical compositon* refers to the chemical elements that make up the rock. This determines how the rock will react with materials of different compositon, such as whether or not it will react with and decay (tarnish, dissolve, chemically disintegrate) in air or water. It also determines rock color. For example, ferromagnesian-rich rocks (iron- and magnesium-rich rocks) generally have a dark color and ferromagnesian-poor rocks generally have a light color. But the chemical elements in a rock are normally bonded together in tangible materials like minerals that, in turn, make up most rocks. So the *phsyical composition* of rocks is a description of what visible materials they are made of, in whole or part. It is your job as a geologist, using your eyes and simple tools (like a hand magnifying lens), to describe and identify what physical materials igneous rocks are made of.

Chemical Composition—Four Groups

Magmas, lavas, and igneous rocks are composed mostly of the same eight elements that characterize the average composition of Earth's crust. They are oxygen (O), silicon (Si), aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), sodium (Na), and potassium (K).

COMPOSITION OF IGNEOUS ROCKS		
Chemical Composition		**Physical Composition**
Compositional Group Name	Silica % (by weight) in the magma, lava, or rock	**Mafic Color Index (MCI):** Percent of mafic (green, dark gray, and black) mineral crystals in the rock
Felsic (acidic)	above 65%	below 15%
Intermediate	54 – 64%	16 – 45%
Mafic	45 – 53%	46 – 85%
Ultramafic	below 45%	above 85%

FIGURE 5.2 Composition of igneous rocks. Magma, lava, and igneous rocks are classified into one of four compositional groups on the basis of their chemical composition (percentage of silica, by weight). The same names are used to describe the physical compositon of igneous rocks, based on their mafic color index (MCI).

All of these elements are cations (positively-charged atoms), except for oxygen (a negatively-charged atom, or anion); oxygen combines with the cations. The most abundant cation is silicon, so silica is the most abundant chemical compound in magmas, lavas, and igneous rocks (FIGURE 5.1). Chemical classification of magmas, lavas, and igneous rocks is based on the amount (percentage by weight) of silica they contain, which is used to assign them to one of four chemical **compositonal groups** (FIGURE 5.2):

- **Felsic (acidic) Compositional Group.** The name *felsic* refers to feldspars (*fel-*) and other silica-rich (*-sic*) minerals, but it is now also used (in place of "acidic") to decsribe magmas, lavas, and igneous rocks containing more than 60% silica.
- **Mafic (basic) Compositional Group.** The name *mafic* refers to minerals with magnesium (*ma-*) and iron (*-fic*) in their chemical formulas (also called *ferromagnesian* minerals), but it is now also used (in place of "basic") to describe magmas, lavas, and igneous rocks containing 45–53% silica.
- **Ultramafic (ultrabasic) Compositional Group.** As the name implies, this term was originally used to describe igneous rocks made almost entirely of mafic minerals. However, it now also is used (in place of "ultrabasic") to describe magmas, lavas, and igneous rocks containing less than 45% silica.
- **Intermediate Compositional Group.** This name refers to magmas, lavas, and igneous rocks that contain 54–64 % silica; a composition between mafic and felsic.

Physical Composition

The visible materials that comprise igneous rocks include volcanic glass and **grains**—mineral crystals and other hard discrete particles.

- **Volcanic glass.** Glass is an amorphous (containing no definite form; not crystalline) solid that forms by cooling viscous molten materials like melted rock (magma, lava) or quartz sand (the main ingredient that is melted to make window glass. Volcanic glass (obsidian) looks and breaks just like window glass, and it is transparent to translucent when held up to a light. It is mostly associated with felsic rocks, because they have a high percentage of silica that can polymerize into glass rather than mineral crystals (FIGURE 5.1). It may be tan, gray, black, or red-brown. The black and red-brown varieties get their dark color from the oxidation of minute amounts of iron in the lavas from which they cooled. It takes just a tiny amount of magnetite or hematite to darken the glass.
- **Mineral grains (crystals).** Most igneous rocks, even pieces of volcanic glass, contain some proportion of mineral crystals—either mafic (dark-colored ferromagnesian minerals) or felsic (light-colored silica-rich minerals). If you have not read Mafic and Felsic Rock-Forming Minerals on page 130, then you should do so now.
- **Pyroclasts (tephra).** *Pyroclasts* (from Greek meaning "fire broken") are rocky materials that have been fragmented and/or ejected by explosive volcanic eruptions (FIGURE 5.3). They include *volcanic ash* fragments (pyroclasts < 2 mm), *lapilli* or *cinders* (pyroclasts 2–64 mm), and *volcanic bombs* or *blocks* (pyroclasts > 64 mm). A mass of pyroclastic debris is called *tephra.*
- **Xenoliths.** Magma is physically contained within the walls of bedrock (crust, mantle) through which it moves. Fragments of the wall rock occasionally break free and become incorporated into the magma. When the magma cools, the fragments of wall rock are contained within the younger igneous rock as xenoliths.

How to Assign Rock Samples to Chemical Groups

The process of chemically anaylzing rocks to determine their proportions of specific elements is generally time consuming and expensive. Therefore, geologists have devised methods of hand sample analysis that enable them to assign igneous rocks to their compositional groups.

Using a Visual Estmation of Percent Chart

You can estimate the abundance of any mineral or other type of grain in a rock by using a Visual Estimation of Percent Chart provided at the back of the manual (GeoTools Sheets 1 and 2). The percentage of the circle that is black is noted on the charts (5%, 15%, 45%, 85%) for both small and large visible grains. The charts on GeoTools Sheet 2 are transparent, so you can lay them directly onto the rock.

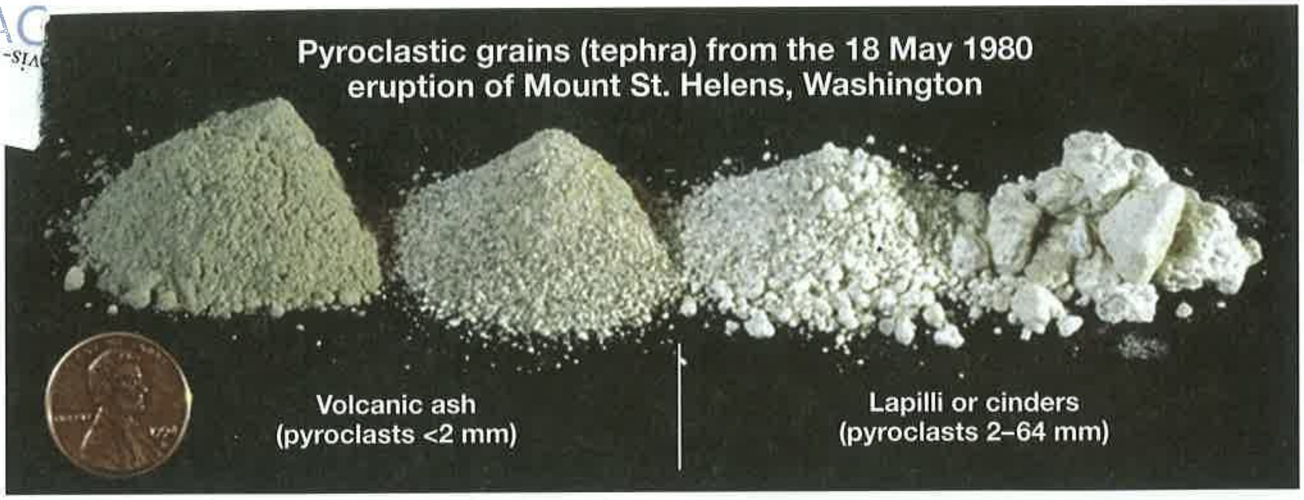


FIGURE 5.3 Pyroclastic grains (tephra). These samples of volcanic ash and lapilli (cinders) were ejected from Mount St. Helens, then collected and photographed by D. Wieprecht. (Image courtesy of U.S. Geological Survey. Scale x1.)

Using the Mafic Color Index (MCI)

The **mafic color index (MCI)** of an igneous rock is the percentage of its green, dark gray, and black mafic (ferromagnesian) mineral crystals. If the rock has no visible mineral crystals, then the overall color of the rock is used to estimate its mafic color index and corresponding compositional group. A white, pale gray, or pink rock has a felsic MCI (0–15%) and compositonal group. A moderately medium-gray rock has an intermediate MCI (16–45%) and compositional group. A very dark gray rock has a mafic MCI (46–85%) and compositional group. A black or dark green rock has a mafic MCI (above 85%) and compositional group.

If the rock has visible crystals, then you should use a Visual Estimation of Percent chart to estimate the mafic color index as closely as possible.

The mafic color index of an igneous rock is only an approximation of the rock's mineral composition, because there are some exceptions to the generalization that "light-colored equals felsic" and "dark-colored equals mafic." For example, labradorite feldspar (felsic) can be dark gray to black. Luckily, it can be identified by its characteristic play of iridescent colors that flash on and off as the mineral is rotated and reflects light. Olivine (mafic) is sometimes a pale yellow-green color (instead of medium to dark green). Volcanic glass (obsidian) is also an exception to the mafic color index rules. Its dark color suggests that it is mafic when, in fact, most obsidian has a very high weight percentage of silica and less than 15% ferromagnesian constituents. (Ferromagnesian-rich obsidian does occur, but only rarely.)

Using Point Counting

Point counting is counting the number of times that each kind of mineral crystal occurs in a specified area of the sample, or along a line randomly drawn across the sample, then calculating the relative percentage of each mineral.

ACTIVITY

5.4 Glassy and Vesicular Textures of Igneous Rocks

THINK About It **What are igneous rock textures? How is texture used to classify and interpret igneous rocks?**

OBJECTIVE Experiment with molten sugar to produce glassy and vesicular textures, then apply your knowledge to interpret rock samples.

PROCEDURES

1. **Before you begin**, read about Textures of Igneous Rocks below. Also, this is **what you will need:**
   - ____ Activity 5.4 Worksheet (p. 146) and pencil
   - ____ sugar
   - ____ materials provided in lab: hot plate, small metal sauce pan with handle or 500 mL Pyrex™ beaker and tongs, water (~50 mL), safety goggles, aluminum foil, hand lens, sugar (~50 mL, 1/8 cup), and hot plate
   - ____ collection of numbered igneous rock samples
2. **Then follow your instructor's directions** for completing the worksheet.

Textures of Igneous Rocks

Texture of an igneous rock is a description of its constituent parts and their sizes, shapes, and arrangement. You must be able to identify the common textures of igneous rocks described below and understand how they form. Notice the list of textures and their origins in FIGURE 5.4.

ACTIVITY

5.5 Crystalline Textures of Igneous Rocks

THINK About It | **What are igneous rock textures? How is texture used to classify and interpret igneous rocks?**

OBJECTIVE Review a crystallization experiment, infer how rate of cooling affects crystal size, and then apply your knowledge to interpret a rock with porphyritic texture.

PROCEDURES

1. **Before you begin**, read about Textures of Igneous Rocks (p. 133). Also, this is **what you will need:**

   ____ Activity 5.5 Worksheet (p. 147) and pencil

2. **Then follow your instructor's directions** for completing the worksheet.

Igneous rocks are also classified into *two textural groups*: intrusive (plutonic) versus extrusive (volcanic).

Intrusive (plutonic) rocks form deep underground, where they are well insulated (take a long time to cool) and pressurized. The pressure prevents gases from expanding, just like carbonation in a sealed soft drink. The cap seals in the pressure—an intrusive process. If you remove the cap, then the carbon dioxide inside the bottle expands and bubbles—an extrusive process. Therefore, **extrusive (volcanic) rocks** form near and on Earth's surface, where the confining pressure is low and gases begin to bubble out of the magma. This can help cause explosive eruptions and textures related to fragmenting of rocks. Cooler surface temperatures also rob thermal energy from magma, so it cools quickly.

The size of mineral crystals in an igneous rock generally indicates the rate at which the lava or magma cooled to form a rock and the availability of the chemicals required to form the crystals. Large crystals require a long time to grow, so their presence generally means that a body of molten rock cooled slowly (an intrusive process) and contained ample atoms of the chemicals required to form the crystals. Tiny crystals generally indicate that the magma cooled more rapidly (an extrusive process). Volcanic glass (no crystals) can indicate that a magma was quenched (cooled immediately), but most volcanic glass is the result of poor nucleation as described below.

Nucleation and Rock Texture

The crystallization process depends on the ability of atoms in lava or magma to *nucleate. Nucleation* is the initial formation of a microscopic crystal, to which other atoms progressively bond. This is how a crystal grows. Atoms are mobile in a fluid magma, so they are free to nucleate. If such a fluid magma cools slowly, then crystals have time to grow—sometimes to many centimeters in length. However, if a magma is very viscous (thick and resistant to flow), then atoms cannot easily move to nucleation sites. Crystals may not form even by slow cooling. Rapid cooling of very viscous magma (with poor nucleation) can produce igneous rocks with a **glassy texture** (see FIGURE 5.4), which indicates an extrusive (volcanic) origin.

Textures Based on Crystal Size

Several common terms are used to describe igneous rock texture on the basis of crystal size (FIGURE 5.4). Igneous rocks made of crystals that are too small to identify with the naked eye or a hand lens (generally <1 mm) have a very fine-grained **aphanitic texture** (from the Greek word for *invisible*). Those made of visible crystals that can be identified with a hand lens or unaided eye are said to have a **phaneritic texture** (coarse-grained; crystals 1–10 mm) or **pegmatitic texture** (very coarse-grained; >1 cm).

Some igneous rocks have two distinct sizes of crystals. This is called **porphyritic texture** (see FIGURE 5.4). The large crystals are called *phenocrysts*, and the smaller, more numerous crystals that surround them form the *groundmass*, or *matrix* (FIGURE 5.4). Porphyritic textures may generally indicate that a body of magma cooled slowly at first (to form the large crystals) and more rapidly later (to form the small crystals). However, recall from above that crystal size can also be influenced by changes in magma composition or viscosity.

Combinations of igneous-rock textures also occur. For example, a *porphyritic-aphanitic* texture signifies that phenocrysts occur within an aphanitic matrix. A *porphyritic-phaneritic* texture signifies that phenocrysts occur within a phaneritic matrix.

Vesicular and Pyroclastic Textures

When gas bubbles get trapped in cooling lava they are called *vesicles*, and the rock is said to have a **vesicular texture**. Scoria is a textural name for a rock having so many vesicles that it resembles a sponge. Pumice has a glassy texture and so many tiny vesicles (like frothy meringue on a pie) that it floats in water.

Recall that *pyroclasts* (from Greek meaning *fire broken*) are rocky materials that have been fragmented and/or ejected by explosive volcanic eruptions (FIGURE 5.3). They include *volcanic ash* fragments (pyroclasts < 2 mm), *lapilli* or *cinders* (pyroclasts 2–64 mm), and *volcanic bombs* or *blocks* (pyroclasts > 64 mm). Igneous rocks composed mostly of pyroclasts have a **pyroclastic texture** (see FIGURE 5.4).

How to Identify Igneous Rocks

The identification and interpretation of an igneous rock is based on its composition and texture (FIGURES 5.4 and 5.5). ***Follow these steps to classify and identify an igneous rock:***

Steps 1 and 2: Identify the rock's mafic color index (MCI). Then, if possible, identify the minerals that make up the rock and estimate the percentage of each.

IGNEOUS ROCK ANALYSIS AND CLASSIFICATION

STEP 1 & 2: MCI and Mineral Composition

Mafic Color Index (MCI): the percent of mafic (green, dark gray, black) minerals in the rock.
See the top of Figure 5.2 and GeoTools Sheets 1 and 2 for tools to visually estimate MCI.

FELSIC MINERALS

Quartz
hard, transparent, gray, crystals with no cleavage

Plagioclase Feldspar
hard, opaque, usually pale gray to white crystals with cleavage, often striated

Potassium Feldspar
hard, opaque, usually pastel orange, pink, or white crystals with exsolution lamellae

Muscovite Mica
flat, pale brown, yellow, or colorless, crystals that scratch easily and split into sheets

MAFIC MINERALS

Biotite Mica
flat, glossy black crystals that scratch easily and split into sheets

Amphibole
hard, dark gray to black, brittle crystals with two cleavages that intersect at 56 and 124 degrees

Pyroxene (augite)
hard, dark green to green-gray crystals with two cleavages that intersect at nearly right angles

Olivine (gemstone peridot)
hard, transparent to opaque, pale yellow-green to dark green crystals with no cleavage

STEP 3: Texture

INTRUSIVE ORIGIN

Pegmatitic
mostly crystals larger than 1 mm: very slow cooling of magma

Phaneritic
crystals about 1–10 mm, can be identified with a hand lens: slow cooling of magma

Porphyritic
large and small crystals: slow, then rapid cooling and/or change in magma viscosity or composition

EXTRUSIVE (VOLCANIC) ORIGIN

Aphanitic
crystals too small to identify with the naked eye or a hand lens; rapid cooling of lava

Glassy
rapid cooling and/or very poor nucleation

Vesicular
like meringue: rapid cooling of gas-charged lava

Vesicular
some bubbles: gas bubbles in lava

Pyroclastic or Fragmental:
particles emitted from volcanoes

STEP 4: Igneous Rock Classification Flowchart

Texture is pegmatitic or phaneritic
- Feldspar > mafic minerals
  - K-spar > Plagioclase
    - quartz present... GRANITE[1,2]
    - no quartz.......... SYENITE[1,2]
  - K-spar < Plagioclase.......... DIORITE[1,2]
- Feldspar < mafic minerals
  - MCI = 45–85.......... GABBRO[1,2]
  - MCI = 85–100 (< 15% felsic minerals).......... PERIDOTITE

Texture is aphanitic and/or vesicular
- felsic (MCI = 0–15) and/or pink, white, or pale brown.......... RHYOLITE[2,3]
- intermediate (MCI = 15–45) and/or green to gray.......... ANDESITE[2,3]
- mafic (MCI ≥ 45) and/or dark gray to black.......... BASALT[2,3]
- mafic with abundant vesicles (resembles a sponge).......... SCORIA
- intermediate or felsic with abundant tiny vesicles—like meringue, floats in water.. PUMICE

Glassy texture.......... OBSIDIAN

(GRANITE through OBSIDIAN: Also refer to Figure 5.2)

Pyroclastic (fragmental) texture
- fragments ≤ 2mm.......... TUFF
- fragments > 2mm.......... VOLCANIC BRECCIA

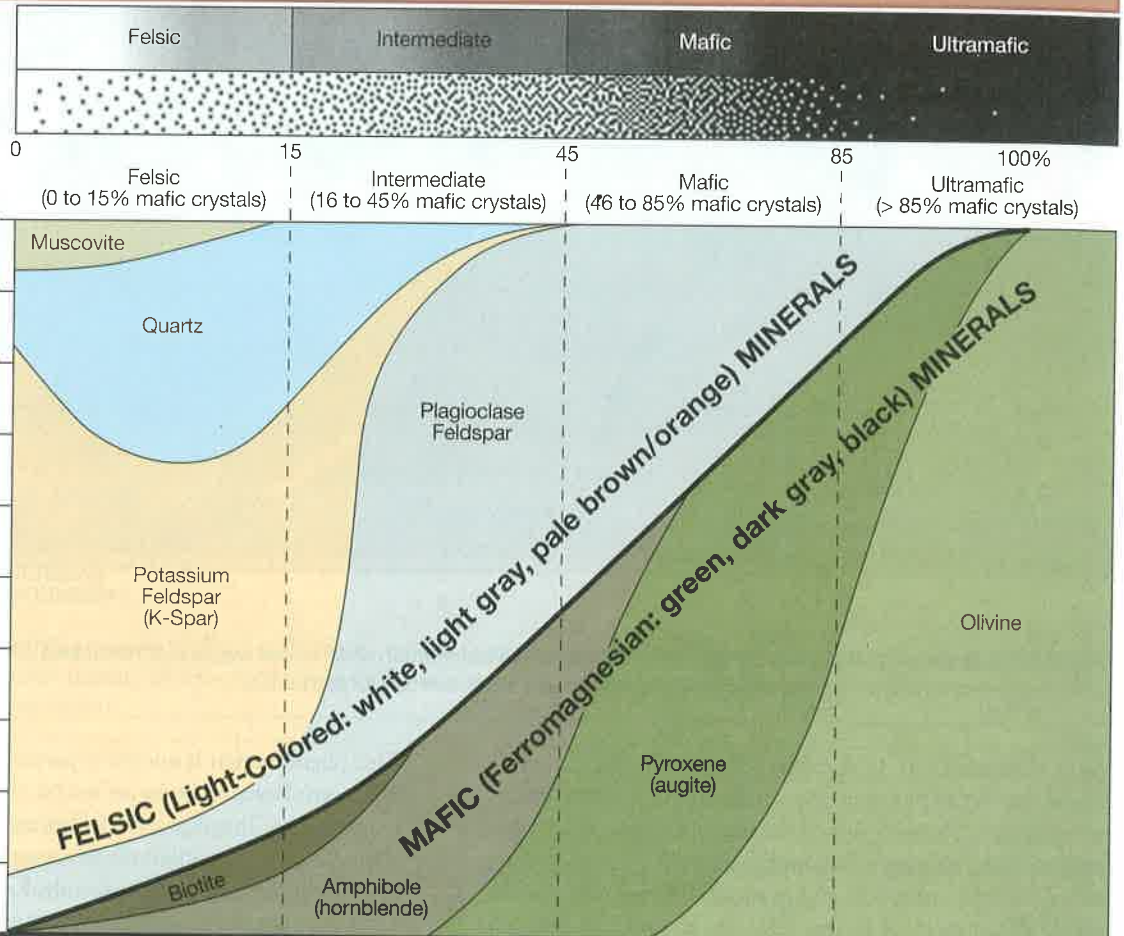
[1]Add *pegmatite* to end of name if crystals are > 1 cm (e.g., granite-pegmatite).
[2]Add *porphyritic* to front of name when present (e.g., porphyritic granite, porphyritic rhyolite).
[3]Add *vesicular* to front of name when present (e.g., vesicular basalt).

FIGURE 5.4 Igneous rock analysis and classification. Step 1—Estimate the rock's mafic color index (MCI). Step 2—Identify the main rock-forming minerals if the mineral crystals are large enough to do so, and estimate the relative abundance of each mineral (using a Visual Estimation of Percent chart from GeoTools Sheet 1 or 2). Step 3—Identify the texture(s) of the rock. Step 4—Use the Igneous Rock Classification Flowchart to name the rock. Start on the left side of the flowchart, and work toward the right side to the rock name.

IGNEOUS ROCKS CLASSIFICATION

1. Mafic Color Index (MCI)
Estimate the rock's percent of mafic (green, dark gray, and black) mineral crystals. You can also use visual estimators in GeoTools 1 and 2.

2. Minerals
Identify minerals in the rock, if possible, and the percent of each one. You can use visual estimators in GeoTools 1 and 2. Skip this step if the rock is glassy or aphanitic.



3. Texture(s) Identify the rock's texture(s).

4. Rock Name: Select name below, based on data from steps 1–3.

Origin	Texture	Felsic	Intermediate	Mafic	Ultramafic
INTRUSIVE ORIGIN	Pegmatitic: very coarse-grained	PEGMATITIC GRANITE	PEGMATITIC DIORITE	PEGMATITIC GABBRO	PEGMATITIC PERIDOTITE
INTRUSIVE ORIGIN	Phaneritic: coarse-grained	**GRANITE** (SYENITE, if no quartz)	**DIORITE**	**GABBRO**	**PERIDOTITE**
INTRUSIVE ORIGIN	Phenocrysts[1] in a phaneritic groundmass	PORPHYRITIC GRANITE	PORPHYRITIC DIORITE	PORPHYRITIC GABBRO	PORPHYRITIC PERIDOTITE
EXTRUSIVE ORIGIN	Phenocrysts[1] in an aphanitic groundmass	PORPHYRITIC RHYOLITE	PORPHYRITIC ANDESITE	PORPHYRITIC BASALT	KOMATIITE (resembles basalt but has 1–10 cm long criss-crossing needles of olivine or pyroxene)
EXTRUSIVE ORIGIN	Aphanitic: fine-grained	**RHYOLITE**	**ANDESITE**	**BASALT**	
EXTRUSIVE ORIGIN	Glassy	OBSIDIAN			
EXTRUSIVE ORIGIN	Vesicular	PUMICE (abundant tiny vesicles–like meringue; very lightweight; white or gray; floats in water)		SCORIA (resembles a sponge) VESICULAR BASALT (has few scattered vesicles)	
EXTRUSIVE ORIGIN	Pyroclastic or Fragmental	VOLCANIC TUFF (fragments < 2 mm) VOLCANIC BRECCIA (fragments > 2 mm)			

[1]Phenocrysts are crystals conspicuously larger than the finer grained groundmass (main mass, matrix) of the rock.

FIGURE 5.5 Igneous Rock Classification Chart. Obtain data about the rock in Steps 1–3, then use that data to select the name of the rock (Step 4). Also refer to FIGURE 5.4 and the examples of classified igneous rocks in FIGURES 5.8–5.14.

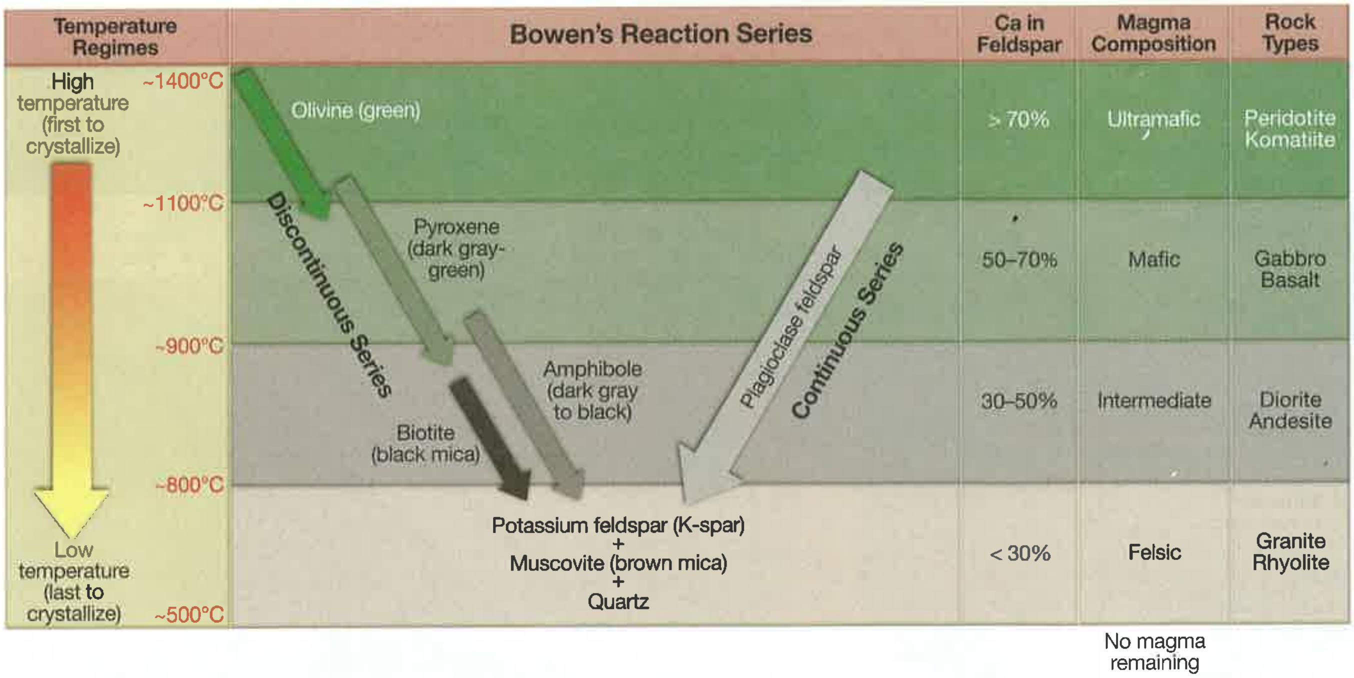


FIGURE 5.6 Bowen's Reaction Series—A laboratory-based conceptual model of one way that different kinds of igneous rocks can differentiate from a single, homogeneous body of magma as it cools. See text for discussion.

cools to about 1100° C, then the olivine starts to react with it and dissolve as pyroxene (next mineral in the series) starts to crystallize. More cooling of the magma causes pyroxene to react with the magma as amphibole (next mineral in the series) starts to crystallize, and so on. If the magma cools too quickly, then rock can form while one reaction is in progress and before any remaining reactions even have time to start.

Continuous Crystallization of Plagioclase (Right Branch). The right branch of Bowen's Reaction Series (FIGURE 5.6) shows that plagioclase feldspar crystallizes continuously from high to low temperatures (~1100–800° C), but this is accompanied by a series of continuous change in the composition of the plagioclase. The high temperature plagioclase is calcium rich and sodium poor, and the low temperature plagioclase is sodium rich and calcium poor. If the magma cools too quickly for the plagioclase to react with the magma, then a single plagioclase crystal can have a more calcium rich center and a more sodium rich rim.

Crystallization of Quartz (Bottom of the Series). Finally, notice what happens at the bottom of Bowen's Reaction Series (FIGURE 5.6). At the lowest temperatures, where the last crystallization of magma occurs, the remaining elements form abundant potassium feldspar (K-spar), muscovite, and quartz.

Partial Melting and Bowen's Reaction Series. When a plastic tray of ice cubes is heated in an oven, the ice cubes melt long before the plastic tray melts (i.e., the ice cubes melt at a much lower temperature). As rocks are heated, their different mineral crystals also melt at different temperatures. Therefore, at a given temperature, it is possible to have rocks that are partly molten and partly solid. This phenomenon is known as *partial melting*. When minerals of Bowen's Reaction Series are heated, they melt at different temperatures. The plagioclase feldspars melt continuously from about 1100–1500° C, but the ferromagnesian minerals, quartz, and K-feldspar melt discontinuously. K-feldspar melts at about 1250° C, pyroxene at 1400° C, quartz at 1650° C, and olivine at 1800° C. Because feldspars tend to melt at lower temperatures than the ferromagnesian minerals, partial melting of an igneous rock tends to produce magma of more felsic composition than the original rock from which it melted. So when a rock like basalt partially melts, it tends to form a magma that is more felsic and would cool to form andesite.

Magmatic Differentiation. Bowen's Reaction Series is an example of one way that more than one rock type can form from a single body of magma. It was generated under controlled laboratory conditions. There is no known natural location where an ultramafic magma evolved to a felsic one according to Bowen's Reaction Series. However, there are many examples where parts of Bowen's Reaction Series have occurred in nature.

Bowen's continuous series of crystallization leads to the depletion of calcium and sodium from the magma, so the composition of the magma changes. However, along the discontinuous series, early-formed mafic mineral crystals in a cooling body of magma have been shown to react with the magma at lower temperatures to form new mafic minerals. If this recycling of elements occurred perfectly, then the concentrations of iron and magnesium in the magma would never change. In nature, some of the early-formed crystals either settle out of the magma or are encrusted with different minerals before they can react, so they can no longer react with the original magma. This is called *fractional crystallization*. On the other hand,

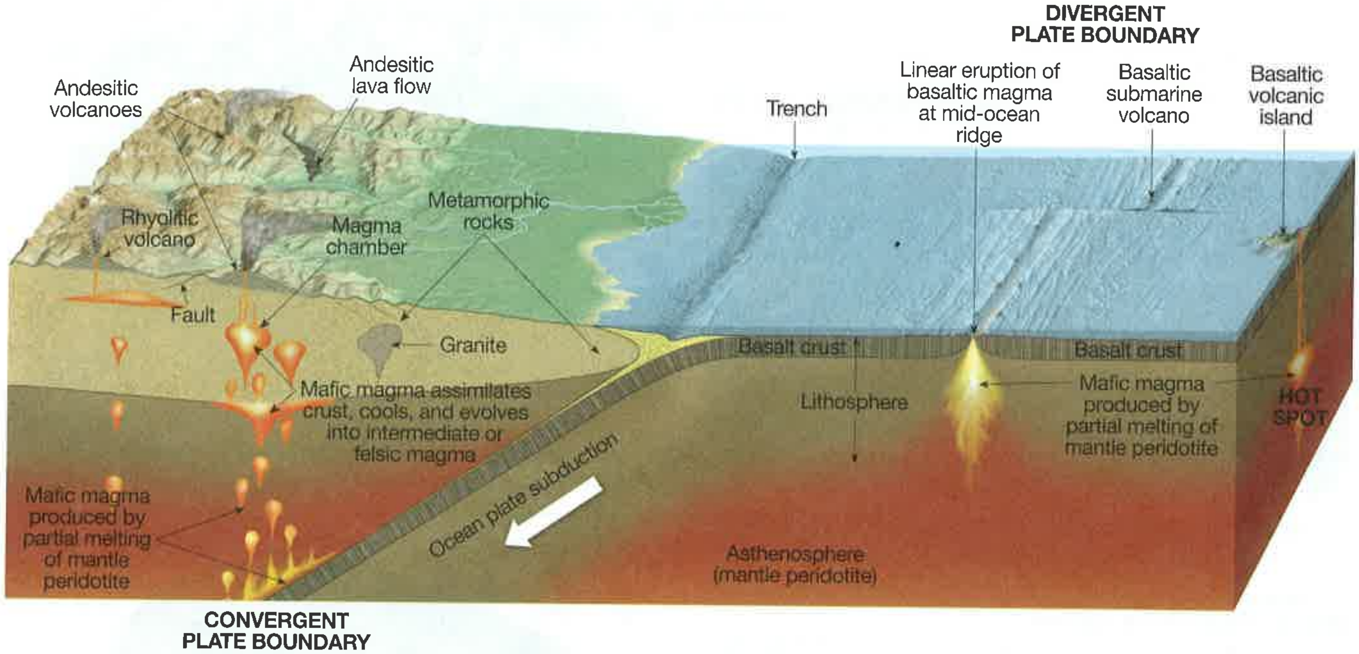


FIGURE 5.7 Tectonic settings where igneous rocks form. Different types of igneous rocks are formed in different geologic settings: a hot spot (such as the Hawaiian Islands), divergent plate boundary (mid-ocean ridge), convergent plate boundary (subduction zone), and Earth's mantle. See text for discussion.

a magma may melt some of the wall rocks surrounding it and assimilate its elements. This is called *assimilation. Magma mixing* may also occur. Bowen's continuous series of crystallization, fractional crystallization, assimilation, and magma mixing are all factors that can contribute to **magmatic differentiation** (any process that causes magma composition to change). Magmatic differentiation produces more than one rock type from a single body of magma.

Plate Tectonics and Igneous Rocks

The four compositional groups of igneous rocks occur in specific tectonic settings (FIGURE 5.7).

Ultramafic Rocks Occur in the Mantle

Ultramafic igneous rocks, like peridotite, are associated with Earth's mantle. They are denser than rocks of the crust, so they are not normally found at Earth's surface. Billions of years ago, when the body of Earth was much hotter and the crust was thinner, ultramafic magmas occasionally erupted to the surface. However, no such eruptions have occurred for more than 60 million years. Xenoliths of peridotite found in some volcanic rocks are thought to have originated in the mantle (FIGURE 5.8).

Mafic Rock at Divergent Plate Boundaries and Ocean Hot Spots

Partial melting of mantle peridotite beneath ocean hot spots and mid-ocean ridges produces mafic magma rather than ultramafic magma (FIGURE 5.7). When the mafic magma cools along the mid-ocean ridges and ocean hot spots (e.g., Hawaiian Islands), it forms gabbro (FIGURE 5.9) and seafloor basalt (FIGURE 5.10).

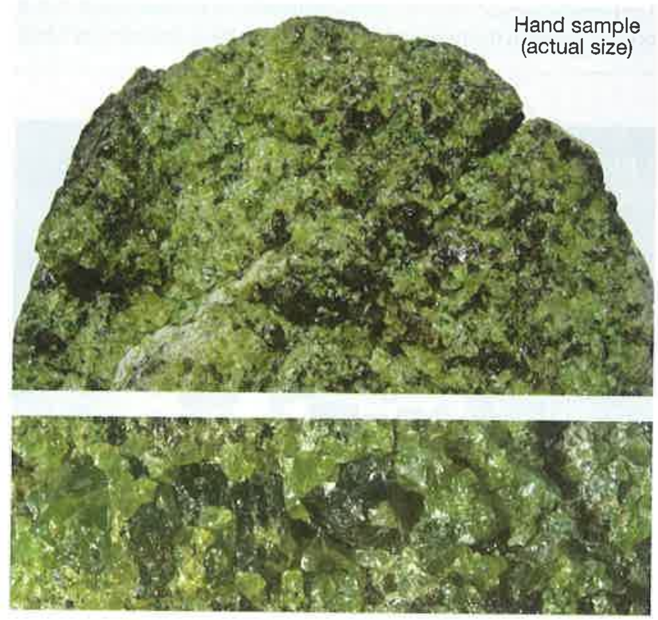


FIGURE 5.8 Peridotite (ultramafic, intrusive, phaneritic). Peridotite—an intrusive, phaneritic igneous rock having a very high MCI (>85%) and mostly made of ferromagnesian mineral crystals. This sample is a peridotite xenolith extracted from a basaltic volcanic rock. It is made mostly of olivine mineral crystals.