NATURAL DISASTERS

Ninth Edition

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VOLCANIC ERUPTIONS: PLATE TECTONICS AND MAGMAS

CHAPTER 6

INTERNAL ENERGY

Lava meets the sea on Hawaii.
Photo from © StockTrek/Getty Images RF.

LEARNING OUTCOMES

Volcanic eruptions can be overwhelming events. Understanding of magma types and plate-tectonic settings explains a lot of volcanic behaviors. After studying this chapter, you should:

- know the plate-tectonic settings of volcanoes.
- understand the variations in magma characteristics that control peaceful versus catastrophic eruptions.
- comprehend the roles of magma gas content and pressure reductions in volcanic eruptions.
- be able to explain the three Vs of volcanism, and relate them to volcanic eruption styles, and to volcanic landforms.
- be familiar with the Volcanic Explosivity Index.
- be able to describe hot spots.

OUTLINE

- How We Understand Volcanic Eruptions
- Plate-Tectonic Setting of Volcanoes
- Chemical Composition of Magmas
- Viscosity, Temperature, and Water Content of Magmas
- How a Volcano Erupts
- The Three Vs of Volcanology: Viscosity, Volatiles, Volume

"The simplest explanation that covers all the facts is the best one."

—*Occam's Razor, attributed to*
William of Occam, c. 1295–1349

Volcanoes deal out overwhelming doses of energy no human can survive. The dangers of volcanic eruption are obvious, but the quiet spells between active volcanism are seductive. Some people are lured to volcanoes like moths to a flame, even those who should know better. On 14 January 1993, volcanologists attending a workshop in Colombia, as part of the international decade of natural disaster reduction, hiked into the summit crater of Galeras Volcano to sample gases and measure gravity. They were looking for ways to predict imminent eruptions. The volcano had been quiet since July 1992, but during their visit, an unexpected, gas-powered secondary eruption killed six in the scientific party—four Colombians, a Russian, and an Englishman. Their deaths were not an unusual event (table 6.1). They serve as a small-scale example of the larger drama played out when a volcano suddenly buries an entire city. During long periods of volcanic quiescence, people tend to build cities near volcanoes. For example, 400,000 people live on the flanks of Galeras Volcano, defying the inevitability of a large, life-snuffing eruption.

An individual volcano may be active for millions of years, but its eruptive phases are commonly separated by centuries of inactivity, lulling some into a false sense of security. Around 410 BCE, Thucydides wrote, "History repeats itself." We know well that those who do not learn the lessons of history are doomed to repeat them. Every year, people inadvertently sacrifice their lives to volcanic eruptions.

How We Understand Volcanic Eruptions

Two primary building blocks of knowledge are paramount to understanding volcanic eruptions:

1. Plate tectonics has given us great insight into earthquakes; now it will help us understand volcanoes.
2. Magmas (liquid rocks) vary in their chemical composition, their ability to flow easily, their gas content, and their volume. These variations govern whether eruptions are peaceful or explosive.

In this chapter we first take a brief look at plate tectonics and volcanism. Then we examine magma variations and how they control eruptive style. Finally, we apply this knowledge globally to understand why volcanoes occur where they do, why only some volcanoes explode violently, and how volcanoes can kill.

Plate-Tectonic Setting of Volcanoes

Convection of heat in the mantle drives plate tectonics. More than 90% of volcanism is associated with the edges of tectonic plates (figure 6.1). Most other volcanism occurs above hot spots (see figure 2.23). More than 80% of Earth's magma extruded through volcanism takes place at the oceanic spreading centers. Solid, but hot and ductile, mantle rock rises upward by convection into regions of lower pressure, where up to 30–40% of the rock can melt and flow easily as magma on the surface (figure 6.2). The worldwide rifting process releases enough magma to create 20 km^3 (about 5 mi^3) of new oceanic crust each year. Virtually all this volcanic activity takes place below sea level and is thus difficult to view.

Subduction zones cause the tall and beautiful volcanic mountains we see at the edges of the continents, but the volume of magma released at subduction zones is small compared to that of spreading centers. Subduction zones account for the eruption of 7–13% of all magma. The down-going plate carries oceanic-plate rock covered with water-saturated sediments into much hotter zones (figure 6.2). The presence of water lowers the melting point of rock. Rising magma partially melts some of the continental crust it passes through. This adds new melt of different composition to rising plumes of magma. Each rising plume has its own unique chemical composition.

TABLE 6.1

Volcanologists Killed by Eruptions

Year	Volcano	Total Deaths	Dead Volcanologists
1951	Kelut, Indonesia	7	3
1952	Myojin-sho, Japan	31	9
1979	Karkar, New Guinea	2	2
1980	St. Helens, United States	62	2
1991	Unzen, Japan	44	3
1991	Lokon-Umpong, Indonesia	1	1
1993	Galeras, Colombia	9	6
1993	Guagua Pichincha, Ecuador	2	2
2000	Semeru, Indonesia	2	2

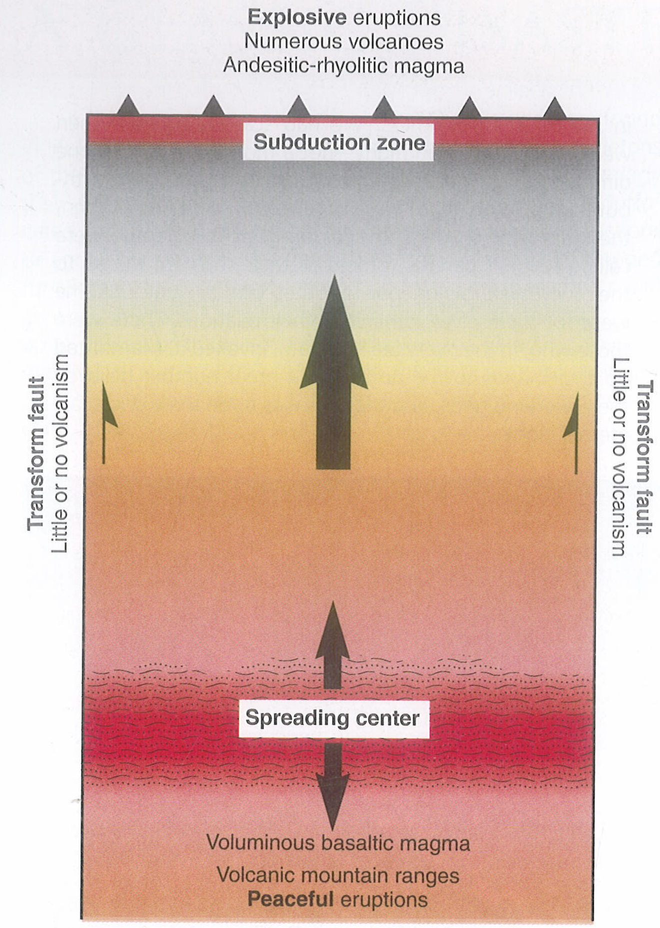


FIGURE 6.1 An idealized oceanic plate showing styles of volcanism.

Transform faults and continent-continent collision zones have little or no associated volcanism. Thinking three-dimensionally, this is understandable. At a transform fault, the two plates simply slide past each other in a horizontal sense and at all times keep a quite effective "lid" on the hot asthenosphere some 100 km (60 mi) below. At continent-continent collisions, the continental rocks stack up into extra-thick masses that deeply bury the hot mantle rock, making it difficult for magma to rise to the surface.

From a volcanic disaster perspective, the differences are clear. Oceanic volcanoes are relatively peaceful, whereas subduction-zone volcanoes are explosive and dangerous. Ironically, humans tend to congregate at the seaward edges of the continents, where the most dangerous volcanoes operate.

People commonly speculate upon whether an individual volcano is active, dormant, or extinct. Because of the strong hope that a volcano is extinct and the nearby land is thus available for use, many dormant volcanoes are misclassified. But consider this: a subduction zone commonly lasts for tens of millions of years, and its province of volcanoes is active for the entire time. An individual volcano may be active for hundreds of thousands to several million years, despite "slumbers" of centuries between eruptions. As a general rule, if a volcano has a well-formed and aesthetic conical shape, it is active. A pretty shape is dangerous.

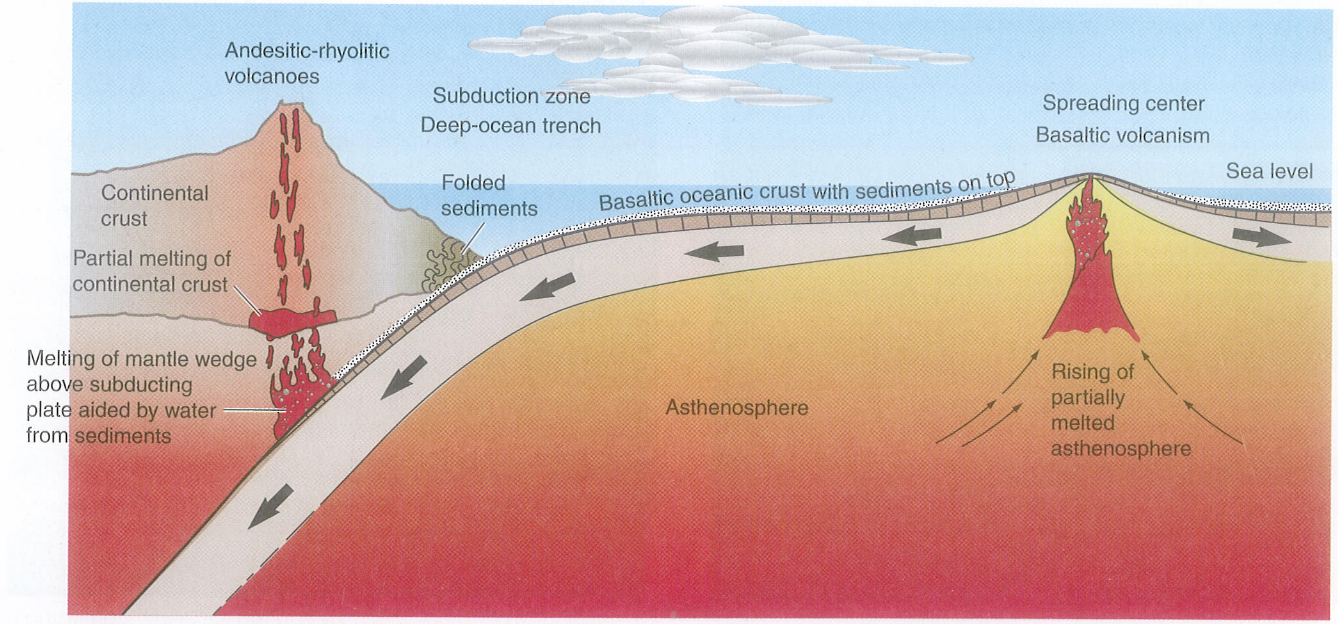


FIGURE 6.2 Idealized cross-section showing production of basaltic magma at spreading centers. Plates pull apart, and some asthenosphere liquefies and rises to fill the gap. Andesitic-rhyolitic magmas are created above subduction zones, where rising magma partially melts the continental crust on its way up, thus altering the melt by increasing SiO_2 content and viscosity.

A Classic Disaster

Eruption of Mount Vesuvius, 79 CE

The most famous of all volcanoes is probably Vesuvius in Italy, and the most famous of all its eruptions must be those of 79 CE. It was then that the cities of Pompeii and Herculaneum were buried and forgotten for more than 1,500 years. A warning of the natural hazards near Vesuvius arrived on 5 February 62 CE, when a major earthquake destroyed much of Pompeii and caused serious damage in Herculaneum and Neapolis (Naples). Additional earthquakes, although not as large as this first one, were a common occurrence for the next 17 years.

Pompeii had been a center of commerce for centuries. In 79 CE, the city had a population of about 20,000 people, 8,000 of whom were slaves. Robert Etienne described it as:

> An average city inhabited by average people, Pompeii would have achieved a comfortable mediocrity and passed peacefully into the silence of history, had the sudden catastrophe of the volcanic eruption not wiped it from the world of the living.

The 24th of August 79 CE was a warm summer day, but then Vesuvius began erupting and the day became even hotter. Vesuvius blew out 4 km^3 (1 mi^3) of volcanic material. About half of the old volcanic cone was destroyed. A modern example of a similar eruption occurred in 1991 at Mount Pinatubo in the Philippines (figure 6.3). In Pompeii, great clouds of hot gas and volcanic ash flowed across the city, killing the people who had not fled (figure 6.4). Today, the excavated city is a major attraction for tourists (figure 6.5).

In 79 CE, the fine volcanic ashes settling out from the great heights of the eruption cloud affected a large region. Pliny the Younger was at Misenum and wrote:

> And now came the ashes, but at first sparsely. I turned around. Behind us, an ominous thick smoke, spreading over the earth like a flood, followed us. "Let's go into the fields while we can still see the way," I told my mother—for I was afraid that we might be crushed by the mob on the road in the midst of darkness. We had scarcely agreed when we were enveloped in night—not a moonless night or one dimmed by cloud, but the darkness of a sealed room without lights. To be heard were only the shrill cries of women, the wailing of children, the shouting of men. Some were calling to their parents, others to their children, others to their wives—knowing one another only by voice. Some wept for themselves, others for their relations. There were those who, in their very fear of death, invoked it. Many lifted up their hands to the gods, but a great number believed there were no gods, and that this was to be the world's last eternal night.

FIGURE 6.3 The first big explosive blast from Mount Pinatubo occurred on 15 June 1991.
Photo by R. S. Culbreth, *US Geological Survey*.

FIGURE 6.4 Body cast of a man killed by a flow of hot gas and volcanic ash from Vesuvius in late August in the year 79 CE.

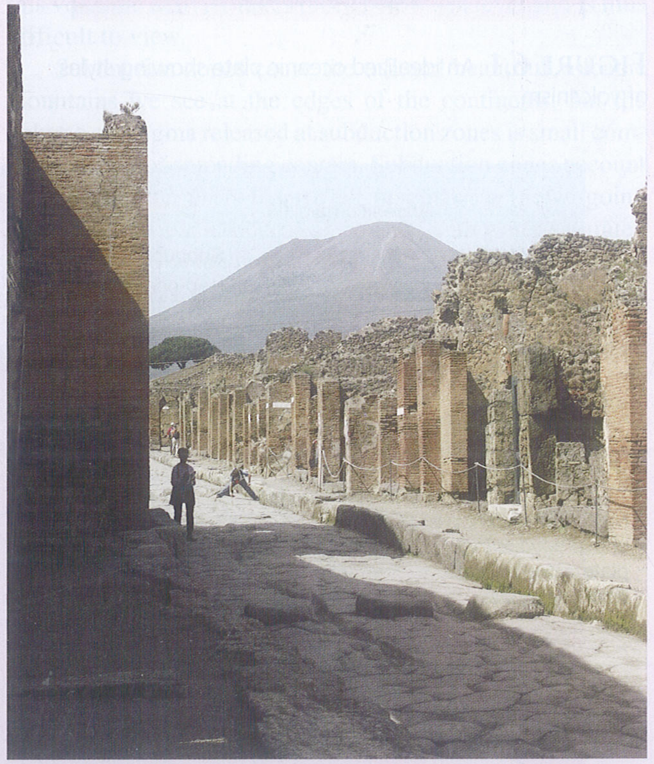


FIGURE 6.5 Tourists walk through the heart of Pompeii away from Vesuvius, the volcano that destroyed the city in 79 CE.
Photo by Pat Abbott.

A Classic Disaster

In the coastal city of Herculaneum, 300 skeletons were found in lifelike positions in boat chambers at the beach. The skeletons of these people killed by the eruption testify to the lethal energy they experienced. The people had not been battered or suffocated; they did not display any voluntary self-protection reactions or agony contortions. In other words, their vital organs stopped functioning in less than a second, in less time than they could consciously react. The types of bone fractures, tooth cracks, and bone coloration indicate the victims were covered by volcanic material at about 500°C (930°F). At this temperature, their soft tissues vaporized; their feet flexed in an instantaneous muscle contraction (figure 6.6).

FIGURE 6.6 Feet of a child killed by an eruption from Vesuvius in 79 CE. The flexed toes and feet were an involuntary contraction when surrounded by 500°C (930°F) volcanic material. Death was instantaneous.
Photo from Mastrolorenzo, G., Petrone, P., Pagano, M., Incoronato, A., Baxter, P., Canzanella, A., Fattore, L., in *Nature* 410:769, 2001.

The timing of the major eruptions of Vesuvius offers an interesting lesson. Apparently Vesuvius did not have a major eruption from the 7th century BCE until 79 CE. People had at least 700 years to lose their fears and yield to the allure of the rich agricultural soils on Vesuvius. After 79 CE, large eruptions occurred more often: in the years 203, 472 (ash blown over much of Europe), 512, 685, 993, 1036 (first lava flows in historic time), 1049, and 1138–1139. Then nearly 500 years passed—plenty of time to forget the past and recolonize the mountain. But in 1631, Vesuvius poured out large volumes of lava that destroyed six towns; mudflows ruined another nine towns, and about 4,000 people perished. The two long periods of volcanic quiescence in the last 2,700 years seem like long times to short-living, land-hungry humans, but this is the time schedule of an active volcano. Humans' lack of appreciation for the time involved between eruptions leads them to falsely regard many active volcanoes as extinct.

Since 1631, the eruptions from Vesuvius have been smaller and not as dangerous. There were 18 eruption cycles between 1631 and 1944; each lasted from 2 to 37 years, with quiet intervals ranging from 0.5 to 6.8 years. Since 1944, Vesuvius has been quiet. Is this interval of calm setting the stage for another major eruption? We do not know for sure, but almost 3 million people live within reach of Vesuvius today, including about 1 million on the slopes of the volcano (figure 6.7).

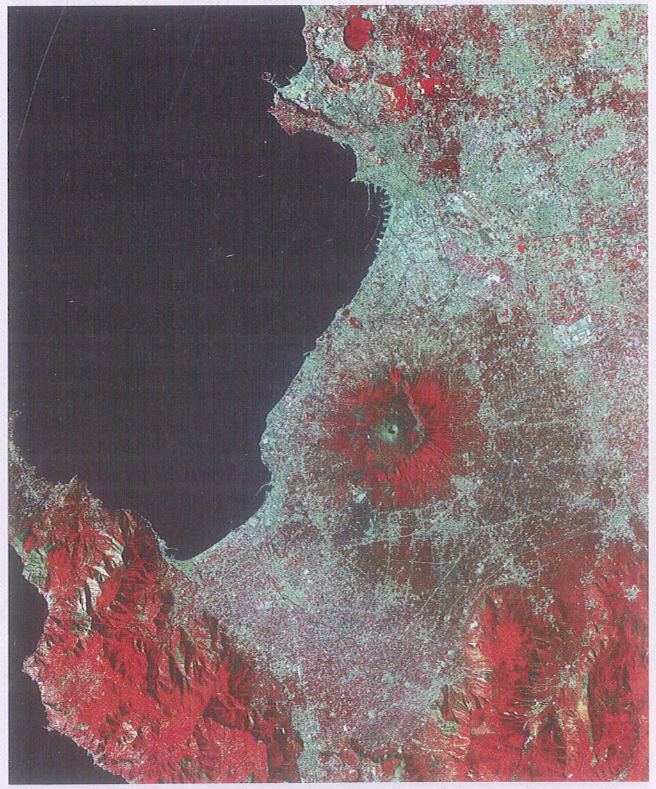


FIGURE 6.7 Mount Vesuvius, near center of photo, is surrounded by the urbanized Naples region housing 3 million people.
Photo from NASA.

Why do spreading-center volcanoes have relatively peaceful eruptions? And why do subduction-zone volcanoes explode violently? The answers to these questions are found in knowing how different magmas behave.

CHEMICAL COMPOSITION OF MAGMAS

Although there are 92 naturally occurring elements, a mere eight make up more than 98% of the Earth's crust (table 6.2). The next four most abundant elements add another 1.2% to the crust, bringing the weight percent contributed by these 12 elements to 99.23%. The remaining 0.77% includes gold, silver, copper, carbon, sulfur, tin, and many other familiar elements.

Oxygen and silicon are so abundant that their percentages dwarf those of all other elements. Oxygen atoms carry negative charges (–2), while silicon atoms are positively charged (+4). As magma begins cooling, some silicon and oxygen atoms bond. Silicon and oxygen link up with four oxygen atoms ($4 \times -2 = -8$) surrounding a central silicon atom (+4) to form the silicon-oxygen tetrahedron (SiO_4) (figure 6.8). The SiO_4 tetrahedron presents a –4 charge on its exterior that attracts and ties up positively charged atoms. After negatively charged oxygen, the 11 elements of greatest abundance are all positively charged (table 6.2); they are attracted to, and bound up by, oxygen. This process is so common that elemental abundances in the crust are usually listed in combination with oxygen (as oxides). The weight percentages of elements are quite different for continental versus oceanic crust (table 6.3). Marked differences in silicon dioxide percentages produce magmas of variable eruptive behavior.

TABLE 6.2
Common Elements of the Earth's Crust (weight %)

Eight Most Common	
Oxygen (O^{-2})	45.20%
Silicon (Si^{+4})	27.20
Aluminum (Al^{+3})	8.00
Iron ($Fe^{+2,+3}$)	5.80
Calcium (Ca^{+2})	5.06
Magnesium (Mg^{+2})	2.77
Sodium (Na^{+1})	2.32
Potassium (K^{+1})	1.68
Total	98.03%
Next Four Most Common	
Titanium ($Ti^{+3,+4}$)	0.86%
Hydrogen (H^{+1})	0.14
Phosphorus (P^{+5})	0.10
Manganese ($Mn^{+2,+3,+4}$)	0.10
Total	99.23%

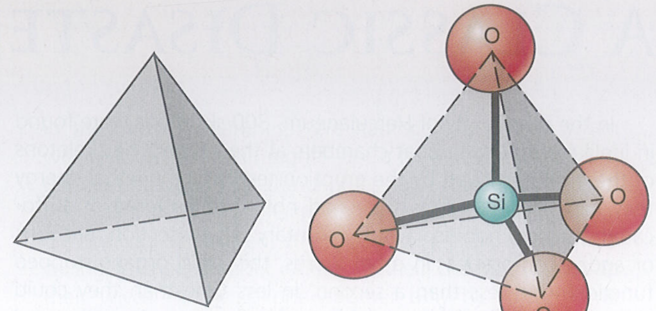


FIGURE 6.8 A silicon atom with +4 charge is linked to four oxygen atoms, each with a –2 charge.

TABLE 6.3
Crustal Elements in Weight-Percent Oxides

Continental Crust		Oceanic Crust	
SiO_2	60.2%	SiO_2	48.7%
Al_2O_3	15.2	Al_2O_3	16.5
Fe_2O_3	2.5	Fe_2O_3	2.3
FeO	3.8	FeO	6.2
CaO	5.5	CaO	12.3
MgO	3.1	MgO	6.8
Na_2O	3.0	Na_2O	2.6
K_2O	2.9	K_2O	0.4

VISCOSITY, TEMPERATURE, AND WATER CONTENT OF MAGMAS

Liquids flow freely; their volumes are fixed, but their shapes can change. Liquids vary in how they flow; some flow quickly, some flow slowly, and some barely flow at all. The fluidity of a liquid is measured by its **viscosity,** its internal resistance to flow; viscosity may be thought of as a measure of fluid friction. The lower the viscosity, the more fluid is the behavior. For example, tilt a glass of water and watch it flow quickly; water has low viscosity. Now tilt the same glass filled with honey and watch the slower flow; honey has higher viscosity. Low-viscosity magma flows somewhat like ice cream on a hot day. High-viscosity magma barely flows.

IN GREATER DEPTH

MINERALS AND VOLCANIC ROCKS

The eight most common elements bond in different configurations to make up hundreds of different **minerals.** The process of mineral formation in a cooling magma is called **crystallization.** Just as with elements, a degree of simplicity occurs in a crystallizing magma because the overwhelming majority of Earth's crust is composed of just eight common rock-forming minerals. Laboratory experiments and microscopic examination of rock-forming minerals have shown the order in which these minerals crystallize from a cooling magma (figure 6.9).

Magmas at the surface with temperatures of around 800° to 1,300°C (1,470° to 2,370°F) have two separate lines of mineral growth:

1. Iron and magnesium link up with the silicon-oxygen tetrahedron as magma temperature decreases to sequentially form four distinct and discontinuous families of minerals—olivine, pyroxene, amphibole, and biotite mica.
2. Calcium combines with Al and SiO_4 to begin forming the plagioclase feldspar family, a continuous and gradational series of minerals. As temperature decreases, progressively more sodium (and less calcium) is locked within the plagioclase crystal structure. By the time magma has cooled down to the 800° to 1,000°C (1,470° to 1,830°F) range, it is largely depleted in Fe, Mg, and Ca. Now potassium crystallizes within muscovite mica and potassium-rich feldspar minerals, and excess Si and O combine without other elements to make the mineral quartz.

TABLE 6.4
Igneous Rock Types

Magma Type	Plutonic Rock	Volcanic Rock
$SiO_2 < 55\%$	Gabbro	**Basalt**
$SiO_2 = 55–65\%$	Diorite	**Andesite**
$SiO_2 > 65\%$	Granite	**Rhyolite**

Just as elements combine to make minerals, so minerals aggregate to make **rocks** (see page 5). Magmas have a broad range of compositions, resulting in many different types of igneous rocks that generations of geologists have classified into a dizzying array of rock names. Nonetheless, a working understanding can be gained by considering only three magma types and the three clans of igneous rocks that form from them. The rock types are based on their silicon and oxygen (SiO2) percentages (table 6.4). If the magma cools and solidifies below the surface, it crystallizes as **plutonic rock,** named for Pluto, the Roman god of the underworld. If the magma reaches the surface, it forms **volcanic rock,** named for Vulcan, the Roman god of fire. The left side of figure 6.9 shows three main types of volcanic rock next to their respective mineral compositions. Table 6.4 tells more about the rocks, and figure 6.10 shows pictures of the rocks. Their magmas behave differently due to their varying temperatures, water contents, and viscosities.

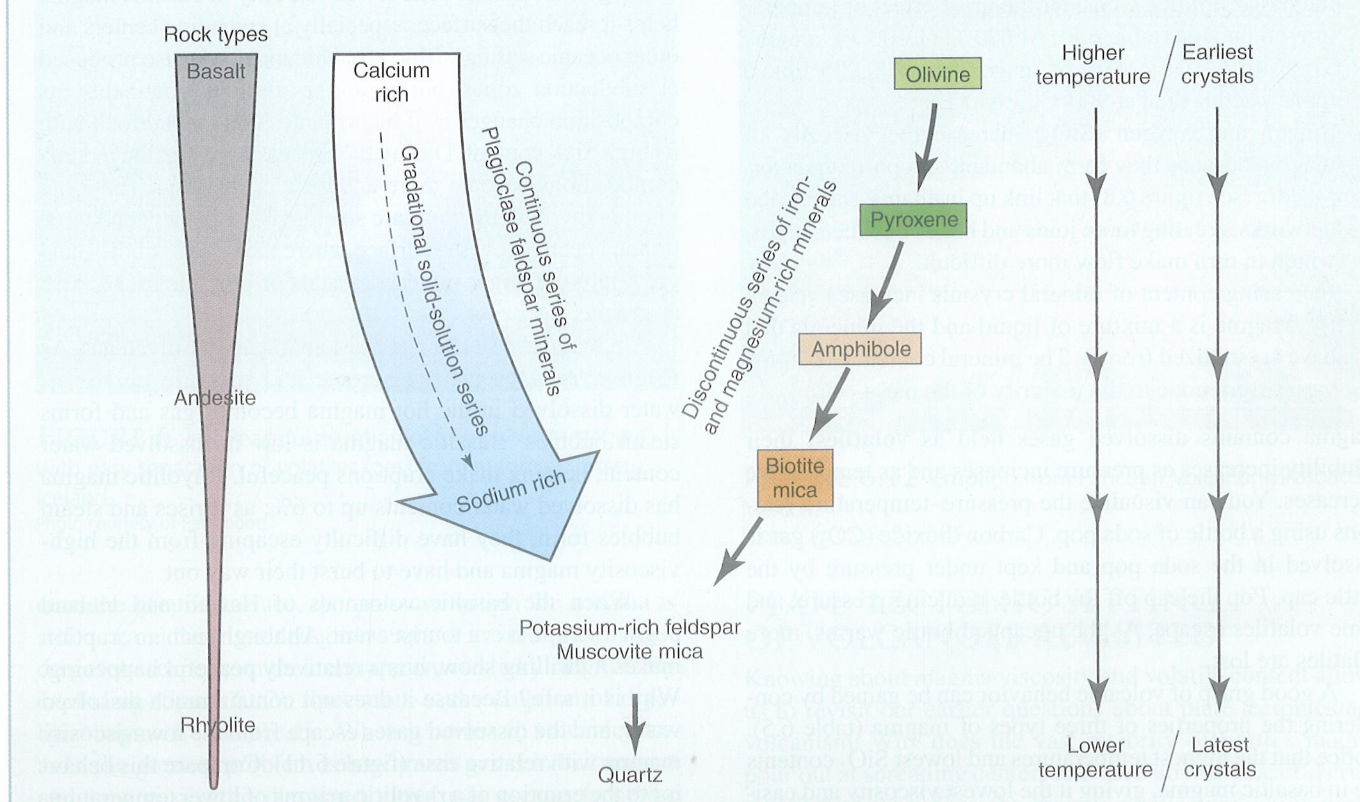
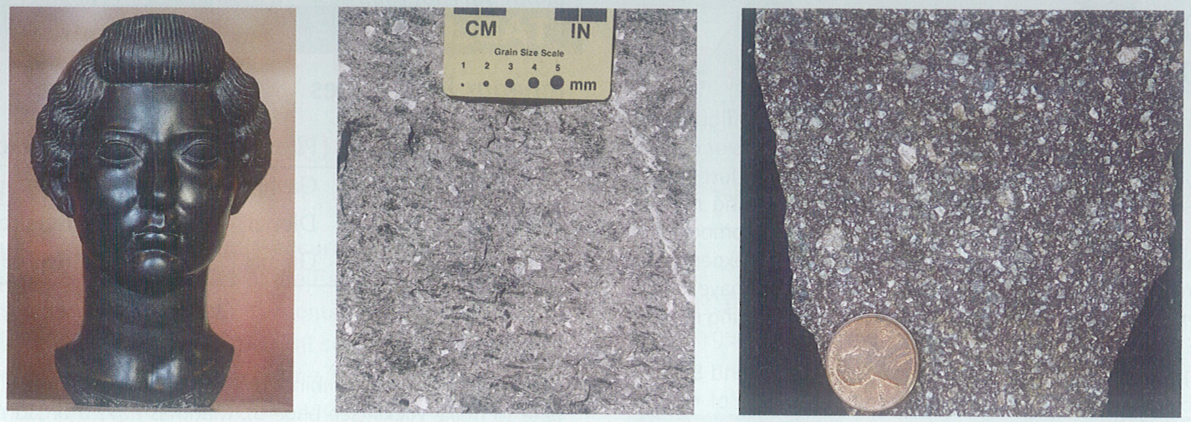


FIGURE 6.9 Order of crystallization of minerals from a magma cooling at depth.

In Greater Depth (Continued)



(a) (b) (c)

FIGURE 6.10 Volcanic rock types. (a) Basalt is dark-colored and finely crystalline. Bust of Livia Drusilla, wife of Augustus Caesar, ~31 BCE. 32 cm tall, Louvre Museum, Paris. (b) Andesite is medium-colored volcanic rock with plagioclase feldspar minerals and, in this sample, fragments of other volcanic rocks. Santiago Peak Volcanics, San Diego. (c) This sample of rhyolite contains quartz and feldspar minerals in great abundance. Poway, California.
Photos (b) and (c) by Pat Abbott.

The viscosity of magma is changed by various means:

1. Higher temperature lowers viscosity; it causes atoms to spread farther apart and vibrate more vigorously. Thus atomic bonds break and deform more, resulting in increased fluidity. Consider the great effect of temperature on magma (table 6.5). At 600°C (1,100°F), magma viscosity is five orders of magnitude (100,000 times) more viscous than at 900°C (1,650°F).
2. Silicon and oxygen (SiO_2) increase the viscosity of magma because they form abundant silicon-oxygen tetrahedra (see figure 6.8) that link up in chains, sheets, and networks, creating more joins and bonds between atoms, which in turn make flow more difficult.
3. Increasing content of mineral crystals increases viscosity. Magma is a mixture of liquid and the minerals that have crystallized from it. The mineral content of magma varies from none to the majority of the mass.

Magma contains dissolved gases held as **volatiles;** their solubility increases as pressure increases and as temperature decreases. You can visualize the pressure–temperature relations using a bottle of soda pop. Carbon dioxide (CO_2) gas is dissolved in the soda pop and kept under pressure by the bottle cap. Pop the cap off the bottle, reducing pressure, and some volatiles escape. As the uncapped bottle warms, more volatiles are lost.

A good grasp of volcanic behavior can be gained by considering the properties of three types of magma (table 6.5). Notice that the highest temperatures and lowest SiO_2 contents are in basaltic magma, giving it the lowest viscosity and easiest fluid flow. The lowest temperatures and highest SiO_2 contents occur in rhyolitic magma, material so viscous that it commonly does not flow. Table 6.5 also states that about 80% of the magma reaching Earth's surface is basaltic, with only about 10% andesitic and 10% rhyolitic. Why the difference? Basaltic magma is produced in great abundance by partial melting of the mantle. The lower viscosity of basaltic magma helps it reach the surface, especially at spreading centers and other oceanic settings. Much basaltic magma is also produced at subduction zones, but as it rises through continents, its composition changes as it incorporates continental rock with its high SiO_2 content. During the process of rising, the magma compositions become more andesitic or rhyolitic. The more viscous rhyolitic magmas are so sluggish that they tend to be trapped deep below the surface where they cool, solidify, and grow into the larger mineral crystals of plutonic rocks, such as granite.

In magma, water is the most abundant dissolved gas. As magma rises toward the surface and pressure decreases, water dissolved in the hot magma becomes gas and forms steam bubbles. Basaltic magma is low in dissolved water content, helping make eruptions peaceful. Rhyolitic magma has dissolved water contents up to 6%; as it rises and steam bubbles form, they have difficulty escaping from the high-viscosity magma and have to burst their way out.

When the basaltic volcanoes of Hawaii and Iceland begin to erupt, it is a tourist event. Although such an eruption makes a thrilling show, it is a relatively peaceful happening. Why is it safe? Because it does not contain much dissolved water, and the dissolved gases escape from the low-viscosity magma with relative ease (figure 6.11). Compare this behavior to the eruption of a rhyolitic magma of lower temperature, greater dissolved water content, higher percentage of SiO_2, and very high viscosity. When rhyolitic magma oozes out onto the ground surface, the pressure within the magma is reduced and the dissolved gases expand in volume. But how do gases escape from their entrapment in sticky magma? By exploding (figure 6.12). Spectators at the eruption of rhyolitic magma frequently die. When it comes to volcanic hazards, the greatest problem is how much gas is in the magma and how easily the dissolved gases can escape from the magma. As Frank Perret stated: "Gas is the active agent, and magma is its vehicle."

TABLE 6.5

Comparison of Three Types of Magma

	Basaltic	Andesitic	Rhyolitic
Volume at Earth's Surface	80%	10%	10%
SiO_2 Content	45–55%	55–65%	65–75%
	Increasing SiO_2 →		
Temperature of Magma	1,000–1,300°C	800–1,000°C	600–900°C
	Decreasing temperature →		
Viscosity	Low (melted ice cream)		High (toothpaste)
	Increasing viscosity →		
Water Dissolved in Magma	~0.1–1 weight %	~2–3 weight %	~4–6 weight %
	Increasing water →		
Gas Escape from Magma	Easy		Difficult
	Increasing difficulty →		
Eruptive Style	Peaceful		Explosive
	Increasing explosiveness →		
Rock Description	Black to dark gray; contains Ca-plagioclase, pyroxene, olivine	Medium to dark gray; contains amphibole, pyroxene, intermediate Ca-Na-plagioclase	Light-colored; contains quartz, K-feldspar, biotite, Na-plagioclase

FIGURE 6.11 Peaceful eruption of low-viscosity magma with easy separation of volatiles (gas) from magma, Surtsey, Iceland.
Photo courtesy of Pat Abbott.

FIGURE 6.12 Eruption from Paricutin Volcano, Michoacan, Mexico.
Photo from *US Geological Survey*.

PLATE-TECTONIC SETTING OF VOLCANOES REVISITED

Knowing about magma viscosity and volatile content allows us to revisit our earlier questions about plate tectonics and volcanism. Why does the vast majority of Earth's magma pour out at spreading centers and in relatively peaceful eruptions? And why does the magma above subduction zones commonly explode violently? Spreading centers operate in oceanic crust, and subducting plates commonly are pulled beneath continental crust. The chemistries of oceanic crust and continental crust are different (see table 6.3), their magmas are different (see table 6.5), and their volcanic behaviors differ.

Spreading centers are ideal locations for volcanism because (1) they sit above the high-temperature asthenosphere, (2) the asthenosphere rock has low percentages of SiO_2, and (3) the oceanic plates pull apart, causing hot asthenosphere rock to rise, experience lower pressure, and change to magma that continues to rise. This magma is high-temperature, low SiO_2, low-volatile content, low-viscosity basalt, allowing easy escape of gases (see figure 6.2). Spreading centers combine all the factors that promote the peaceful eruption of magma.

When a subducting oceanic plate reaches a depth of about 100 km (over 60 mi), magma is generated and rises toward the surface (see figure 6.2). The subducting plate stirs up the mantle, causing the hotter rock at depth to rise and then melt as pressure decreases. A significant reason magma forms here is that the subducting plate carries a cover of sediments, water, and hydrated minerals down with it. Water, even in slight amounts, promotes partial melting by lowering the temperature necessary for rock to melt. The partial melting process affects only those minerals with lower melting temperatures. As this partial melt rises upward, it in turn melts part of the overlying crust to produce magmas of highly variable compositions (figure 6.13). Magma compositions depend on the amount of crustal rock melted and incorporated into the rising magma. In general, in the subduction-zone setting, magma temperature decreases while SiO_2, water content, and viscosity increase. All these changes in magma add to its explosive potential.

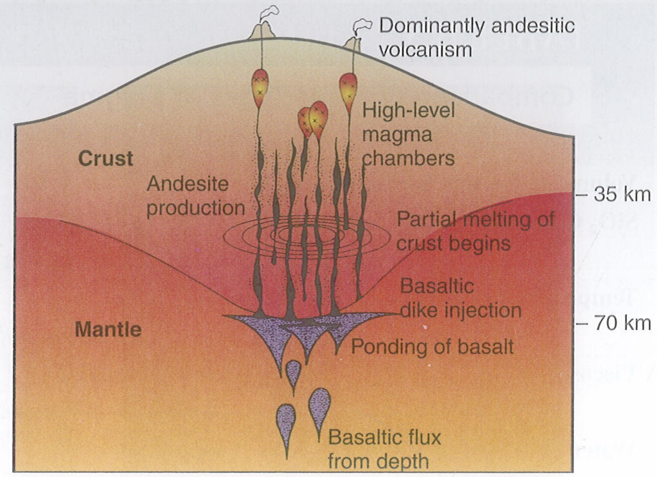


FIGURE 6.13 Schematic cross-section of magma rising from a subduction zone and being contaminated by crustal rocks en route.

HOW A VOLCANO ERUPTS

Earth's internal energy flows outward as heat (see chapter 2). The eruptions of volcanoes are rapid means for Earth to expel some of its internal heat.

A volcanic eruption begins with heat at depth. Superheated rock will rise to levels with lower pressure, and some solid rock may change phase to liquid magma, resulting in volume expansion and leading step-by-step to eruption.

Magma is generated by the melting of existing rock. Rock may melt by (1) lowering the pressure on it, (2) raising its temperature, or (3) increasing its water content. How do most rocks melt? The two most relevant melting agents are reductions in pressure (decompression) and increases in volatile content (mostly water).

Most magma is generated by decreasing the pressure on hot rock. For example, as the solid, but mobile, hot rock of the mantle rises upward, it experiences progressively less pressure and spontaneously melts, without the addition of more heat. Melting caused simply by a decrease in pressure is called **decompression melting.** The process of decompression melting is so important that it is worth restating: most of the rock that melts to form magma does so because the pressure on it decreases, not because more heat is added.

The largest nearby reservoir of superhot, ready-to-melt rock exists in the nearly molten asthenosphere. This rock, hot enough to flow without being liquid, is the main source of magma. As this superheated rock rises, the pressure on it decreases, allowing some rock to melt. The hot, rising rock-magma mixture also raises the temperature of rock it passes through, thus melting portions of the overlying rocks.

If pressure in the asthenosphere or lithosphere is decreased, some rock melts, with a resultant increase in volume that causes overlying rocks to fracture. The fractures allow more material to rise to lower pressure levels, causing more rock to liquefy. For example, at a depth of 32 km (20 mi), basaltic rock melts at 1,430°C (2,600°F), but this same rock will melt at only 1,250°C (2,280°F) at the Earth's surface. Since upward-moving rock/magma reaches ever-lower pressures, rising rock can liquefy and magma can increase in fluidity, which in turn causes more superheated rock to become magma.

Magma at depth does not contain gas bubbles because the high pressure at depth keeps volatiles dissolved in solution. But as magma rises toward the surface, pressure continually decreases, and gases begin to come out of solution, forming bubbles that expand with decreasing pressure (figure 6.14). The added lift of the growing volume of gas bubbles helps propel magma upward through fractures or pipes toward an eruption. Gas bubbles continue increasing in number and volume as magma keeps rising upward to lower pressures. As gas-bubble volume increases, the gas can overwhelm magma, fragmenting the magma into pieces that are carried up and out by a powerful gas jet (figure 6.15). Upon escape from the volcano, the gas jet draws in air, which adds to buoyancy in the turbulent, rising plume (see figure 6.14).

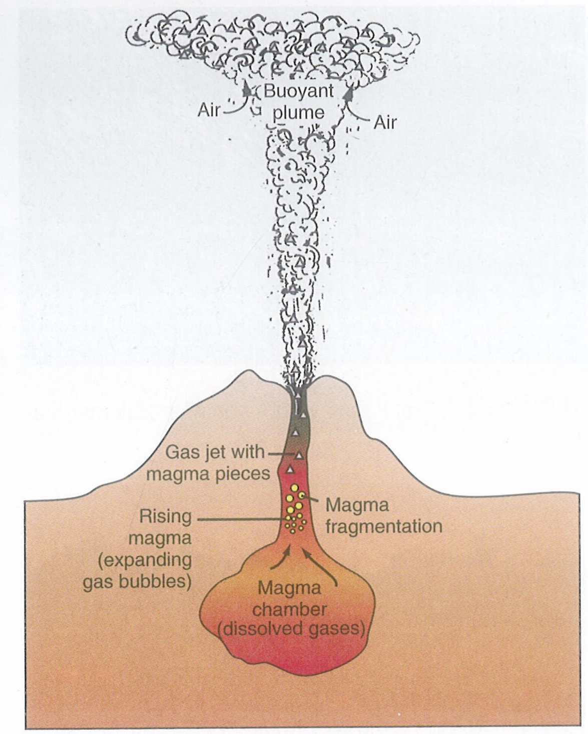


FIGURE 6.14 Anatomy of an eruption. As magma rises to levels of lower pressure, gas comes out of solution, forming bubbles that overwhelm the magma and create a gas jet leading to a buoyant plume.

FIGURE 6.15 Remarkable view into the crater of Mount Pinatubo just as a major explosive eruption was beginning its upward blast, 1 August 1991.
Photo from NOAA.

ERUPTION STYLES AND THE ROLE OF WATER CONTENT

Whether a volcanic eruption is peaceful or explosive depends significantly on the concentration of water in the magma. For example, if all magmas contained low concentrations of water (such as 0.3 weight %; see table 6.5), there would be no highly explosive eruptions. Even a high-viscosity rhyolite magma with a low concentration of water only leads to slow flows or no flow as the magma oozes upward and builds a dome.

The most important requirement for explosive eruptions is high concentrations of volatiles (mainly water). Volatiles drive explosive eruptions. Given a high concentration of water, even a basalt magma can erupt violently, as occurred at Hawaii in 1790. Rhyolitic magma is often associated with explosive eruptions because of its high content of water (see table 6.5). Water concentration in magma plays a controlling role, and viscosity plays a secondary role, in determining the peaceful versus explosive style of eruption.

Different volcanic behaviors have been classified according to the eruptive style of individual volcanoes (figure 6.16).

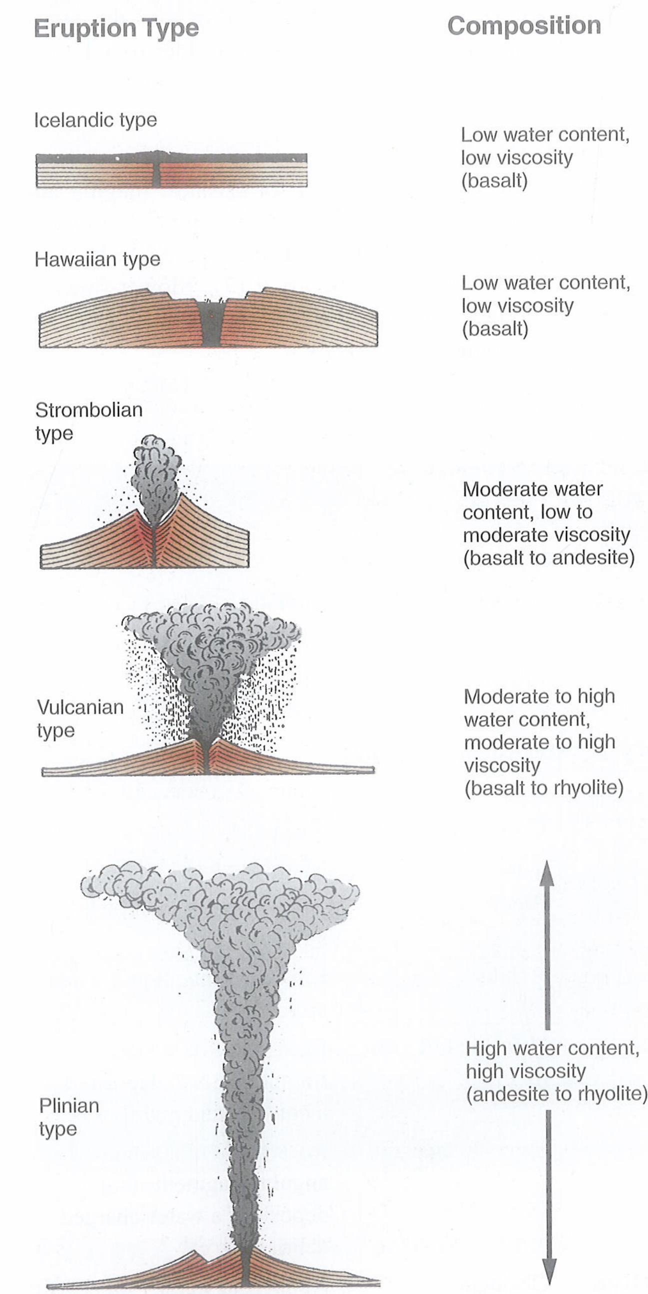


FIGURE 6.16 Some types of volcanic eruptions.

Nonexplosive eruptions are commonly subdivided into *Icelandic* and *Hawaiian* types. *Strombolian* types are somewhat explosive. Explosive eruptions can be described as *Vulcanian* or *Plinian* types. These classifications are just for general purposes; each volcano varies in its eruptive behavior over time.

SOME VOLCANIC MATERIALS

Magmas vary in their dissolved-gas (volatile) content and viscosity. Low-water-content, low-viscosity magma that reaches the surface typically moves as lava flows, with easy gas escape yielding nonexplosive eruptions. High-water-content, high-viscosity magma holds its volatiles, making gas escape difficult. Gas is forced to burst out of the magma, yielding explosive eruptions. Gas blasting into the atmosphere takes along chunks of magma and older rock known as **pyroclastic** debris (*pyro* = fire; *clastic* = fragments).

Nonexplosive Eruptions

Lava flows are especially typical of basaltic magma and exhibit a variety of textures (table 6.6). Highly liquid lava may cool with a smooth, ropy surface called **pahoehoe,** (pronounced pa-Hoy-Hoy) (figure 6.17). Slower-flowing, more viscous lava commonly has a rough, blocky texture called **aa** (pronounced ah-ah) (figure 6.18).

TABLE 6.6

Volcanic Materials

Lava	Pahoehoe	Smooth, ropy surface
	Aa	Rough, blocky surface
	Pillow	Ellipsoidal masses formed in water
Pyroclastic Air-fall Fragments		
	Fine ash (dust)	Flour-size material
	Coarse ash	Sand size
	Cinders	Marble to baseball size
	Blocks	Big fragments, solid while airborne
	Bombs	Big fragments, liquid while airborne
	Volcanic tuff	Rock made of smaller fragments (e.g., deposit of a hot, gas-charged flow)
	Volcanic breccia	Rock made of coarse, angular fragments (e.g., deposit of a water-charged debris flow)
Glass	Obsidian	Nonporous glass
	Pumice	Porous glass (froth)

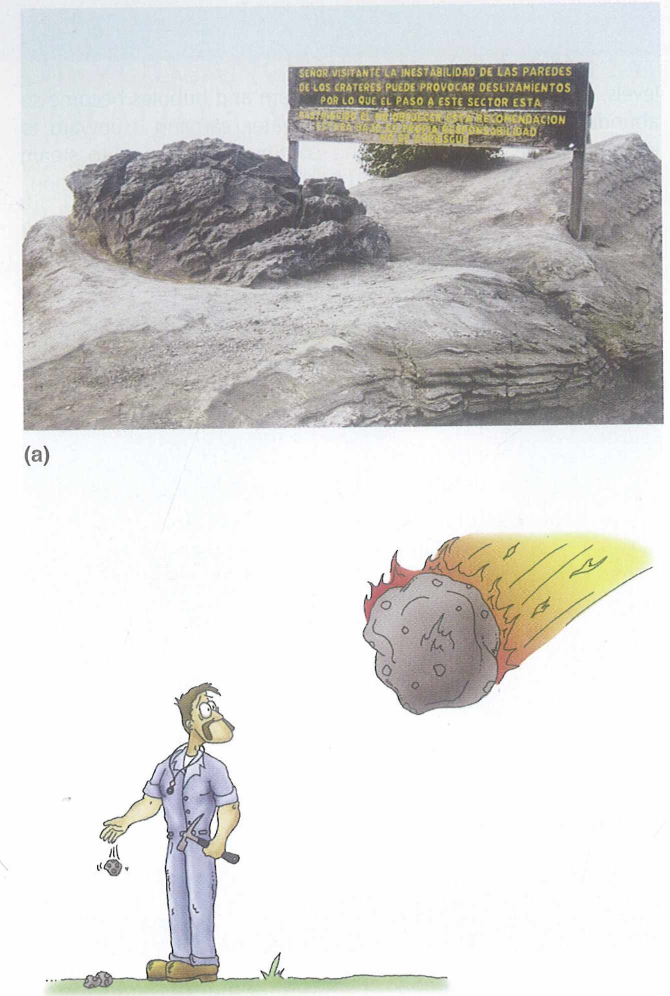
FIGURE 6.17 Small-scale *pahoehoe* near Halemaumau, Hawaii.
Photo by Pat Abbott.

FIGURE 6.18 *Aa* flow in Hawaii.
Photo by Pat Abbott.

Explosive Eruptions

Gaseous explosions break rock and tear apart magma and older rock into pyroclastic debris with a wide range of sizes, from dust to huge blocks and bombs (table 6.6; figure 6.19). Airborne pyroclasts have their coarsest grains fall from the atmosphere first, closest to the volcano, followed by progressively finer material at greater distances away (figure 6.20). An air-fall deposit can be recognized by the sorting of pyroclasts into layers of different sizes. Pyroclastic debris also can be blasted out over the ground surface as high-speed, gas-charged flows that dump material quickly, producing indistinct layering and little or no sorting of the various-size particles.

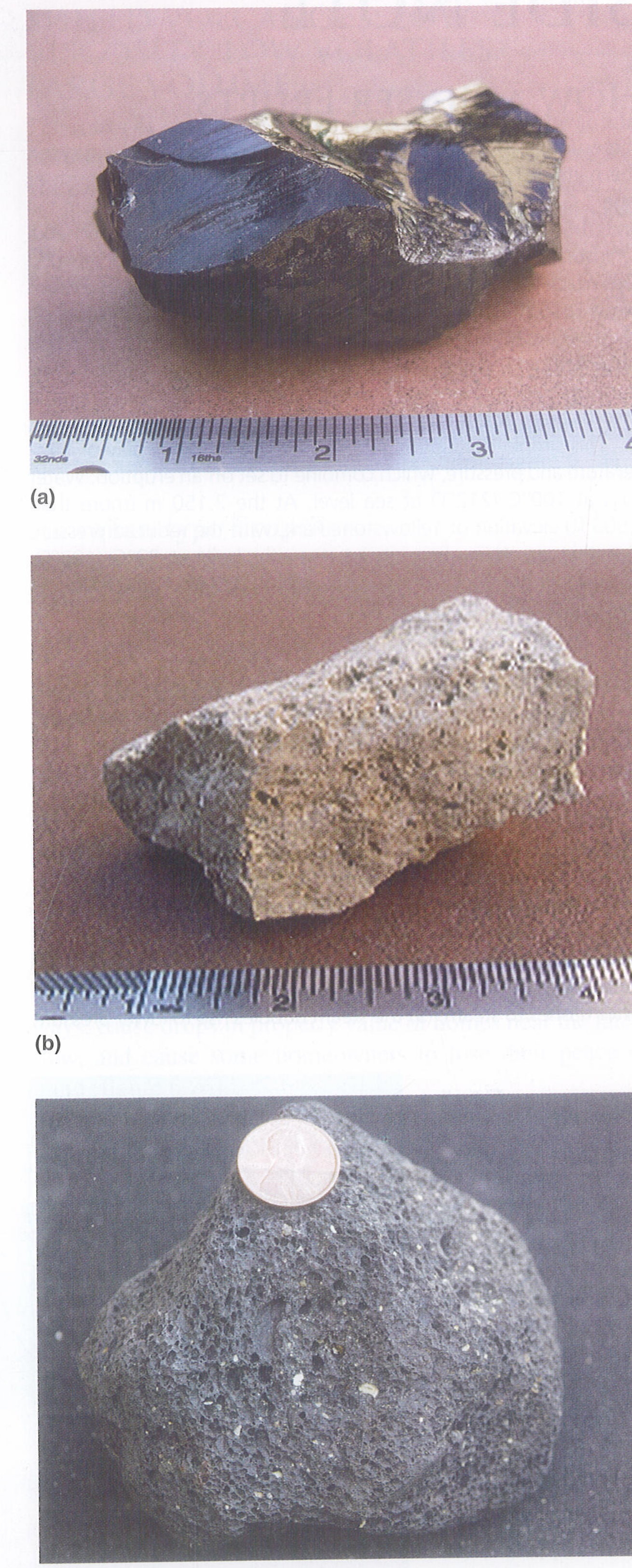
Magma reaching the surface can solidify so quickly that crystallization cannot take place because there is no time for atoms to arrange themselves into the ordered atomic structures of minerals. When magma cools this fast, it produces glass (table 6.6). Cooled volcanic glass is known as **obsidian** (figure 6.21). When gas escapes quickly and violently from lava, it may produce a frothy glass full of holes left by former gas bubbles; this porous material, known as **pumice,** contains so many holes it can float on water (figure 6.21b). **Scoria** are rough crusts or chunks of basaltic rock full of holes made by expanding gases before solidification (figure 6.21c).



(b)

FIGURE 6.19 (a) This large blob of magma cooled while airborne and fell as a *volcanic bomb*, Irazu Volcano, Costa Rica. (b) *Pyroclastic bombs* kill people every year.
(a) Photo by Pat Abbott. (b) Drawing by Jacobe Washburn.

FIGURE 6.20 *Volcanic ash* covers a house near Mount Pinatubo in the Philippines, June 1991.
Photo by R. P. Hoblitt, *US Geological Survey*.



(a)

(b)

(c)

FIGURE 6.21 Volcanic glass and scoria. (a) Obsidian is a dense, dark glass. (b) Pumice, a porous, light glass, floats in water. (c) Scoria, a basaltic rock with large pores, sinks in water.
Photos (a) and (b) from NASA; (c) by Pat Abbott.

Side Note

How a Geyser Erupts

The eruption of water superheated by magma is called a **geyser.** The name is from the Icelandic word *geysir,* meaning "to gush or rage." Geyser areas include Iceland, Chile, Yellowstone Park in the United States, North Island of New Zealand, and the Kamchatka Peninsula of Russia. All of these sites share common characteristics: subsurface water is present, and heat is abundant. Water from snow, rain, streams, and lakes is pulled below the ground surface by gravity, where it slowly moves through the network of voids presented by fractures and cavities, or **pores,** in rocks. The downward-circulating water encounters heat from a body of magma, absorbs heat, and then erupts (figure 6.22).

This simple description ignores the complex interplay of temperature and pressure, which combine to set off an eruption. Water boils at 100°C (212°F) at sea level. At the 2,150 m (more than 7,000 ft) elevation of Yellowstone Park, with the reduced pressure of a thinner atmosphere above it, water boils at 93°C (193°F). However, water encountered while drilling 332 m (1,088 ft) below the surface at Norris Geyser Basin in Yellowstone Park was still liquid at 241°C (465°F) because the pressure at that depth is too great for it to change to steam.

When superheated water at depth does boil, its volume expands as liquid changes to steam, helping lift surrounding water upward to lower pressure levels, where more water flashes to steam helping lift more superheated water to lower pressure levels, and so on (figure 6.23).

Reduction of pressure on superheated water causes it to change from liquid to gas, triggering the geyser eruption, analogous to the *reduction of pressure* that causes hot rock to change from solid to liquid, triggering a volcano eruption. A geyser eruption usually follows this sequence of events: (1) At depth, superheated water flows out of tiny pressurized cracks into geyser reservoirs of larger volume; (2) as water temperature rises, some water flashes to steam; (3) the steam bubbles rise to lower pressure levels, expanding continuously; (4) steam and bubbles become so abundant that they overwhelm the water, carrying it upward to levels of lower pressure, causing continual conversion to steam along the upward route; and (5) finally—the spectacular eruption.

FIGURE 6.22 Eruption of a geyser at Rotorua, North Island, New Zealand.
Photo by Pat Abbott.

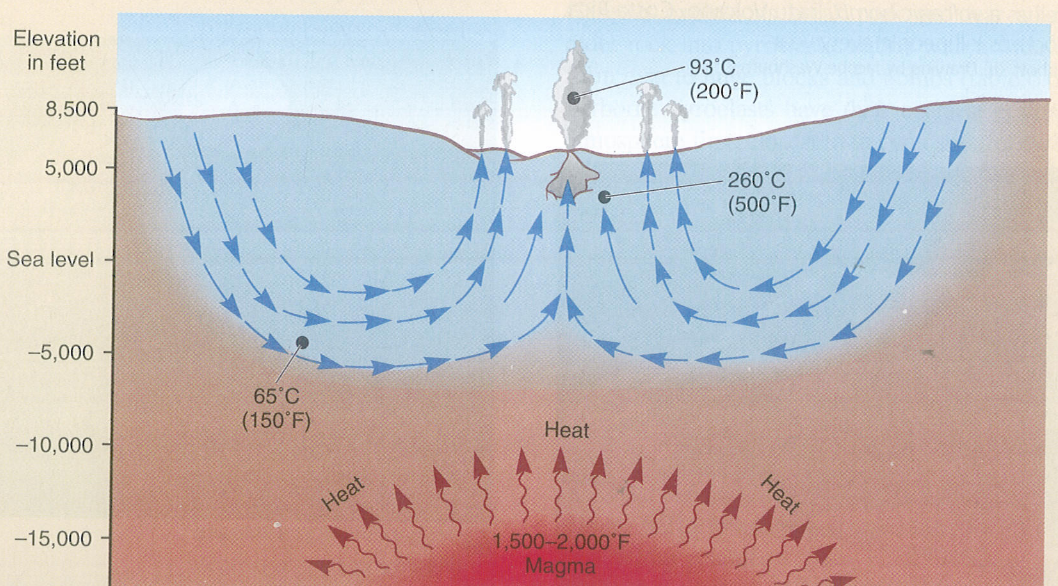


FIGURE 6.23 Surface water is pulled below ground by gravity, flows through holes in rocks, is superheated by magma, and through complex reductions in pressure, erupts at the surface as geysers.

The Three Vs of Volcanology: Viscosity, Volatiles, Volume

We can understand volcanoes anywhere in the world using the three Vs of volcanology: viscosity, volatiles, volume. *Viscosity* may be low, medium, or high, and it controls whether magma flows away or piles up. *Volatile* abundance may be low, medium, or high, and volatiles may ooze out harmlessly or blast out explosively. *Volume* of magma may be small, large, or very large. Volume correlates fairly well with eruption intensity; the greater the volume, the more intense the eruption.

Consider the five eruptive styles in figure 6.16 in terms of viscosity and volatiles (table 6.7). The lower the volatile content and the viscosity, the more peaceful the eruption. As the volatile content increases, so can the explosiveness of the eruptions.

Applying what we have learned about magmas allows us to see linkages between eruptive behaviors and the landforms built by volcanic activity. By mixing and matching the values among the three Vs, you can define volcanic landforms (table 6.8) and forecast the eruptive styles that occur at each of them.

TABLE 6.7
Eruption Styles and Explosiveness

Eruption Style	Viscosity	Volatiles	Volcanic Explosivity Index
Icelandic	Low	Low	0–1 (very low)
Hawaiian	Low	Low	0–1 (very low)
Strombolian	Moderate	Moderate	1–3 (low)
Vulcanian	High	High	2–5 (high)
Plinian	High	High	3–8 (very high)

Shield Volcanoes: Low Viscosity, Low Volatiles, Large Volume

The rocks of **shield volcanoes** form mostly from the solidification of lava flows of basalt. These lava flows are low viscosity, contain less than one weight % volatiles, and are so fluid that they travel for great distances, somewhat analogous to pouring pancake batter on a griddle. Each basaltic flow cools to form a gently dipping, relatively thin volcanic rock layer. Many thousands of these lava flows must cool on top of each other over a long time to build a big volcano. A shield volcano, such as Mauna Loa in Hawaii, has a great width compared to its height, whereas a volcano built of high-viscosity magma, such as Mount Rainier in Washington, has a great height compared to its width (figure 6.24).

Hawaiian-type Eruptions

As with virtually all volcanic eruptions, Hawaiian-type eruptions are commonly preceded by a series of earthquakes as rock fractures and moves out of the way of swelling magma. When these fractures split the ground surface, they suddenly reduce pressure, allowing gas to escape from the top of the magma body. This can create a beautiful "curtain of fire" where escaping jets of gases form lines of lava fountains up to 300 m (1,000 ft) high. Also common in the Hawaiian eruption is formation of a low cone with high fountains of magma. After the initial venting of gas, great floods of basaltic lava spill out of the fissures and flow down the mountain slopes as red-hot rivers (figure 6.25). These eruptions may last from a few days to a year or more. Although few lives are lost to Hawaiian volcanism, the ubiquitous lava flows engulf and incinerate buildings, bury highways, cause drops in property value of homes near the latest flow, and cause some homeowners to lose their peace of mind (figure 6.26).

Hawaiian volcanoes capable of eruption include Haleakala on the island of Maui, the five volcanoes that make up the island of Hawaii, and the growing but still subsea volcano of Loihi. Haleakala last erupted around 1790. Today, its 49 km^2 (19 mi^2) summit caldera is a major tourist attraction.

TABLE 6.8
Volcanism Control by the Three Vs (Viscosity, Volatiles, Volume)

Viscosity	+	Volatiles	+	Volume	=	Volcanic Landforms
Low		Low		Large		Shield volcanoes
Low		Low		Very large		Flood basalts
Low/medium		Medium/high		Small		Scoria cones
Medium/high		Medium/high		Large		Stratovolcanoes
High		Low		Small		Lava domes
High		High		Very large		Calderas

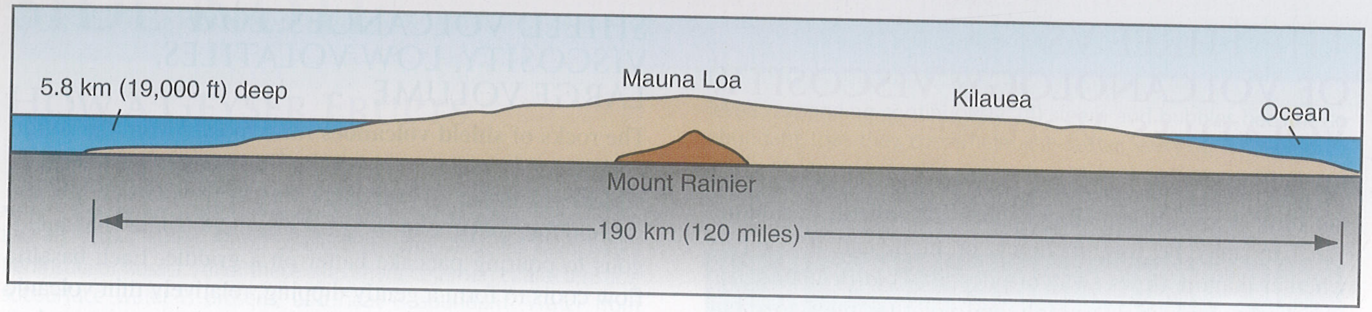


FIGURE 6.24 A shield volcano, such as Mauna Loa in Hawaii, has a great width compared to its height. A stratovolcano, such as Mount Rainier in Washington, has a great height compared to its width.
Data source: Tilling, R. I., et al., Eruptions of Hawaiian Volcanoes, *US Geological Survey*, 1987.

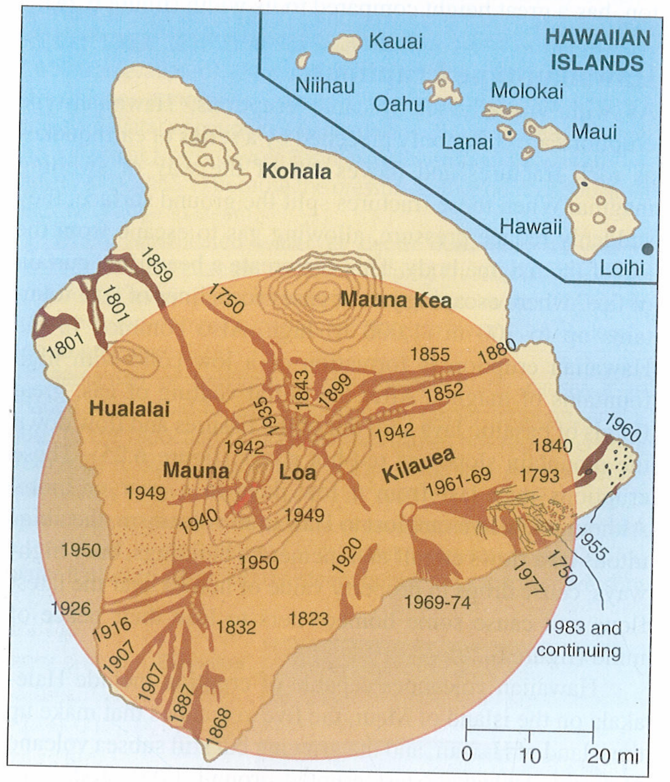


FIGURE 6.25 Map of Hawaii showing some historic lava flows. The circular color overlay shows boundaries of mantle plume rising from the hot spot at depth.

FIGURE 6.26 Lava flows caused the Wahalua Visitor's Center in Hawaii Volcanoes National Park to burn to the ground in 1989.
Photo by J. D. Griggs, *US Geological Survey*.

In the last 200 years, eruptions have occurred only on the three southernmost volcanoes on the island of Hawaii and below sea level on Loihi. The island-to-be (Loihi) is located about 30 km (19 mi) off the southeastern shore of Hawaii. Loihi's peak is about 969 m (3,175 ft) below sea level, and the weight of the overlying ocean water suppresses the explosiveness of the eruptions for now, but the volcano is building upward impressively.

In general, the volcanism on Hawaii is relatively peaceful and acts as a magnet attracting tourists to witness nature's spectacle. But there are exceptions to this statement.

Killer Event of 1790

Although less than 0.5% of Hawaiian magma is blown out as pyroclastic material, rare killer events do occur. In 1790, traveling parties from King Keoua's army were caught and many of the people killed by a blast from Kilauea Volcano. The army was passing through the area but was stopped by eruptions. After three days of waiting, it split into three parties of about 80 people each. As the parties marched southwest down the trail from Kilauea, disaster struck. An explosion column burst upward, with a **base surge** sweeping outward as a dense, basal cloud. Base surges can travel at hurricane speeds as masses of ground-hugging hot water and gases with or without magma fragments. The base surge in 1790 overtook King Keoua's middle party, killing them all. The victims huddled together, grasping each other to withstand the hurricane-force blast, but the hot gases seared their lungs and the intense heat scorched their skin. The base surge caught up with the lead party, but it had weakened, allowing most of those people to survive. The trailing party was alongside the blast and suffered no deaths or

IN GREATER DEPTH

VOLCANIC EXPLOSIVITY INDEX (VEI)

How often do big volcanic eruptions occur? On average, about once every three years, according to the volcanic explosivity index (VEI). Combining the historic record with the geologic information stored in the rock record, the major volcanic eruptions occurring between the years 1500 and 1980 were evaluated for their size. Factors evaluated include (1) volume of material erupted, (2) how high the eruption column reached, and (3) how long the major eruptive burst lasted (table 6.9). During the 481-year interval studied, 126 major eruptions occurred, with the number increasing in modern times. The increase in big eruptions in the 19th and 20th centuries is certainly due to better reporting of events, rather than an actual increase in major eruptions.

The VEI ranges from 0 to 8. The biggest event since 1500 CE was the VEI 7 eruption of Tambora in 1815 in Indonesia. This eruption caused a cooling of the world climate during the following year (see chapter 12). Four VEI 6 events occurred in the 481-year period, including the 1883 eruption of Krakatau, also in Indonesia (described in the section on calderas in this chapter). Volcanic events with high VEI values are those of Vulcanian and Plinian-type eruptions. A fifth VEI 6 event occurred in 1991 when Mount Pinatubo erupted.

TABLE 6.9

Volcanic Explosivity Index (VEI)

	VEI								
	0	1	2	3	4	5	6	7	8
Volume of ejecta (m^3)	$<10^4$	10^4–10^6	10^6–10^7	10^7–10^8	10^8–10^9	10^9–10^{10}	10^{10}–10^{11}	10^{11}–10^{12}	$>10^{12}$
Eruption column height (km)	<0.1	<0.1–1	1–5	3–15	10–25	>25			
Eruptive style	<-----Hawaiian----->		<-----Vulcanian----->						
		<-----Strombolian----->				<------------Plinian------------>			
Duration of continuous blast (hours)		<------<1----->		<-----1–6----->			<-------->12-------->		
				<-----6–12----->					

Source: After Newhall and Self (1982).

injuries. Although basaltic magma is not likely to explode, this case history shows how it can incorporate water into the magma and heat groundwater to cause an eruption, including a base surge of superheated steam. The 1790 event is worth remembering for today's watchers of Hawaiian eruptions—at least seek the high ground during your viewing.

FLOOD BASALTS: LOW VISCOSITY, LOW VOLATILES, VERY LARGE VOLUME

Flood basalts are the largest volcanic events known on Earth. Two important characteristics are (1) the immense amounts of mass and energy they pour onto Earth's surface, and (2) their geologically brief duration. Flood basalts erupt tremendous volumes of magma within a geologically short time—for example, 1 to 3 million years. Hot spots also bring up huge volumes of magma but do so during a long period—for example, 100 million years.

Eruptions from individual volcanoes transfer a lot of heat from Earth's interior to the surface, but the most impressive movements of heat occur with flood basalts. The numbers that describe the volumes of magma they erupt and the surface areas they bury with lava are so large they are hard to visualize. For example, 252 million years ago, up to 3 million km^3 (800,000 mi^3) of basalt flowed out and covered almost 4 million km^2 (1.5 million mi^2) of Siberia, Russia. Visualize basalt flows covering an area measuring about 1,200 mi by 1,200 mi with lava tens of meters thick. How does this area compare with the area of your state or province? Visualize your entire state or province buried beneath lava tens of meters thick.

Flood basalts occur on all continents and on all ocean floors, but none has occurred in historic times. Flood basalt eruptions obviously devastate a region, but can they have global effects? Yes, not from the lavas directly, but from the climate-modifying volatiles such as carbon dioxide (CO_2) or sulfur dioxide (SO_2) they release into the atmosphere. Is it a coincidence that the greatest mass extinction known occurred during the time the Siberian flood basalt was being erupted? Probably not.

Another flood-basalt episode occurred 65 million years ago, when about 1.5 million km^3 (360,000 mi^3) of basalt flowed out and covered about 1.5 million km^2 (580,000 mi^2) of the Deccan region of India. This also coincides with a mass extinction, the famous one that includes non-avian dinosaurs.

SCORIA CONES: MEDIUM VISCOSITY, MEDIUM VOLATILES, SMALL VOLUME

Scoria cones are conical hills, typically of low height, formed of basaltic to andesitic pyroclastic debris piled up next to a volcanic vent. Scoria cones commonly are produced during a single eruptive interval lasting from a few hours to several years. The scoria, or **cinder cone,** has a summit **crater,** the basin on top of the cone that is usually less than 2 km (1.2 mi) in diameter. The summit crater may hold a lava lake during eruption. After the excess gas has been expelled from the magma body, the lava may drain and emerge from near the base of the cone. When that eruption ceases, scoria cones usually do not erupt again.

Strombolian-type Eruptions

Scoria cones are built mainly by Strombolian-type eruptions (see figure 6.16). The volcano Stromboli, offshore from southwestern Italy, has had almost daily eruptions for millennia. Its central lava lake is topped by a cooled crust. Even the tidal cycle disrupts the lava-lake crust, thus triggering eruptions. Gas pressure builds quickly beneath the crust, and eruptions occur as distinct and separate bursts up to a few times per hour. Each eruption tosses pyroclasts tens to hundreds of meters into the air. For many centuries, tourists have climbed Stromboli to thrill at the explosive blasts, but usually every year, a few of those tourists die when hit by large pyroclastic bombs. Strombolian eruptions are not strong enough to break the volcanic cone.

On 20 February 1943, a new volcano was born as eruptions blasted up through a farm field near the village of Paricutin in the state of Michoacan, Mexico (figure 6.27). The volcano erupted for nine years, building a distinctive scoria cone. Pyroclastic debris and lava flows buried about 260 km^2 (100 mi^2) of land and destroyed the towns of Paricutin and San Juan de Parangaricutiro.

STRATOVOLCANOES: HIGH VISCOSITY, HIGH VOLATILES, LARGE VOLUME

Stratovolcanoes, or **composite volcanoes,** commonly are steep-sided, symmetrical volcanic peaks built of alternating layers of pyroclastic debris successively capped by high-viscosity andesitic to rhyolitic lava flows that solidify to form protective caps. Stratovolcanoes may show marked variations in their magma compositions from eruption to eruption, and their eruptive styles include Vulcanian and Plinian. Some of Earth's most beautiful mountains are stratovolcanoes—for example, Mount Kilimanjaro in Tanzania, Mount Shasta in California, Mount Rainier in Washington, and Mount Fuji in Japan (figure 6.28).

Vulcanian-type Eruptions

All volcanoes take their name from Vulcan, the Roman god of fire and blacksmith for the gods. The prototypical volcano

FIGURE 6.27 Paricutin Volcano erupting in 1943. This 400 m (1,300 ft) high scoria cone is in the state of Michoacan, Mexico.
Photo from *US Geological Survey*.

is one of the Aeolian Islands in the Tyrrhenian Sea north of Sicily. The fire and smoke emitted from the top of the mountain reminded observers of the chimney of Vulcan's forge, so the mountain was named Vulcano. Vulcanian eruptions alternate between thick, highly viscous lavas and masses of pyroclastic material blown out of the volcano. Some Vulcanian eruptions are more violent blasts of high-viscosity magma loaded with trapped gases. The material blown out during eruptions covers wide areas. Vulcanian eruptions commonly are the early phase in the eruptions of other volcanoes as they "clear their throats" before emitting larger eruptions.

Plinian-type Eruptions

Plinian eruptions are named after the 17-year-old Pliny the Younger in honor of his detailed written observations of the 79 CE eruptions of Vesuvius that claimed the life of his well-known uncle Pliny the Elder. In Plinian eruptions, the volcano "throat is now clear," and incredible gas-powered vertical eruption columns carry pyroclastic debris, including

FIGURE 6.28 Mount Fuji, a symmetrical stratovolcano rising 3,776 m (12,385 ft) above sea level, Honshu, Japan. The last major eruptions were in 1707–1708.
Photo © Corbis RF.

lots of pumice, up to 50 km (30 mi) into the atmosphere (see figure 6.16). The Plinian eruption is a common final phase in a major eruptive sequence. About two to three Plinian eruptions occur each century.

Vesuvius, 79 CE

Vesuvius began as a submarine volcano in the Bay of Naples. It grew greatly in size, and its rocky debris filled in the waters that once separated it from mainland Italy (figure 6.29). What is the cause of the volcanism at Vesuvius and the neighboring volcanoes of Stromboli, Vulcano, Etna, and others? The subduction of Mediterranean seafloor beneath Europe to make room for the northward charge of Africa.

In 79 CE, when Mount Vesuvius began erupting, most residents fled from Pompeii. Those who stayed first experienced volcanic ash clouds dropping pumice. Pompeii lay downwind and was buried by pumice fragments accumulating up to 3 m (10 ft) deep (figure 6.29). Researchers estimate that about 60% of the people who remained in Pompeii survived the first flows of ash and pumice. About half of the survivors then fled, but many of them died when they were caught outside during later flows of ash and pumice. The people still inside houses remained alive, only to suffocate from breathing hot particles and gases seeping out of the volcanic debris. Death was not always quick. Some bodies were found inside houses on top of thick layers of pumice, giving

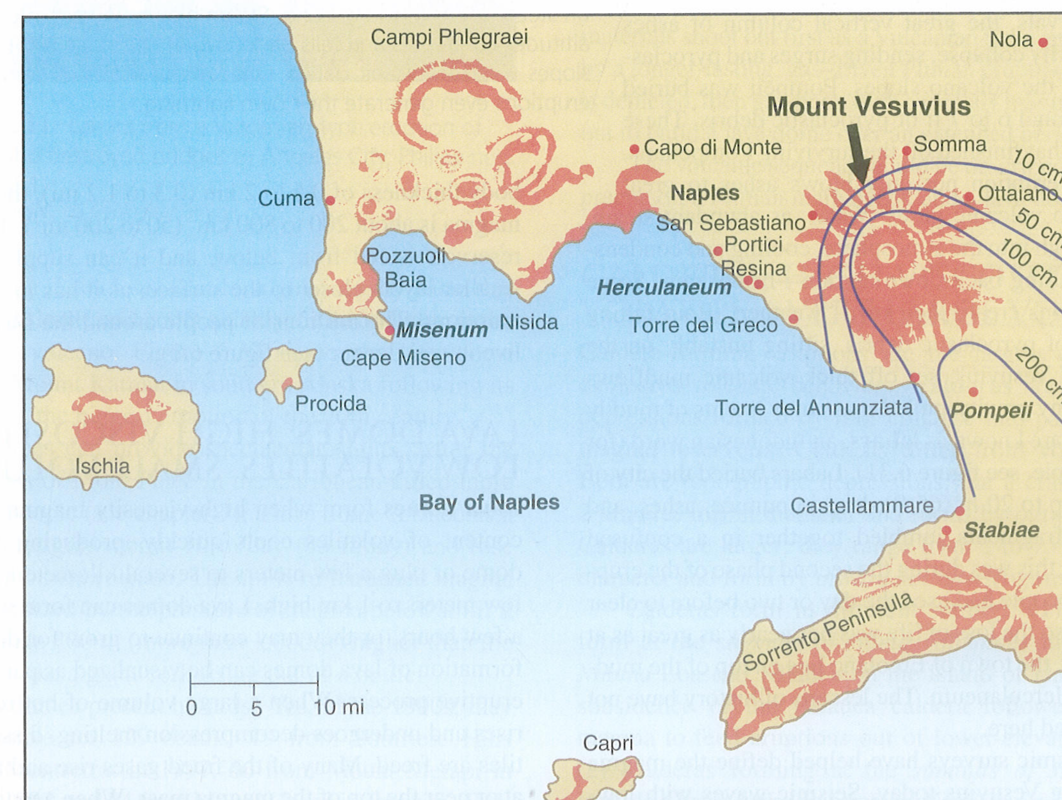


FIGURE 6.29 Map of the Bay of Naples area showing the location of Mount Vesuvius. Pumice fallout from the 79 CE eruption is contoured in centimeters. Pompeii and Stabiae were buried by pumice; Herculaneum by lahars.

evidence of hours of struggle by people fighting to stay alive. Their hands held cloths over their mouths as they tried to avoid asphyxiation from gases seeping out of the pumice.

Many other people were found near the sea (see figure 6.6). They escaped the falling pumice, but ground-hugging **pyroclastic flows,** full of hot gases, finished them off (for a modern example of a major Vulcanian-type eruption, see figure 6.3). About 4,000 people died. The more-distant town of Stabiae was also mostly destroyed. It was here that Pliny the Elder died; the weak heart of the overweight man failed at age 56 under the stress of the farthest-reaching gas-rich flow.

Testing of rocks formed during the 79 CE eruption, as well as roof tiles from Pompeii, indicates that the cloud of volcanic ash and pumice that smothered Pompeii erupted out of Vesuvius at about 850°C (1,550°F) and then cooled to less than 380°C (710°F) by the time it reached the city. Roof tiles in Pompeii were heated to maximum temperatures of 340°C (640°F), while some walls on the partially protected down-flow side of houses reached temperatures of around 180°C (350°F), presumably because cooler air mixed into the volcanic ash cloud.

Following the Vulcanian-type eruption, the volcano entered a second phase, the Plinian phase, where it blew immense volumes of pyroclasts up to 32 km (20 mi) high in the atmosphere. The height of the eruption column varied as the volcanic energy waxed and waned. During weakened intervals, the great vertical column of ashes would temporarily collapse, sending surges and pyroclastic flows down the volcano slopes. Pompeii was buried under an additional 6 to 7 ft of pyroclastic debris. These were the flows that finished off the surviving Pompeiians.

A Plinian eruption not only blows ashes to great heights but also volcanic gases. Water, as abundant steam, can be blown high into the atmosphere, cooling and condensing and then falling back down as rain—heavy rain. Some volcanic eruptions create their own "weather." Rain falling on thick piles of pyroclastic debris, sitting unstably on the steep slopes of Vesuvius, set off thick volcanic mudflows (figure 6.30). Any gravity-pulled mass movements of muddy volcanic debris are known as **lahars,** an Indonesian word (for a modern example, see figure 6.31). Lahars buried the city of Herculaneum up to 20 m (65 ft) deep in pumice, ashes, and volcanic rock fragments jumbled together in a confused mass. However, this was during the second phase of the eruption, and most people had used the day or two before to clear out of the area, so the loss of life was not nearly as great as at Pompeii. Today, the town of Ercolano lies on top of the mudflows burying Herculaneum. The lessons of history have not been well learned here.

Recent seismic surveys have helped define the magma body underlying Vesuvius today. Seismic waves with lowered velocity define a 400 km^2 (150 mi^2) horizontal, broad sheet of partially molten rock. This magma body lies at a depth of 8 km (5 mi) below the surface. Assuming a magma

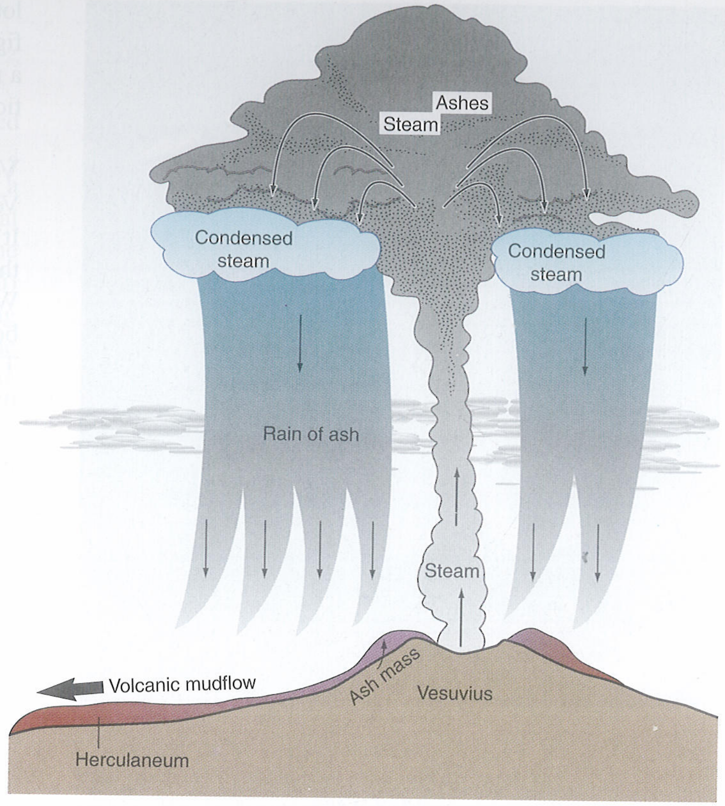


FIGURE 6.30 "Volcano weather" and the formation of lahars. Prolonged vertical eruption leads to accumulation of debris (ash mass) on steep slopes of the volcano. Steam blown upward into cold, high altitudes condenses and falls back as rain. The stage is set: steep slopes + loose volcanic debris + heavy rain = lahars. Some volcanic eruptions even generate their own lightning.

body thickness of 0.5 to 2 km (0.3 to 1.2 mi), the volume of magma is about 200 to 800 km^3 (50 to 200 mi^3). This magma reservoir is fed from below, and it can supply magma to smaller layers closer to the surface, as it has in fueling past eruptions. The millions of people around the Bay of Naples live in real danger (see figure 6.7).

LAVA DOMES: HIGH VISCOSITY, LOW VOLATILES, SMALL VOLUME

Lava domes form when high-viscosity magma with a low content of volatiles cools quickly, producing a hardened dome or plug a few meters to several kilometers wide and a few meters to 1 km high. Lava domes can form in as little as a few hours, or they may continue to grow for decades. The formation of lava domes can be visualized as part of a larger eruptive process. When a large volume of hot rock/magma rises and undergoes decompression melting, dissolved volatiles are freed. Many of the freed gases rise and accumulate at or near the top of the magma mass. When a major eruption occurs, these gases power the initial Vulcanian-type blast and then the succeeding Plinian-type eruption, which lasts until the excess volatiles have escaped. What type of magma

FIGURE 6.31 Lahars from a Vulcanian-type eruption of Mount Pinatubo destroyed bridges to Angeles City, Philippines, 12 August 1991.
Photo by T. Casadevall, *US Geological Survey.*

remains? Often it is a low-volatile, high-viscosity paste that oozes upward slowly and cools quickly, forming a plug in the throat of the volcano. Figure 6.32 shows the lava dome emplaced in Mount Katmai in southern Alaska following its 1912 eruption, the biggest eruption of the 20th century.

Lava domes can provide spectacular sights. After the 1902 eruptions of Mont Pelée in the Caribbean killed more than 30,000 people (see chapter 7), a lava dome formed as a great spine that grew about 10 m/day (33 ft/day) and rose above the top of the volcano. The spine of hardened magma was forced upward by the pressure of magma below until it stood more than 300 m (more than 1,000 ft) higher than the mountaintop, like a giant cork rising out of a bottle.

Do lava domes present hazards? Yes, in the 1990s, they were responsible for 129 deaths: 19 from Soufriere Hills Volcano on Montserrat in 1997, 66 from Mount Merapi in Indonesia in 1994, and 44 from Mount Unzen in Japan in 1991. The hardened, brittle lava dome rock can fail in a gravity-pulled landslide from the mountain, or magma trapped below the brittle lava dome can break out in a violent eruption.

FIGURE 6.32 The Novarupta lava dome formed as hardened magma plugged the central magma pipe of the 1912 eruption of Katmai Volcano in southern Alaska. The dome is 244 m (800 ft) across and 61 m (200 ft) high.
Photo from *US Geological Survey.*

A Typical Eruption Sequence

A common pattern for a major eruptive episode is that gas-rich materials shoot out first as a Vulcanian blast, quickly followed by a longer-lasting, gas-driven Plinian eruption. When the gas is depleted, then gas-poor, high-viscosity magma slowly oozes out to build a lava dome over an extended period of time.

The volcanic sequence could be described as a Vulcanian precursor, a Plinian main event, and a lava dome conclusion.

CALDERAS: HIGH VISCOSITY, HIGH VOLATILES, VERY LARGE VOLUME

Caldera-forming eruptions are the largest of the violent, explosive volcanic behaviors. **Calderas** are large volcanic depressions formed by roof collapse into partially emptied magma reservoirs. Calderas differ from volcanic craters. Both are topographic depressions, but a crater is less than 2 km (1.2 mi) in diameter and forms by *outward explosion.* Calderas are larger; they range from 2 to 75 km (45 mi) in diameter and form by *inward collapse* (figure 6.33).

Calderas form in different settings: (1) Calderas that form at the *summits of shield volcanoes* include those at Mauna Loa and Kilauea on the island of Hawaii. A recent subsidence of the Kilauea caldera followed draining of magma to feed eruptions out of lower-elevation rift zones. (2) Calderas forming at the *summits of stratovolcanoes* include Crater Lake in Oregon, Krakatau in Indonesia, and Santorini in the Aegean Sea (figure 6.34a,b,c). Caldera collapses occurred following sustained Plinian eruptions of 55 km^3 (13 mi^3) of pyroclasts at Crater Lake, 10 km^3

SIDE NOTE

BRITISH AIRWAYS FLIGHT 9

On 24 June 1982, 247 people on British Airways flight 9 boarded a Boeing 747 for a night flight from Kuala Lumpur, Malaysia, to Perth, Australia. The night was moonless but clear, and the weather forecast was good. The crew took the big airplane up to its cruising altitude of 37,000 ft and then relaxed a bit. Weather radar showed that outside conditions were normal. But the pilot noticed puffs of "smoke" and an acrid or electrical odor. As he sat in the pilot's seat and peered through the front windscreens, the atmosphere seemed to be on fire as intense electricity danced about. Out the side windows, the engines were glowing as if they were lit inside. Then the flight engineer called out: "Engine failure number 4," followed shortly by:

"Engine failure number 2.

"Three's gone.

"They've all gone."

The pilot thought, "Four engines do not fail." The instrument panel was contradictory; some gauges read normal while others told of problems with a confusing lack of pattern.

Meanwhile, the plane was descending slowly. At 26,000 ft, the oxygen masks were released, but some didn't work; in this emergency, a steep descent was initiated to get down to atmospheric levels with more oxygen. When the plane reached 14,000 ft, the pilot said:

"Good evening ladies and gentlemen. This is your captain speaking. We have a small problem. All four engines have stopped. We are doing our darndest to get them going again. I trust you are not in too much distress." His words could not have brought much comfort to those passengers in window seats who had been watching the engines that seemed to be on fire.

What to do? Land on the ocean during a dark night? Too dangerous. Finally, at 12,000 ft, engine number 4 started, and 90 seconds later, the other three engines started. The pilot set the plane to climbing to avoid hitting the mountainous Indonesian topography, but at 15,000 ft, the bad atmospheric problems began again. Descent was once again initiated. Permission was granted for an emergency landing at Jakarta, but the approach was hazardous. The front and side windows were frosted and opaque, so the co-pilot had to look out a little side window and give instructions to the pilot landing the huge, fast-moving plane. At last, the plane landed smoothly, and the passengers cheered and clapped.

What happened that night to BA9? It flew during an eruption of Mount Galunggung and passed through its seething cloud of hot volcanic ash and larger pyroclastic debris. The volcanic ash clogged the engines, frosted the windscreen, and turned BA9 into a terror-filled flight. Airplanes must avoid volcanoes in eruption.

FIGURE 6.33 A crater (less than 2 km across) formed atop the volcano in the foreground during eruptions. The large caldera (more than 2 km across) at low elevation in the background formed when its volcano collapsed during a massive eruption, Kamchatka Peninsula, Russia.
Photo from *US Geological Survey*.

(2.4 mi³) at Krakatau, and 40 km³ (10 mi³) at Santorini. These eruptions opened void spaces that caused mountain peaks to collapse into their magma chambers. (3) *Giant continental calderas* are huge negative landforms such as Lake Yellowstone in Wyoming or Long Valley in California. These broad and deep depressions formed following the rapid eruption of 2,000 km³ (475 mi³) of pyroclasts at Yellowstone and 600 km³ (140 mi³) at Long Valley. The huge volumes of magma pour out in short amounts of time as **ultra-Plinian** eruptions with extra-high ash columns and widespread sheets of outward-flowing ash and pumice.

The most recent example of an ultra-Plinian eruption occurred 74,000 years ago at Toba, on the island of Sumatra in Indonesia. The caldera at Toba is 30 km (20 mi) by 100 km (60 mi) long and has a central raised area inside it that is more than 1 km high. The raised area formed during the millennia following the giant eruption; this resurgent topography inside the caldera gives these features their name—**resurgent calderas.**

Crater Lake (Mount Mazama), Oregon

Crater Lake is one of the jewels in the U.S. national park system. Its intense blue waters are pure and lie cradled in a high-rimmed, nearly circular basin. Crater Lake is about 9.5 km (6 mi) across and as deep as 589 m (1,932 ft) (figure 6.35).

Several thousand years ago, the *stratovolcano* Mount Mazama stood about 3,660 m (12,000 ft) high as one of the Cascade Range volcanoes above the Cascadia subduction zone (figure 6.36a). More than 7,600 years ago, a major eruption began blowing sticky magma out of the mountain as glassy, gas-bubble-filled pumice and ashes (figure 6.36b). The magma had too high a viscosity to flow as a liquid, so it erupted as pyroclastic flows and Plinian columns. As the erupted material grew in volume, its debris covered much of the U.S. Pacific Northwest and part of Canada with a thick, distinctive ash layer that is easily recognizable. Mazama ash is found

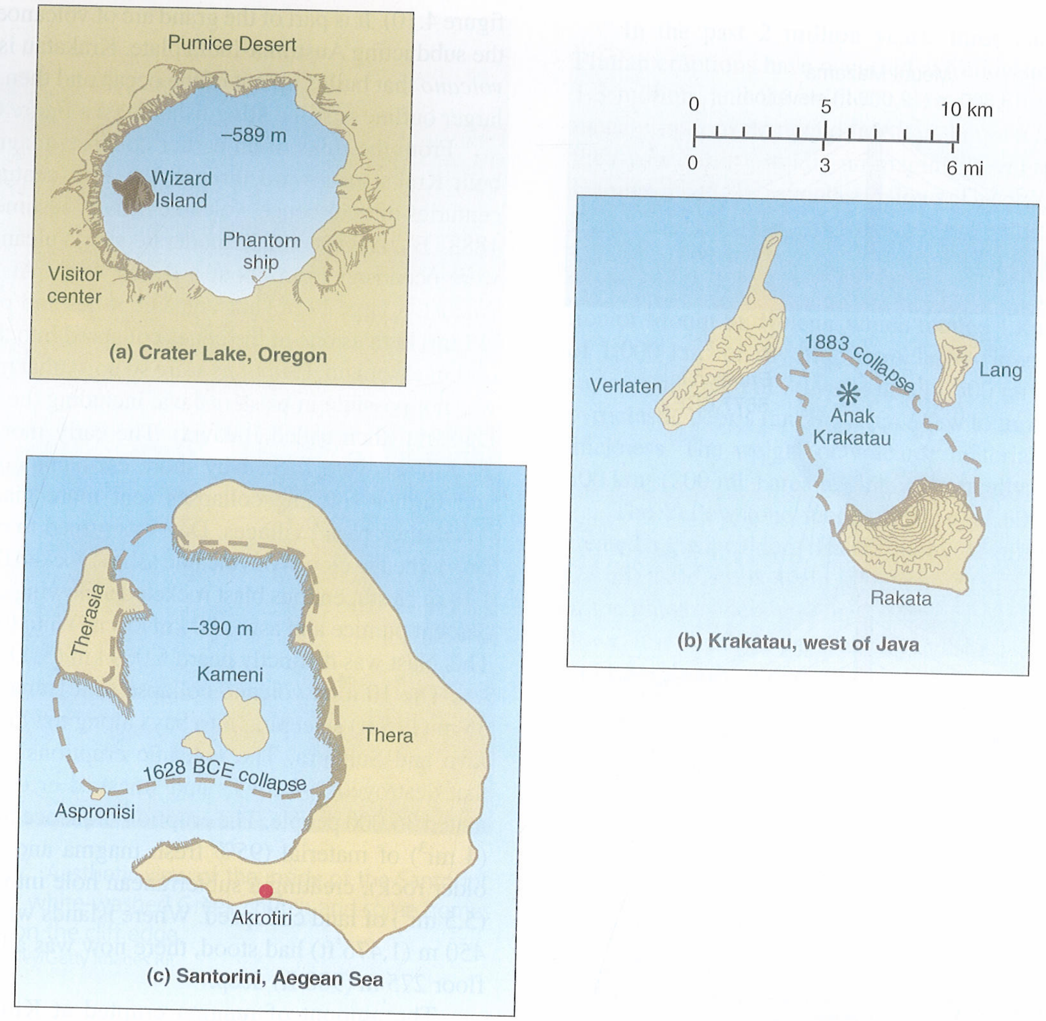


FIGURE 6.34 Map of some collapse calderas. (a) The nearly circular caldera of Crater Lake, Oregon, formed about 5677 BCE. (b) Island remnants of old volcano Krakatau; crudely ovoid shape of the 1883 collapse; and the new and growing volcano, Anak Krakatau. (c) Caldera in volcano Santorini that collapsed into the Aegean Sea about 1628 BCE.

FIGURE 6.35 Crater Lake, Oregon, fills the caldera of Mount Mazama, which collapsed in the year 5677 BCE. Wizard Island is visible.
Photo © Robert Glusic/Getty Images RF.

in the Greenland glacier within the ice layer formed during the snowfall season of the year 5677 BCE. About 40 km³ (10 mi³) of magma was ejected. Evacuation of this immense volume of magma left so tremendous a void below the surface that the weakened mountain peak collapsed and moved down in pistonlike fashion into the emptied magma chamber (figure 6.36c). The collapse produced a caldera about 10 km (6 mi) across that has collected the water for Crater Lake and hosted the growth of a 1,000-year-old successor volcanic cone called Wizard Island (figures 6.34a and 6.35).

The eruption of Mount Mazama affected American Indians, as evidenced by moccasin tracks and artifacts found beneath the distinctive ash layer. What have caldera-forming collapse events wrought elsewhere?

Krakatau, Indonesia, 1883

Today, Krakatau (Krakatoa) is a group of Indonesian islands in the Sunda Strait between Sumatra and Java (see lower right

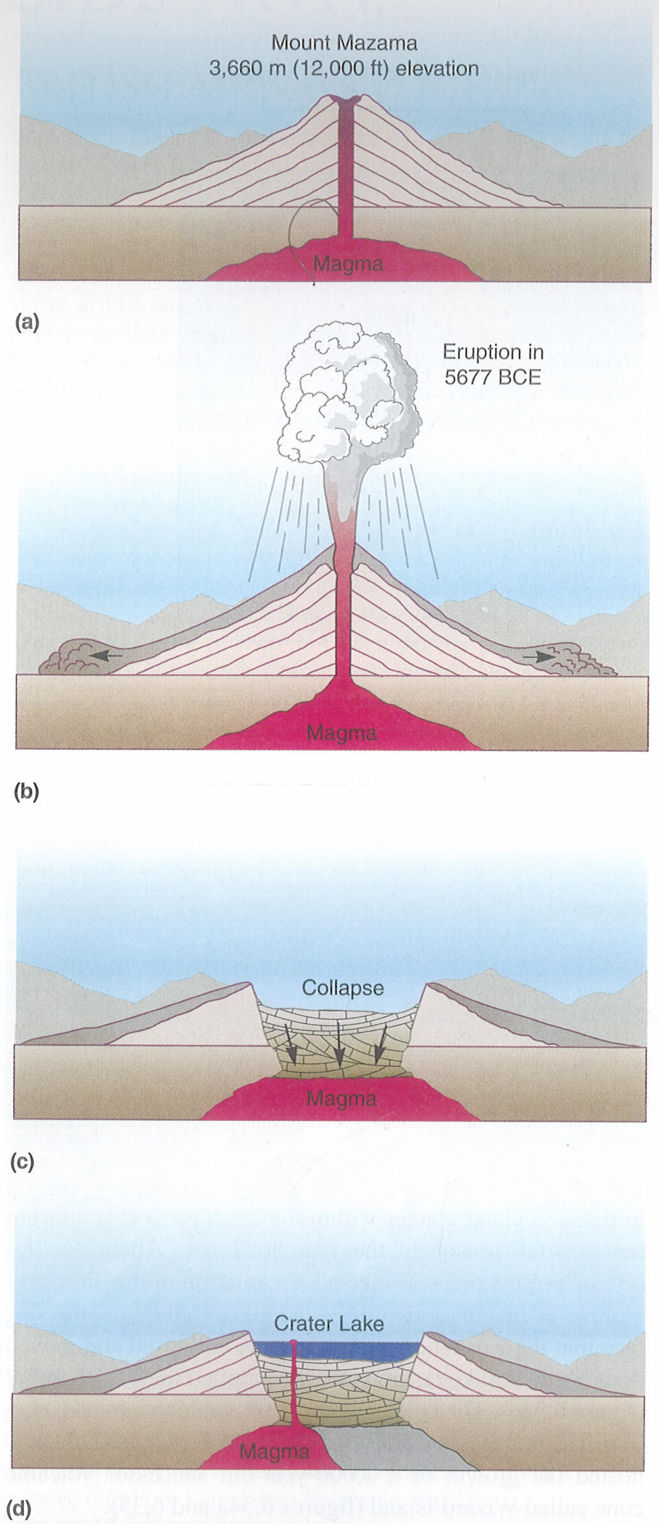


FIGURE 6.36 How Crater Lake formed. (a) The Mount Mazama volcano stood high. (b) A gaseous eruption in the year 5677 BCE emptied a huge volume of viscous magma. (c) The gigantic eruption left a void inside the weakened mountain, and the unsupported top fell down into the emptied magma chamber. (d) The waters of Crater Lake now fill the caldera, and a small new volcanic cone (Wizard Island) rises above lake level.

figure 4.10). It is part of the grand arc of volcanoes built above the subducting Australia-India plate. Krakatau is a big *stratovolcano* that builds up out of the ocean and then collapses. Its larger outline is still distinguishable (see figure 6.34b).

From the ruins of an earlier collapse, magmatic activity built Krakatau upward through the 17th century. After two centuries of quiescence, volcanic activity resumed on 20 May 1883. By August 1883, moderate-size Vulcanian eruptions were occurring from about a dozen vents. At 2 p.m. on 26 August, a large blast shot volcanic ashes and pumice 28 km (17 mi) high as one of the cones collapsed into the sea, setting off huge tsunami. Eruptions were so noisy that night that sleep was not possible in western Java, including the capital city of Djakarta (then called Batavia). The early morning hours of 27 August were rocked by more ear-hammering eruptions, and further volcanic collapses sent more giant tsunami to wrack the coastal villages. Day was turned to nightlike darkness as heavy clouds of volcanic ashes blocked the sunlight. At 10 a.m., a stupendous blast rocketed a glowing cloud of incandescent pumice and ashes 80 km (50 mi) into the atmosphere. This blast was distinctly heard 5,000 km (3,000 mi) away.

The 10 a.m. volcano collapse sent tsunami higher than 35 m (115 ft) sweeping into bays along the low coastlines of Java and Sumatra. The volcanic eruptions caused tsunami that destroyed 295 towns and smashed or drowned an estimated 36,000 people. The eruption sequence blew out 18 km^3 (4 mi^3) of material (95% fresh magma and 5% pulverized older rock), creating a subterranean hole into which 23 km^2 (5.5 mi^2) of land collapsed. Where islands with elevations of 450 m (1,476 ft) had stood, there now was a hole in the seafloor 275 m (900 ft) deep.

The amount of magma erupted at Krakatau in 1883 was less than half that of the Mount Mazama eruption. But Krakatau collapsed into the sea, sending off tsunami.

In 1927, Krakatau began rebuilding a new volcanic cone called Anak Krakatau—"child of Krakatau"; it is still growing (see figure 6.34b). We will hear more from Krakatau.

Santorini, Greece

As the Mediterranean oceanic plate subducts beneath Europe, it causes numerous volcanoes. One of the biggest is the *stratovolcano* Santorini in the Aegean Sea. Today, Thera is the largest island in a circular group marking the sunken remains of Santorini (see figure 6.34c). Thera is one of the most popular tourist sites in the Greek islands (figure 6.37), but around 1628 BCE, Santorini underwent an explosive series of eruptions that buried the Bronze Age city of Akrotiri on Thera to depths of 70 m (230 ft) in four distinct phases. Where there had been a large island made of several volcanic cones, there now exists a huge caldera with depths of 390 m (1,280 ft) below sea level.

Caldera-forming eruptions are low-frequency, high-impact events. Santorini had a major eruption more than 21,000 years ago, then about 18,000 years passed without a huge eruption—until the ultra-Plinian eruption and volcano collapse during the Minoan civilization. A recent study of chemically zoned crystals of plagioclase that grew in the 855°C (1,570°F) rhyolitic magma reservoir determined how much time it took to recharge the magma reservoir before the overwhelming eruption of 1628 BCE. The results are surprising. After 18,000 years of waiting, it took less than 100 years to supply the 40–60 km^3 (10–15 mi^3) of magma that were erupted. The huge supply of viscous magma forced relatively small-volume dikes or columns of magma to the surface, initiating the pressure drop that triggered the eruption.

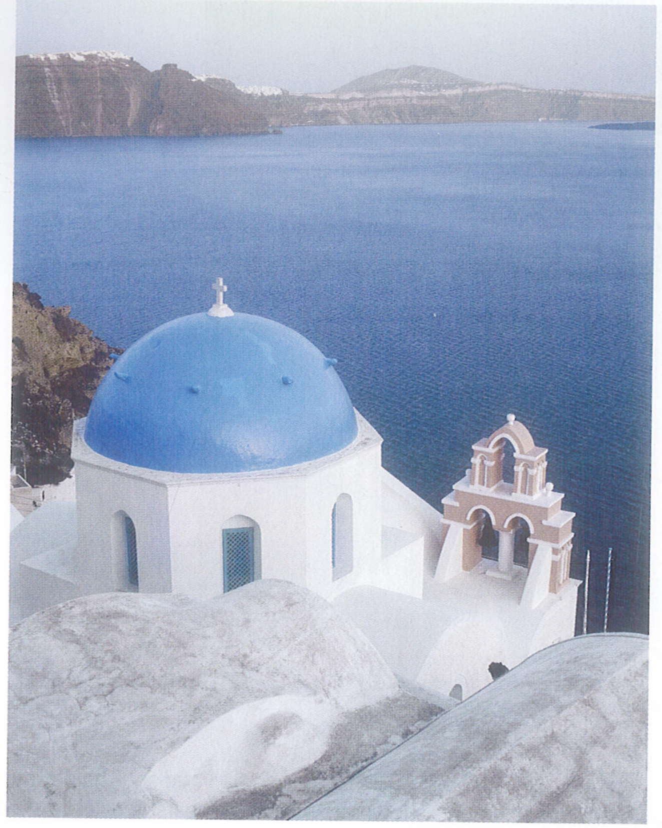


FIGURE 6.37 Aesthetic view of the inside of the Santorini caldera. A classic white-washed Greek church and some homes have been built on the cliff edge.
Photo © Adam Crowley/Getty Images RF.

It is sobering for us today to consider that a civilization-changing mega-eruption might take only a few decades of magma recharge before occurring.

Yellowstone National Park

A *giant continental caldera* exists in Yellowstone above a hot spot, a long-lived mantle plume that the North American continent is drifting across. The hot spot occupies a relatively fixed position above which the North American plate moves southwestward about 2 to 4 cm/yr (0.8 to 1.6 in/yr). Plate movement over the hot spot during the last 15 million years is recorded by a trail of surface volcanism cut across the Snake River plain in Idaho and on into Wyoming (figure 6.38). At present, Yellowstone National Park sits above the hot spot, and a large body of rhyolitic magma lies about 5 to 10 km (3 to 6 mi) beneath it.

In the past 2 million years, three catastrophic ultra-Plinian eruptions have occurred at Yellowstone at 2 million, 1.3 million, and 0.6 million years ago (figure 6.39). Such mega-eruptions do not come often, but in a few short weeks, they pour forth virtually unimaginable volumes of rhyolitic magma, mostly as pyroclastic flows. The oldest event erupted 2,500 km^3 (600 mi^3) of magma, the middle one emptied 280 km^3 (70 mi^3), and the youngest dumped out 1,000 km^3 (240 mi^3). (Compare these magma volumes to the 1980 eruption of Mount St. Helens, which totaled 1 km^3.) An eruption of 1,000 km^3 of rhyolitic pyroclastic flows would cover a surrounding area of 30,000 km^2 (11,500 mi^2) with a mass of pyroclastic debris ranging from a few to more than 100 m in thickness. The weight of volcanic material would cause a 500 km^2 (200 mi^2) area to sink isostatically.

The Yellowstone mega-eruption of 600,000 years ago created a giant caldera that is 75 km (47 mi) long and 45 km (28 mi) wide. Look again at figure 6.39 and consider the size of the giant caldera and the extent of its emitted pyroclastic flows: in a matter of days, all life in the area would have died and been deeply buried.

Eruptive Sequence of a Resurgent Caldera

Giant caldera-forming eruptions go through a characteristic sequence. They begin when a very large volume of rhyolitic magma rises to within a few kilometers below the surface, bowing the ground upward (figure 6.40a). The magma body accumulates a cap rich in volatiles and low-density components such as SiO_2.

A mega-eruption begins with a spectacular circular ring of fire as Plinian columns jet up from circular to ovoid fractures surrounding the magma body (figure 6.40b). The escaping magma erodes the fractures, thus increasing the size of the eruptive vents so that more and more magma escapes.

As greater volumes of gas "feel" the lessening pressure, the magma begins gushing out of the fractures in mind-boggling volumes (figure 6.40c). The outrushing magma is too voluminous to all go airborne, so most of it just pours away from the vents as pyroclastic flows, the fastest way to remove gas-laden, sticky magma.

As the subsurface magma body shrinks, the land surface sinks as well, like a piston in a cylinder, creating a giant caldera (figure 6.40d). The removal of 1,000 km^3 (240 mi^3) of magma creates a void, an isostatic imbalance, that is filled by a new mass of rising magma that bows up the caldera floor to create a **resurgent dome** (figure 6.41). Resurgent domes may be viewed as the reloading process whereby magma begins accumulating toward the critical volume that will trigger the next eruption.

The areas alongside resurgent domes are commonly occupied by lakes (see figure 6.39). Imagine driving the many miles from Yellowstone Lake to Old Faithful Geyser, all the time staying within the gigantic collapse caldera of the 600,000-year-old eruption. When will the next mega-eruption occur?

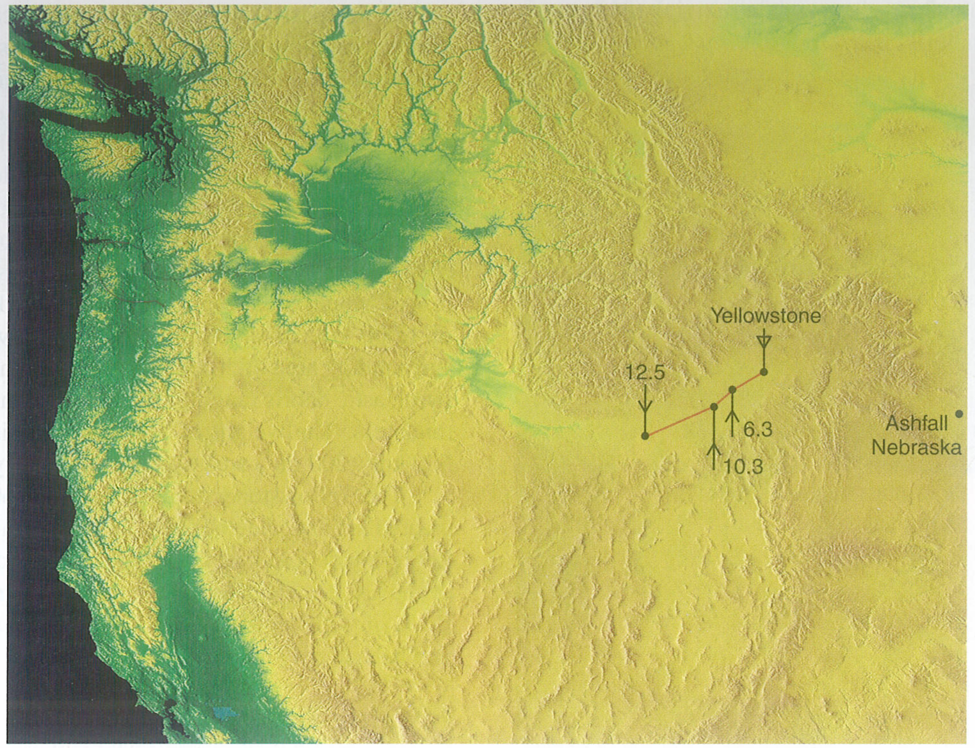


FIGURE 6.38 Track of the Yellowstone hot spot in western North America. See the 600 km (370 mi) long trail marking the path of the North American plate. Today, the hot spot underlies Yellowstone National Park. Numbers shown are millions of years since each site was over the hot spot.
Photo from NOAA.

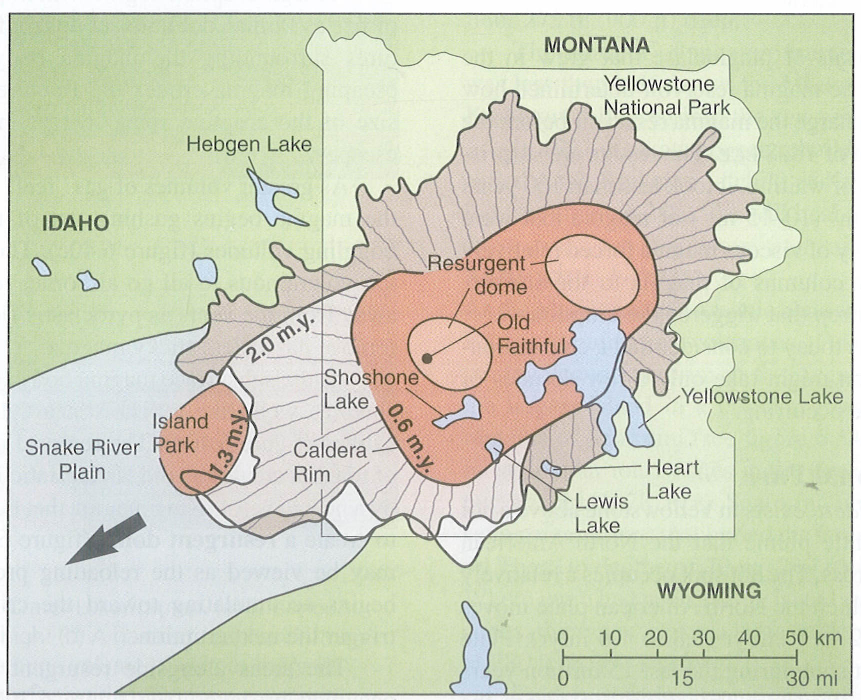


FIGURE 6.39 The Yellowstone hot-spot area. The North American plate is moving southwest, and thus the hot-spot magma plume erupts progressively farther northeast with time. Three giant calderas have erupted in the past 2 million years—at 2, 1.3, and 0.6 million years ago. The wiggly-lined area was covered by hot, killing pyroclastic flows during the eruption of 600,000 years ago. Notice the resurgent domes.

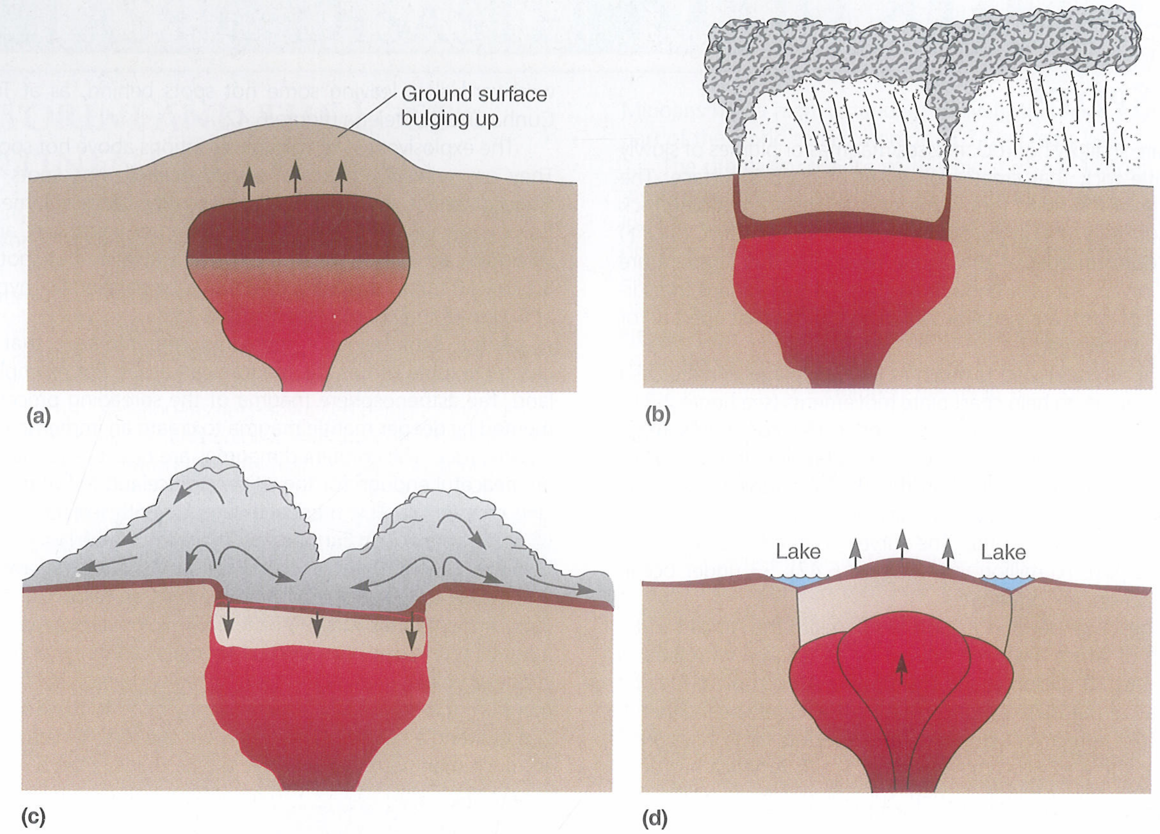


FIGURE 6.40 Stages in the formation of a giant continental caldera. (a) A rising mass of magma forms a low-density cap rich in SiO_2 and gases, causing the ground surface to bulge upward. (b) Plinian eruptions begin from circular fractures surrounding the bulge. (c) Magma pours out in pyroclastic flows of tremendous volume, causing the ground surface to sink into a giant caldera. (d) Removal of magma decreases the crustal pressure, allowing new magma to rise and cause the caldera floor to bulge up.

FIGURE 6.41 View over the town of Mammoth Lakes to tree-covered hills in Long Valley. The hills compose a resurgent dome up to 500 m (1,600 ft) high above the caldera floor.
Photo from *US Geological Survey.*

In Greater Depth

Hot Spots

Hot spots are shallow hot rock masses/magmas or plumes of slowly rising mantle rock that create volcanism on Earth's surface. The temperature of the rising rock is hotter than the surrounding rock by about 300°C (570°F) in the plume center and only 100°C (212°F) along the outer margin of the plume head. But this temperature difference lowers viscosity enough to start the rise toward the surface. Most hot spots are visualized as rising plumes that operate for about 100 million years.

Hot spots do not move as much as tectonic plates and are used as reference points to help chart plate movements (see figure 2.21). They occur under the oceans and under the continents (e.g., Yellowstone), in the center of plates (e.g., Hawaii), and as part of spreading centers (e.g., Iceland). In the 1970s, a survey was made of hot spots that create elevated volcanic domes with diameters greater than 200 km (125 mi). The survey counted 122 hot spots active in the past 10 million years (figure 6.42): 53 under ocean basins and 69 under continents.

The largest number of hot spots lies beneath the African plate. The drifting of Africa has been slowed by its collision with Eurasia during the last 30 million years. The slowed African plate may be acting like a thermal blanket concentrating the mantle heat beneath it. With Africa effectively stopped from making large horizontal movements, the westward movement of South America has doubled, and the mid-Atlantic Ocean spreading center is moving westward also, leaving some hot spots behind, as at Tristan da Cunha and St. Helena (figure 6.42).

The explosiveness of volcanic eruptions above hot spots varies. They are relatively peaceful above oceanic hot spots, such as Hawaii, where low-volatile, low-viscosity, large-volume magma flows easily, analogous to spreading-center volcanism, and builds shield volcanoes (see figure 6.24). The Hawaiian hot spot is about 80 km (50 mi) in diameter, as defined by earthquake hypocenters at 60 km (37 mi) depth (see figure 6.25).

A hot spot below a spreading center means that a much greater volume of basaltic magma can erupt. For example, at Iceland, the asthenosphere magma of the spreading process is augmented by deeper mantle magma to create an immense volume of basaltic rock. The combined magmas are basalt, and the eruptions are peaceful enough for the citizens of Iceland to live prosperously (see chapter 7). The mantle plume beneath Iceland is the most vigorous hot spot on Earth today. The rising plume has created crust beneath Iceland that is four to five times thicker than average.

Above continental hot spots, such as at Yellowstone National Park, the eruptions may be incredibly explosive because the rising magma breaks off and absorbs so much continental rock that it creates a volatile-rich, high-viscosity, very-large-volume magma. The mention of a big volcanic eruption may bring to mind a tall mountain emitting a powerful explosion, but the really big eruptions emit so much magma that they leave a hole bigger than a mountain, a giant caldera that can be 100 km (more than 60 mi) long.

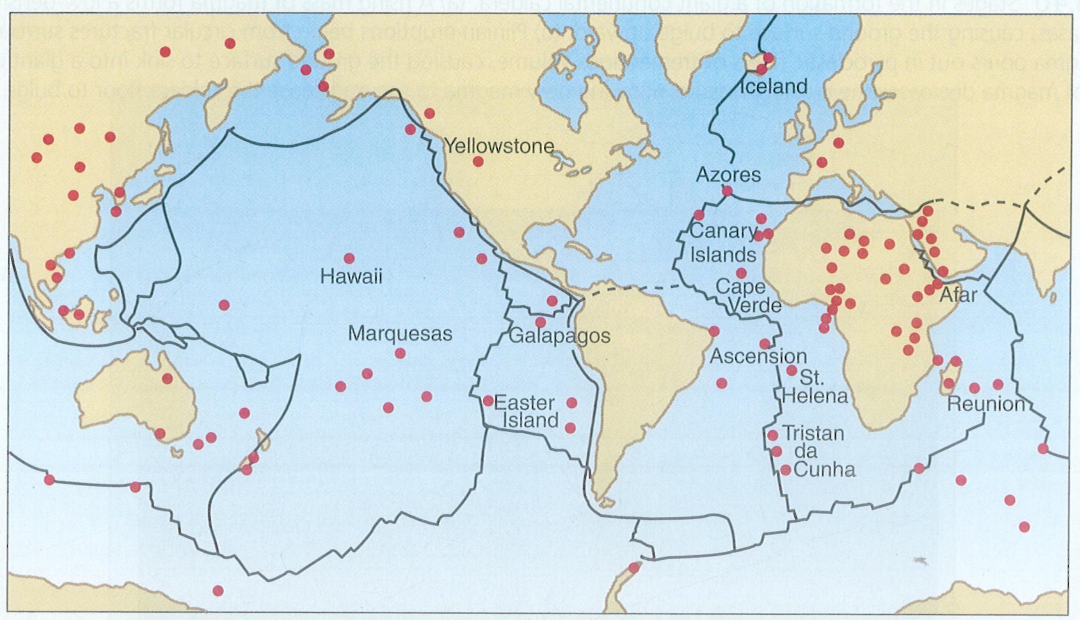


FIGURE 6.42 Hot spots active in the past 10 million years. Antarctica is not shown but lies above 11 hot spots, raising questions about the effects of melting massive volumes of ice.

A Classic Disaster

Santorini and the Lost Continent of Atlantis

What were the effects of the eruption of Santorini on the Mediterranean world? So huge that they may be the basis of the Atlantis myth.

Akrotiri was an important city, a part of the Minoan civilization based in Crete. The Minoans created an advanced civilization. In 1628 BCE, Akrotiri had three-story houses; paved streets with stone-lined sewers beneath them; advanced ceramic and jewelry work; regular trade with the Minoans' less-advanced neighbors in Cyprus, Syria, Egypt, and Greece; and colorful wall frescoes that depicted their wealthy and comfortable life (figure 6.43). In short, these Minoans had a higher standard of living than many people in this part of the world today, more than 3,600 years later.

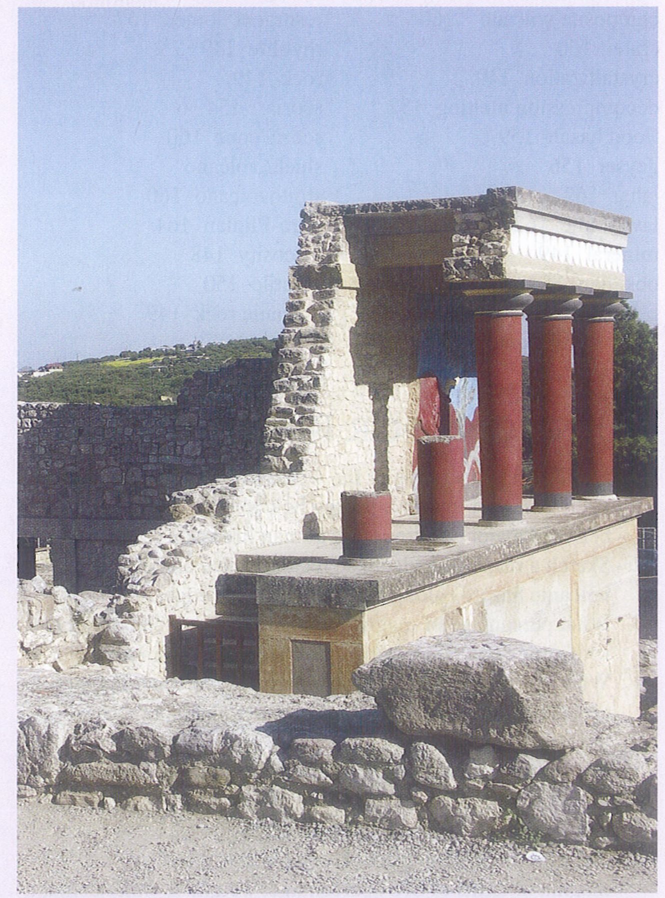


FIGURE 6.43 View of a portion of Knossos, on the island of Crete, the center of the Minoan civilization. These buildings were hit hard by the Santorini eruption.
Photo by Pat Abbott.

The dramatic collapse of this piece of the Minoan civilization must have made an indelible impression on the people of that time. In fact, this may be the event passed down to us by Plato as the disappearance of the island empire of Atlantis, which after violent earthquakes and great floods "in a single day and night disappeared beneath the sea." Plato lived in Greece from 427 to 347 BCE. He told the tale in the dialogues of Critias, the historian, who recounted the visit of Solon to Egypt, where he learned the account of Atlantis from the Egyptian priests in their oral histories. About 1,200 years after the event, Plato wrote a reasonably good description of a caldera-forming collapse with attendant earthquakes, floods (steam surges or tsunami), and a landmass sinking below the sea in a day and a night.

The eruption and caldera-forming collapse into the sea at Santorini seem similar to the events at Krakatau 3,500 years later, except the Santorini event was bigger. The Santorini eruption is estimated to have blown out more than 40 km^3 (10 mi^3) of rhyolitic magma; Krakatau blew out 18 km^3 (4 mi^3). Krakatau sent out ocean waves 35 m (115 ft) high; Santorini must have done as much. The Aegean Sea region is one of the most island-rich areas on Earth. Tsunami in this region must have had a devastating effect on coastal towns and people, as well as leaving profound impressions on survivors, who passed these memories down to succeeding generations. The tales of Plato, the excavations by archaeologists, and the reconstructions by volcanologists all point to a remarkably consistent story.

This overpowering eruption was addressed by Loren Eiseley in his poem *Knossus.*

They died in one night, the pillars of the
palace buckling,
great stones cast down, the galleys
beached on the shore, ruin and ashes
assailing men from the sky.
Thera, the burst throat of the world,
coughing fire and brimstone
there to the north, its voice like the
bellowing of a loosed god
long propitiated to no purpose.
We have known it in our own lives—
the fear of the moving atoms, but
these people
endured the actual megaton explosion,
and their
remnants
faded from history, while the timeless,
practical
Egyptians
regretted a small loss of trade.
Civilizations die as men die, by
accident then.

SUMMARY

Some of Earth's internal heat causes rock to rise via convection and then to melt near the surface and erupt as volcanoes. Spreading centers provide such ideal settings for volcanism that 80% of all extruded magma occurs there. Plates pull apart, and magma rises up the fractures with relatively peaceful eruptions. Subduction-zone eruptions involve magma contaminated by incorporated crustal rock, yielding high-viscosity, gas-rich magma that erupts explosively. Transform faults and continent-continent collision zones have little or no volcanism associated with them.

Hot rock at depth rises buoyantly. This hot rock may melt near the surface and become magma due to increased temperature, decreased pressure, and/or increased water content. Most magma is produced as pressure is lowered on rising hot rock via decompression melting or an increase in its water content. When magma nears the surface, gases come out of solution and help cause volcanic eruption. Whether magma erupts peacefully or explosively depends on magma types. Eruption styles and volcanic landforms can be understood via the three Vs of volcanology—viscosity, volatiles, volume. Beneath the ocean basins, magmas are basaltic in composition with low contents of SiO_2, low weight % content of water, and high temperatures, producing low viscosity, easy escape of volatiles (gases), and peaceful eruptions. Beneath continents, rising basaltic magmas are contaminated by melting continental-crust rocks, thus altering magma compositions. The resultant andesitic-to-rhyolitic magmas have high contents of SiO_2, high weight % content of water, and relatively low temperatures, producing high viscosity, difficult escape for volatiles, and explosive eruptions.

When magma reaches the surface and gas escapes easily, lava flows result. Low-viscosity lava flows may build shield volcanoes much wider than they are tall, as are found in Hawaii, for example. If gas percentage is high and the gases are trapped in magma, explosions result, blasting pyroclastic debris into the air. A scoria cone may be built around a volcanic vent by the settling of pyroclastic debris (e.g., Paricutin). Tall symmetrical volcanic peaks are usually stratovolcanoes built of alternations of lava and pyroclastic material (e.g., Vesuvius).

The volcanic explosivity index (VEI) measures the size of volcanic eruptions on a scale of 0 to 8. Between the years 1500 and 2011, one VEI 7 eruption occurred (Tambora, 1815), along with five VEI 6 events (e.g., Krakatau, 1883; Pinatubo, 1991).

Calderas form when roofs collapse into partially emptied magma chambers. This can occur when a stratovolcano is too weak to stand and its peak collapses downward (e.g., Crater Lake, Oregon). If the peak falls into the ocean, major tsunami can result (e.g., Santorini, 1628 BCE; Krakatau, 1883). The biggest explosive eruptions occur on continents, where collapses may be bigger than mountains at resurgent calderas (e.g., Yellowstone).

TERMS TO REMEMBER

aa 154
andesite 140
basalt 158
base surge 160
caldera 163
cinder cone 160
composite volcano 160
crater 160
crystallization 149
decompression melting 152
flood basalt 159
geyser 156
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obsidian 154
pahoehoe 154
Plinian eruption 160
plutonic rock 149
pore 156
pumice 154
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rhyolite 149
rock 149
scoria 154
scoria cone 160
shield volcano
stratovolcano 160
ultra-Plinian 164
viscosity 148
volatile 150
volcanic rock 149

QUESTIONS FOR REVIEW

1. Mount Vesuvius is one of the world's most active volcanoes, yet it has quiet intervals lasting how long? Compare the times between major eruptions to a human life span.
2. Sketch a map of an idealized tectonic plate and evaluate the volcanic hazards along each type of plate edge.
3. What percentage of magma erupted each year comes out at spreading centers? At subduction zones? At hot spots?
4. What changes in temperature, pressure, and water content cause hot rock to melt? What are the two most relevant melting agents?
5. What common elements combine to form most igneous rocks?
6. What minerals combine to form most igneous rocks?
7. Contrast the differences between basaltic and rhyolitic magma in terms of SiO_2 percentage, weight % water content, temperature, viscosity, and mode of gas escape.
8. How does explosiveness vary between magmas that have a low versus a high weight % content of water?
9. If gas escapes easily from a magma, will the eruption be peaceful or explosive? If gas cannot escape easily, will the eruption be peaceful or explosive?
10. Volcanoes in the ocean tend to erupt peacefully, whereas volcanoes on continents tend to erupt explosively. What explains the differences?
11. Why do volcanoes above subduction zones erupt more explosively than volcanoes at spreading centers?
12. What determines whether volcanic activity will be a lava flow or a pyroclastic eruption?
13. Which magma will make a better lava flow—basalt or rhyolite?
14. Draw a cross-section illustrating a Plinian eruption.
15. Explain the factors controlling the volcanic explosivity index (VEI).
16. Play the three Vs game. Pick various low, medium, and high values for viscosity, volatiles, and volume, and then describe the resultant eruption styles and volcanic landforms.
17. Draw a cross-section showing the difference between a shield volcano and a stratovolcano.
18. Draw a cross-section and describe the collapse of an oceanic volcano, such as Krakatau. What usually is the biggest killer in this process?
19. Explain the eruptive behavior of a hot spot–fed volcano on a continent.
20. How might a volcanic eruption create its own weather?
21. Diagram and explain the sequence of events leading to a geyser eruption. Include temperature and pressure changes in your answer.

QUESTIONS FOR FURTHER THOUGHT

1. Why do people keep returning to a volcano, such as Vesuvius, and building new cities?
2. Evaluate this message: Plate boundaries are bad news.
3. Would you rather watch a volcano erupt in Hawaii or Washington? Why?
4. List the beneficial aspects of volcanoes and volcanism.
5. What evidence suggests that the eruption of the volcano Santorini led to the enduring tale of the lost civilization of Atlantis?British Columbia—Queen Charlotte Island