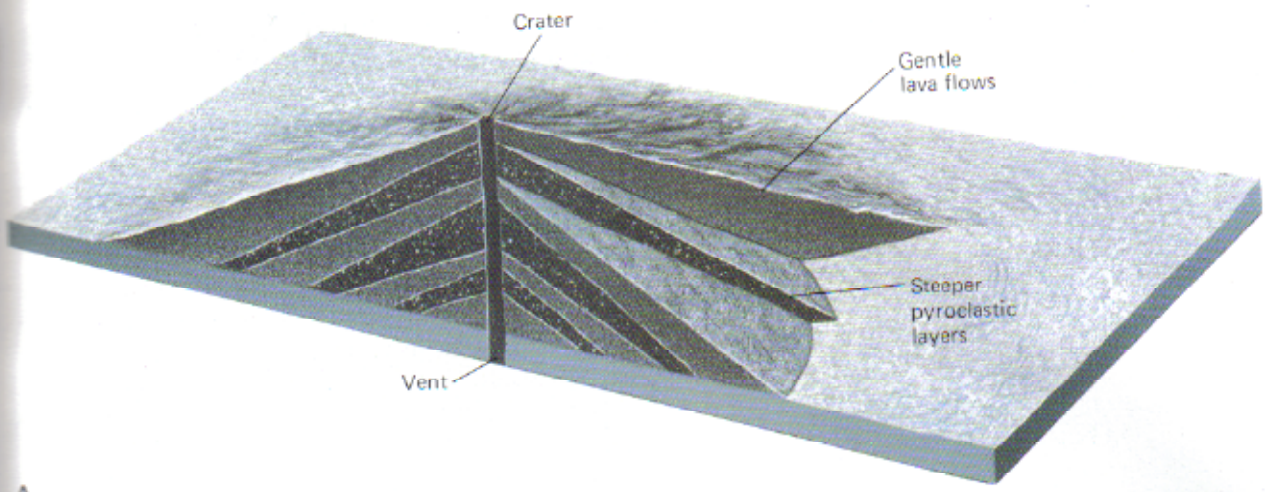


A

B

Figure 4–16 (A) A schematic cross-sectional view of a composite cone. (B) Eruption of Ngauruhoe volcano, a composite cone. (Courtesy of Don Hyndman.)

the border between Chile and Argentina. Like many other composite volcanoes, Aconcagua has been eroded by glaciers and streams, which have carved a precipitous face on the south side of the mountain. To climb the mountain by this side you must be a skilled technical climber. However, the western side has not been severely eroded, and the slope there is representative of the angle formed during the mountain's eruptive history. If you can endure the cold and the altitude, you can easily walk to the summit from the west (Fig. 4–17).

Many composite volcanoes form spectacular mountains along the west coast of North America. Two examples are Mount St. Helens and Mount Rainier (Fig. 4–18). Mount St. Helens erupted in 1980, but Mount Rainier has been dormant in recent times. However, Mount Rainier could become active at any moment; intermittent eruption is one of the trademarks of composite volcanoes.

Volcanic Necks and Pipes

After an eruption, the vent of a volcano may remain filled with magma that later cools and solidifies. Since the cooling and solidification occur underground, rock formed in this manner is technically intrusive. However, the cooling occurs so close to the surface that this intrusive volcanic rock is fine grained and closely resembles extrusive rocks. Commonly this core, called a **volcanic neck**, is

A

B

Figure 4–17 (A) The north side of Aconcagua has not been eroded severely and consequently the slope angle is gentle. (B) The summit ridge of Aconcagua. The relatively gentle north side slopes off to the right. On the left, the eroded, precipitous south face drops off into the shadow. (Courtesy of Mugs Stump.)

harder than the surrounding mountain. Given enough time, the slopes of a volcano may erode, leaving only the tower-like neck exposed (Fig. 4–19).

In some locations, long vertical tunnels called **pipes** extend from the asthenosphere to the Earth's surface. They are the conduits through which magma passed on its way to erupt at a volcano. Pipes become filled with the last bit of magma supplied to the overlying volcano. They are both fascinating and economically important. Most known pipes formed between 70 and 140 million years ago. For a reason that is not well understood, most pipes are emplaced in continental crust that is older than 2.5 billion years. Pipes are interesting because the volcanic rocks now found in them appear to have originated in the asthenosphere. This rock is among the few direct samples of the upper mantle available to geologists; it is commonly a biotite-bearing peridotite called **kimberlite**.

The best evidence indicates that the forces in the asthenosphere were so great that the kimberlite magma traveled upward through the upper mantle and crust at very high, perhaps even supersonic, speeds. Some pipes are commercially important because they contain small concentrations of carbon, which crystallizes as diamond at the intense pressures found in the asthenosphere. The most famous of these structures are the diamond-rich kimberlite

Figure 4–18 Mount Rainier. (Courtesy of Don Hyndman.)

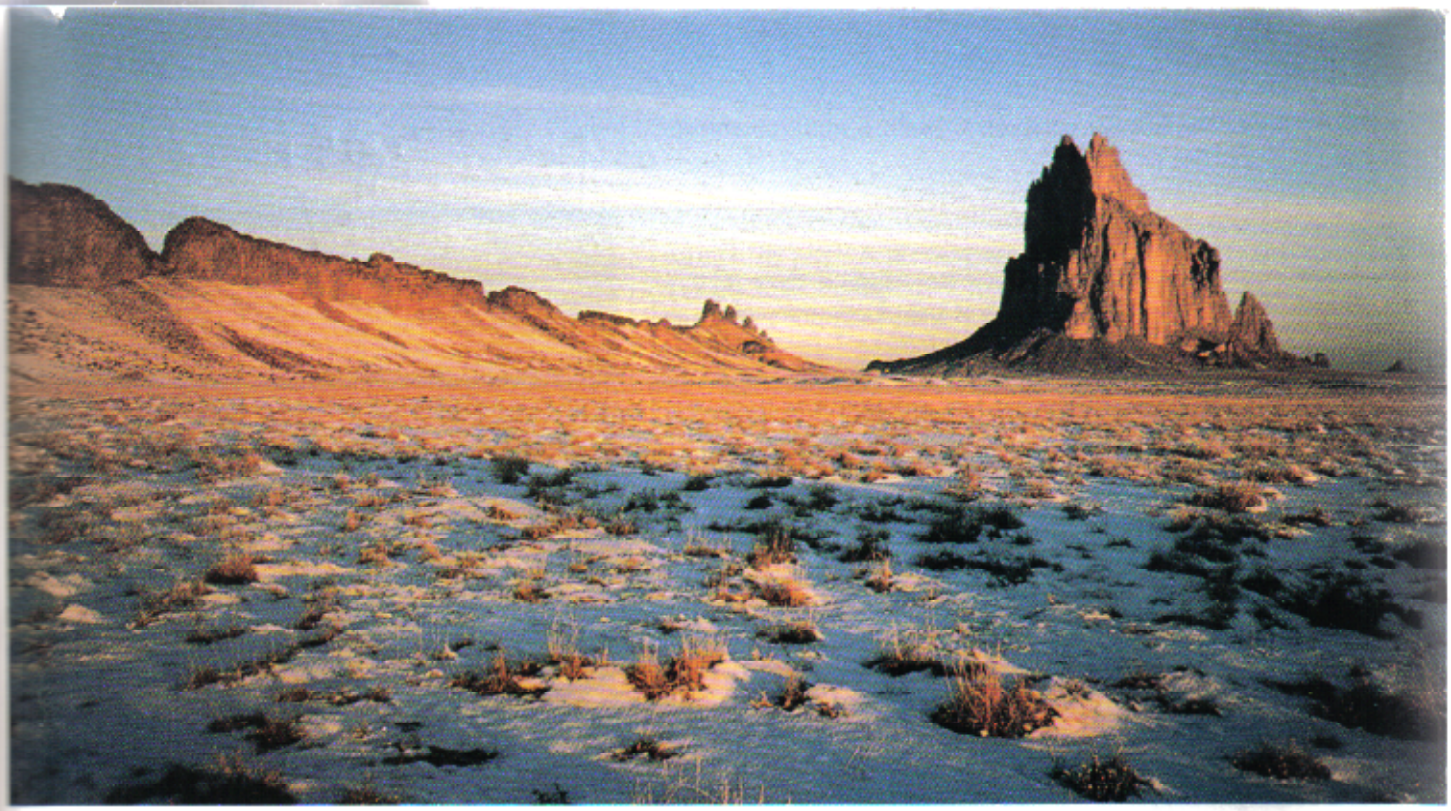


Figure 4–19 Shiprock, a volcanic neck. The free-standing rock that we see today was originally the core of a volcano. The outer flanks of the mountain have eroded away. A dike, several kilometers long, extends to the left. (Courtesy of Dougal McCarty.)

pipes of South Africa. The diamonds crystallized more than 200 kilometers beneath the surface and were then transported upward by the rising magma to depths that can be accessed by modern mining technology.

4.4 The Truly Violent Magmas: Ash-Flow Tuffs and Calderas

Violent Magmas

As we saw in Section 4.1, granitic magmas usually solidify within the Earth's crust due to their high viscosity and because they lose large amounts of water as they rise. Some granitic magmas do, however, rise all the way to the Earth's surface, where they characteristically erupt with great violence. These granitic magmas that rise to the Earth's surface probably start out with a considerably lower water content than "normal" granitic magma, perhaps only a few percent, like basaltic magmas. With such a low water content, a granitic magma would rise to the Earth's surface for the same reasons that a basalt magma does. Why is the volcanic behavior of such magmas so violent and dangerous? What sequence of events leads to the explosive eruptions of this kind of magma?

"Dry" granitic magmas probably rise through the Earth's crust more slowly than basalt magmas due to the higher viscosity resulting from their higher silica content. As a magma of this type rises toward the Earth's surface, the pressure decreases. With the decrease in pressure, the small amount of water and other volatiles (mainly carbon dioxide) that were dissolved in the magma begin to separate to form independent bubbles of gas in the liquid magma (Fig. 4–20A). The water forms a gas rather than a liquid because the temperature is still that of a magma, high enough to turn the water to steam.

As an analogy, think of a bottle of beer or soda pop. When the cap is on and the contents are under pressure, the carbon dioxide gas is dissolved in the liquid. Because the gas is dissolved, there are no visible bubbles. If you slowly start to remove the cap, the pressure is reduced. As a result, the gas escapes from solution and bubbles form and rise to the surface. If the conditions are favorable, the frothy mixture of gas and liquid will erupt through the opening.

In a similar manner, gas bubbles form in a magma body. The gas rises and mixes with the liquid magma to create a frothy, expanding mixture of gas, liquid magma, and whatever crystals may have begun to form. The temperature of this mixture may still be as high as 900°C. As the entire magma body rises to within a few kilometers of the Earth's surface, it creates a blister, or a dome, by uplifting and fracturing the overlying rocks. Fractures commonly occur in this roof rock in a roughly circular pattern,

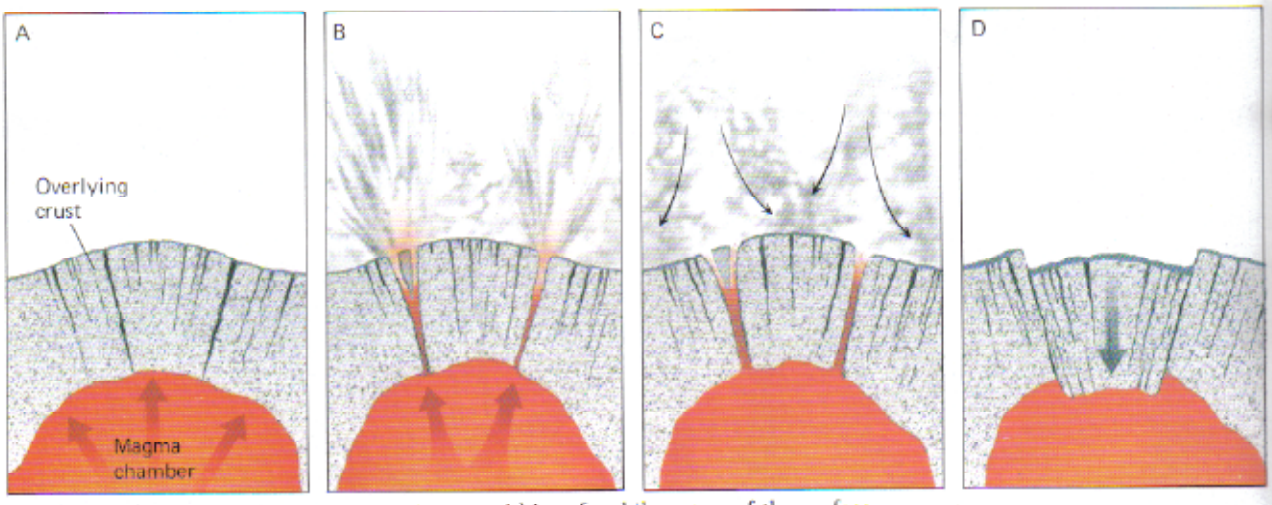


Figure 4–20 (A) As a granitic magma rises to within a few kilometers of the surface, it causes the overlying rock to dome upward and fracture. Gases separate from the magma and concentrate in the upper part of the magma body. (B) The gas-rich magma explodes upward through the main fractures near the periphery of the magma body, creating a vertical column of magma, rock fragments, and gas. (C) When the gas is used up, the vertical column collapses and spreads outward as an ash flow at high speeds, following topographically low areas. (D) Because so much material has erupted from the upper part of the magma chamber, the roof collapses downward to form a caldera.

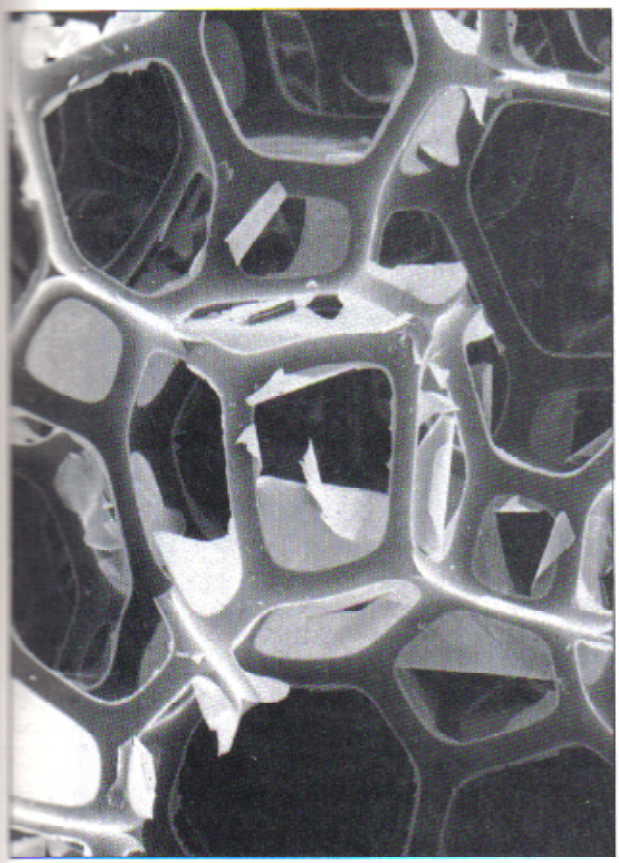
defining the outline of the magma body. As the first of the mixture forces its way through the fractures toward the surface, the decreased pressure allows more and more gas to come out of solution to create more of the hot frothy mixture. In a short time, the gas pressure in the upper part of the magma chamber becomes so high that the mixture of magma, gas, and crystals erupts explosively through the cracks in the roof rock (Fig. 4–20B).

The amount of material ejected in an eruption of this type depends on the size of the magma body and the amount of gas available. In a large eruption, the column of rising pyroclastic material may reach a height of 12 kilometers above the Earth's surface and be several kilometers in diameter. A cloud of fine ash may be blown upward to much greater heights, even into the upper atmosphere. The height of the column is an expression of the explosive violence of the eruption. The column may be held up for several hours or even days by the force of additional material streaming out of the magma chamber.

Ash Flows

When the supply of gas in the upper part of the magma is used up, the eruption ceases rapidly. Since no more material is streaming upward to support it, the frothy column falls back to the surface of the Earth (Fig. 4–20C). The material that made up the column consists mostly of gas (water and carbon dioxide from the magma plus trapped atmospheric gases), glassy magma bubbles, frothy liquid magma, crystals from the magma, and rock fragments that were ripped away from the roof overlying the magma body. Although the material of the collapsing column contains some solid particles, it behaves as a fluid falling from a considerable height. When it reaches the surface of the Earth it flows outward from its point of impact. Because the fluid is denser than air, it follows stream valleys and other topographical lows. Such flows are known as **ash flows**. Observations of relatively small ash flows show that they can travel at speeds of up to 200 kilometers per hour. Larger flows are known to have traveled distances exceeding 100 kilometers. One large flow is known to have crossed over a 700-meter-high ridge as it crossed from one valley into another. The lower parts of small ash flows racing across the land at night have been seen to glow brightly because of their high temperature. For this reason, an ash flow is also called a **nuée ardente**, from the French term for "glowing cloud."

When an ash flow comes to a stop, much of the gas escapes into the atmosphere, leaving a chaotic mixture of volcanic ash, crystals, and rock fragments picked up along the way. Chunks of the frothy magma may solidify to form **pumice**, a rock so full



Scanning electron photomicrograph of pumice. (Courtesy of Kenneth Neuhauser.)

of gas bubbles that it can float on water. The rocks formed by such a process are **ash-flow tuffs** (Fig. 4–21). **Tuff** includes all pyroclastic rocks, that is, any rock comprised mainly or exclusively of volcanic ash or other material formed by a volcanic explosion. In some cases, ash flows are hot enough to deform plastically and partially melt after they stop moving. The rocks that result are commonly very tough and hard and are called **welded tuffs** or **welded ash-flow tuffs**. Welded tuffs often show spectacular structures and textures that result from deformation and flowage after the ash flow stopped moving (Fig. 4–22). Other ash-flow tuffs are unwelded.

A single large eruption may eject a few hundred to a few thousand cubic kilometers of ash. To visualize the quantity of material involved, think of a cube of rock with a volume of 1000 cubic kilometers. The perimeter of the base would be 40 kilometers, or just slightly less than the length of a marathon race. A world-class distance runner could circle it in a little over two hours. The height from the base to the top would be 10 kilometers or 10,000 meters, which is 2000 meters greater than the distance from sea level to the top of Mount Everest. The largest known ash-flow tuff from a single eruption is in the San Juan Mountains of southwestern Colorado and has a volume greater than 3000 cubic kilometers. Another of comparable size has been mapped in southern Nevada.

Figure 4–21 Ash-flow tuff forms when an ash flow comes to a stop. The fragments within the rock are pieces of pumice that were carried along with the volcanic ash and gas. (Courtesy of Geoffrey Sutton.)

Figure 4–22 Welded tuff forms when an ash flow is hot enough to partly melt and flow as a plastic mass after it comes to a stop. The streaky texture formed as pumice fragments similar to those in Figure 4–21 melted and were smeared out as the rock flowed. (Courtesy of Geoffrey Sutton.)

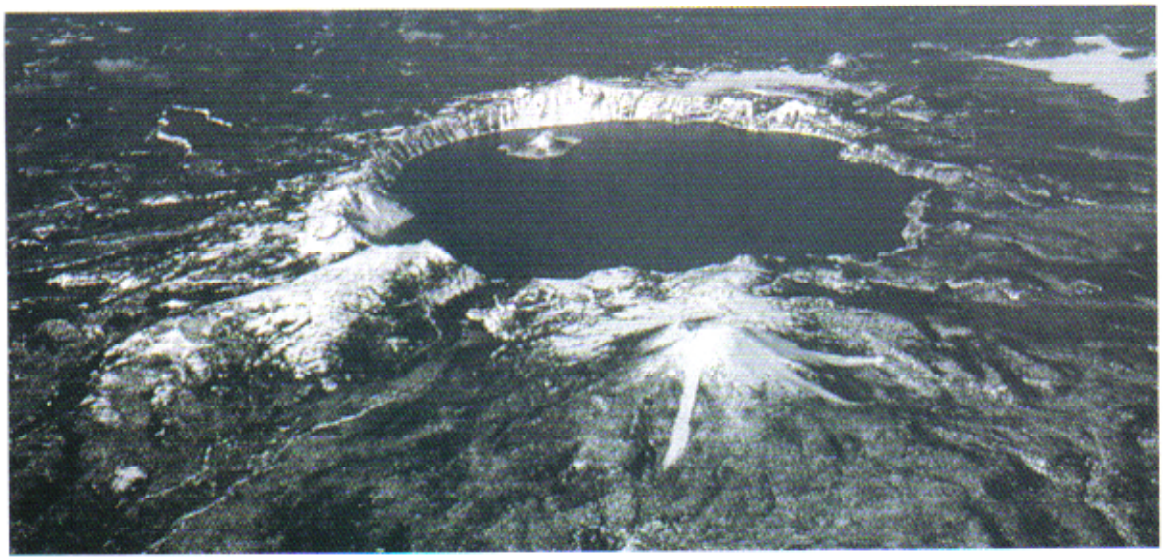


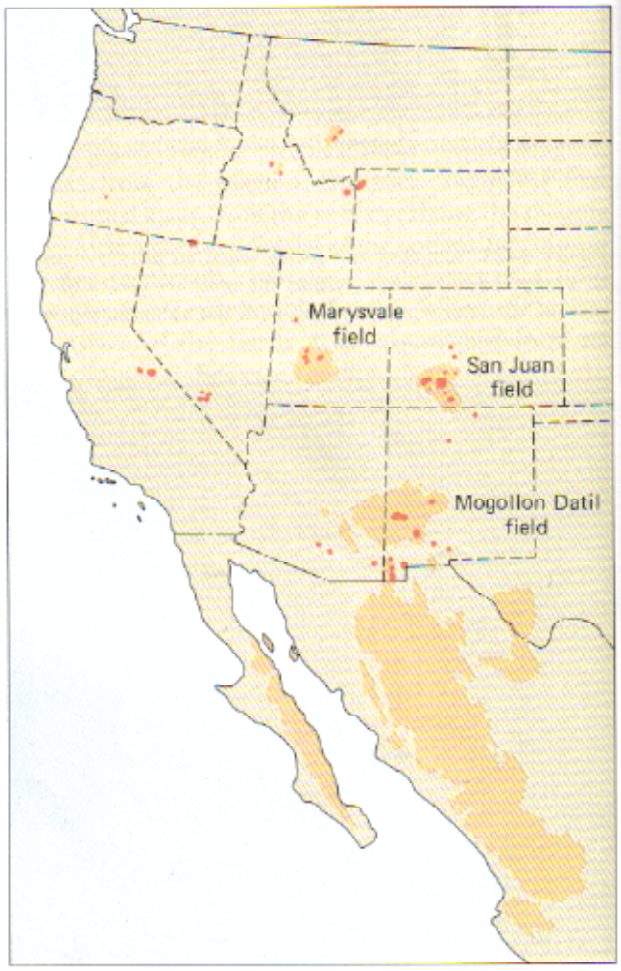
Figure 4–23 Crater Lake, Oregon, shows preservation of caldera topography. (Copyright Science Graphics, Inc./Ward's Natural Science Establishment, Inc.)

Calderas

Think for a moment of what must happen back in the magma chamber when such an immense volume of material is suddenly removed. When this large volume is ejected, there is nothing left to hold up the overlying roof rock. Therefore, the roof of the magma chamber simply collapses downward (Fig. 4–20D). Most large magma bodies are roughly circular when viewed from above. Consequently, roof collapse associated with eruption of ash-flow tuffs usually results in a circular depression called a **caldera**. Large calderas may be 20 to 40 kilometers in diameter and show as much as a kilometer of down-dropping of the roof. Some calderas fill up with ash-flow tuff as the ash column collapses; others show remarkable preservation of the topography resulting from roof collapse (Fig. 4–23). We usually think of volcanic landforms in terms of gracefully symmetrical cones. Calderas, as topographic depressions, are interesting exceptions to this notion.

Only in the last decade or so has it been recognized that calderas and ash-flow tuffs make up a significant portion of the surface geology of western North America. Although most ash-flow tuffs had been recognized as being of volcanic origin, the details of that origin were previously obscure. Figure 4–24 shows the extent of ash-flow tuffs and related rocks in western North America. It is clear that they are of major importance in the geology of southwestern Colorado, Nevada, Utah, eastern California, Arizona, New Mexico, and Mexico.

Figure 4–24 Distribution of calderas (red shading) and ash-flow tuff fields (orange shading) in western North America.



Magmas that produce ash-flow tuffs and calderas commonly erupt more than once, with substantial time intervals between eruptions. Following an initial eruption, the remaining upper part of a magma body is depleted in gases and has consequently lost its explosive potential. However, lower portions of the magma continue to release gases, which rise to concentrate in the upper portion of the magma. These gases accumulate until pressure increases enough to begin a new cycle of eruption. The time interval between successive eruptions varies from a few thousand to about a half million years.

Yellowstone National Park

Yellowstone National Park is the oldest national park in the United States and is located in northwestern Wyoming and southern Montana. The geology of Yellowstone Park is dominated by three large overlapping calderas and the ash-flow tuffs that erupted from them (Fig. 4–25). The oldest of the three eruptions formed the 2500-cubic-kilometer Huckleberry Ridge Tuff and the Big Bend Ridge caldera and occurred 1.9 million years ago. The Big Bend Ridge caldera is an elongate depression about 25 by 40 kilometers, with walls up to 1 kilometer

Figure 4–25 The calderas and ash-flow tuffs of Yellowstone Park. The Big Bend Ridge caldera formed during the eruption of the Huckleberry Ridge Tuff 1.9 million years ago. The Henry's Fork Caldera formed during the eruption of the Mesa Falls Tuff 1.3 million years ago. The Yellowstone Caldera formed during the eruption of the 0.6 million year old Lava Creek Tuff. Portions of older calderas are obliterated by younger calderas. Dashed boundaries of the Huckleberry Ridge and Mesa Falls Tuff are covered by younger rocks. Figure modified from Hildreth *et al.* (1984). *Journal of Geophysical Research*, Vol. 89.