The many hot springs and geysers in Yellowstone National Park have formed because hot magma lies close to the surface. This photograph shows Old Faithful geyser. (Courtesy of National Park Service.)

high, although portions of the walls are obliterated by the two younger calderas. The next major eruption produced the smaller Henrys Fork caldera 1.3 million years ago. The most recent eruption, 0.6 million years ago, produced the Yellowstone caldera in the very center of the park, along with the 1000-cubic-kilometer Lava Creek Tuff.

Yellowstone Park is famous for its numerous geysers and hot springs. Geysers and hot springs often form when groundwater is heated by a shallow magma chamber. The hot water then rises to the surface. This activity is often cited as evidence that an active body of magma still exists beneath Yellowstone Basin. Today, the region is continuously monitored by the United States Geological Survey with devices called **seismographs**, which detect earthquakes. Seismographs are so sensitive that they also detect motions of liquid magma within the Earth's crust. Seismographic evidence supports our empirical observations that liquid magma exists below the surface at Yellowstone.

Consider the periodicity of the three Yellowstone eruptions. They occurred at 1.9, 1.3, and 0.6 million years ago. A 0.6- to 0.7-million-year interval has occurred between each of the eruptions. It has been 0.6 million years since the last eruption. The periodicity of Yellowstone eruptions, the presence of magma at shallow depths, and the well-known tendency of magmas of the Yellowstone type to erupt multiple times all suggest that a fourth eruption may be due. Geologists would not be surprised if an eruption occurred at any time. However, arguments based on periodicity are only approximate. Even if the periodicity were exactly 0.6 million, or 600,000 years, a 1 percent error is 6000 years. Thus, it is conceivable that the next eruption will not occur for several thousand years. It is also possible that Yellowstone has seen its last eruption.

The Long Valley Caldera, California

A situation somewhat similar to that in Yellowstone is found near Yosemite National Park in eastern California. Here the 170-cubic-kilometer Bishop Tuff erupted from the Long Valley caldera 0.7 million years ago. Only one major eruptive cycle has occurred to date in this area, but seismic monitoring indicates that active magma may be located in the vicinity of Mammoth Mountain, a popular California ski area, on the southwest edge of the Long Valley caldera.

4.5 Magma-Forming Environments

Magma forms in large quantities in three geologic environments. Recall that the lithosphere consists of seven major plates separated by large systems of cracks, and that the plates move relative to one another. At the plate boundaries (the cracks), there are three different kinds of relative motion. The first is collision, where two plates meet head on. If at least one of the plates carries oceanic crust, one plate dives beneath the other in a process called "subduction." The second type is rifting, where two plates are spreading apart from one another, and the third is transform motion, where two plates are sliding horizontally past one another. Two of these three types of plate boundaries, subduction zones and rifts, are environments in which large amounts of magma form. Only minor amounts of magma form at transform boundaries. The third type of magma-forming environment is known as a hot spot, many of which have little or nothing to do with plate boundaries.

Subduction Zones

At a **subduction boundary** (Fig. 4–26), the downgoing lithospheric plate dives into the asthenosphere. Three factors can cause large volumes of

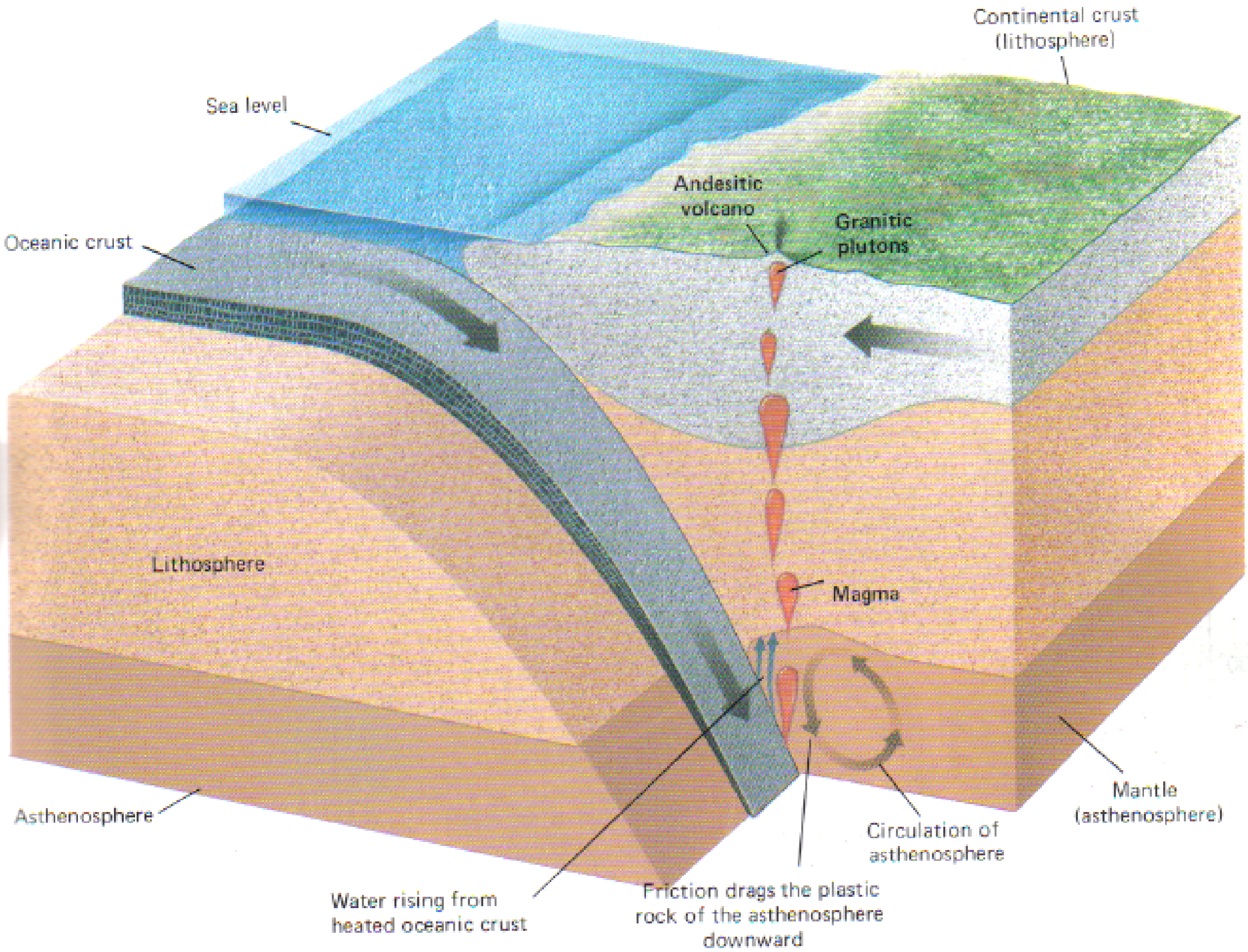


Figure 4–26 Cross-section of a portion of the Earth showing a lithospheric plate carrying oceanic crust subducting beneath another plate carrying continental crust. Friction between the subducting plate and the overlying asthenosphere drags part of the asthenosphere down with the plate, shown by downward arrows. Rock from deeper in the asthenosphere rises (upward arrows) to replace the sinking part of the asthenosphere. The rising asthenosphere rocks melt due to pressure relief and the addition of water from the downgoing oceanic crust. In this way, large volumes of magma form above the subducting plate. The west coast of South America is an example of this type of plate boundary.

hot rock in the asthenosphere near the subducting plate to melt. Obviously, one is an increase in temperature. Heat is generated by friction as the subducting plate scrapes past the opposite plate. Because the asthenosphere is already hot, this additional heat contributes to the melting of nearby rocks.

As the subducting plate descends, friction drags the plastic rock of the asthenosphere downward with the plate, as shown by the arrows in Figure 4–26. Other rock from deeper in the asthenosphere must then rise to replace the sinking part of the asthenosphere, as shown by the rising arrows. Recall that the rock of the asthenosphere is so hot that 1 to 2 percent of it is melted. As parts of the asthenosphere rise, the pressure on those rocks decreases and pressure relief melting generates huge volumes of magma above the subducting plate.

Addition of water is the third factor that can cause a hot rock to melt. In general, rocks containing water have lower melting points than rocks of identical composition with no water. The higher the water content of a rock, the lower its melting point. Oceanic crust contains substantial amounts of seawater incorporated into oceanic sediments and the upper layers of basalt. These water-rich rocks become heated as they dive into the mantle in a subduction zone. All of the water is driven off by the increasing temperature and rises into the overlying mantle. This addition of water aids in the production of large volumes of magma in the asthenosphere directly over a subducting plate.

To summarize, melting of asthenosphere rocks above a subducting plate is due to three factors: (1) frictional heating, (2) pressure relief melting, and (3) addition of water from subducting oceanic

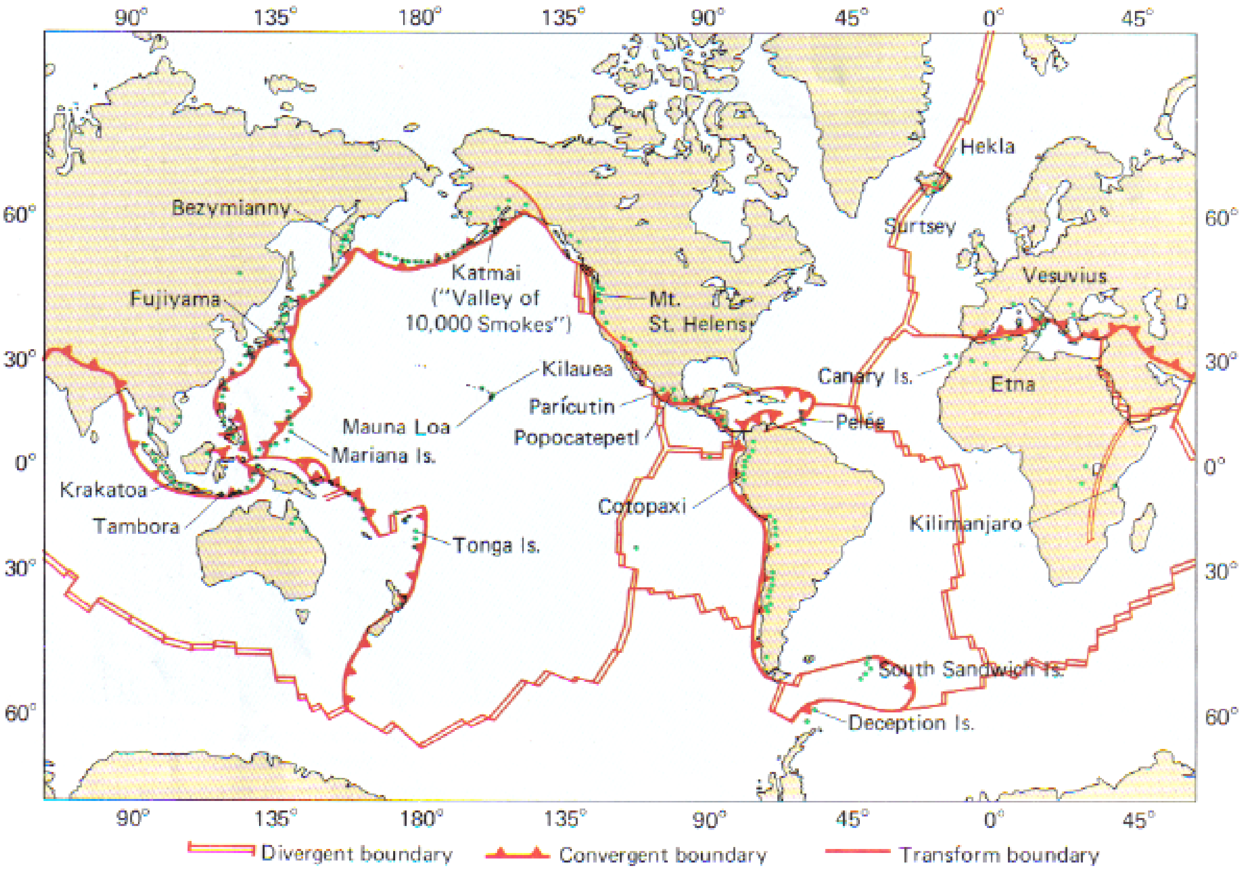


Figure 4–27 The relationship between plate boundaries and explosive volcanic activity. The dots show the location of recent violent eruptions, and the lines show major plate boundaries.

crust. The largest amount of melting and magma production occurs at depths of about 100 kilometers, approximately where the subducting plate passes from the lithosphere into the asthenosphere.

Volcanic Activity at Subduction Zones

A map showing the locations of major violent volcanoes and subduction zones shows the close correspondence between the two (Fig. 4–27). The west coast of the Americas from Chile to Alaska and the east coast of Asia from Siberia to New Zealand, including Japan, the Aleutian Islands, Central America, and the Cascade Range of western Washington and Oregon, form the "ring of fire" around the Pacific Ocean. About 75 percent of the Earth's active volcanoes lie along this zone of active subduction and volcanic activity.

All 18 volcanoes of the Cascade Range, from Mount Baker near the Canadian border to Mount Lassen in northern California, have been active in the past 2 million years, fired by subduction occurring along the west coast of Oregon and Washington. Mount St. Helens erupted in 1980, and Mount Lassen in 1915. About 7000 years ago, a 3000-meter-high Cascade volcano, Mount Mazama, exploded and ejected 10 cubic kilometers of pyroclastic debris. Most of the mountain was blasted away by the explosion, leaving what is now Crater Lake, Oregon (Fig. 4–28). Ash from the eruption is found in soils over much of western and central North America.

All of the volcanoes of the Cascade Range are located in the same active subduction zone as Mounts St. Helens, Lassen, and Mazama. Some exhibit signs of activity today. Mount Baker has recently experienced earthquake swarms, and gases regularly escape from its crater. Mount Rainier has steam caves under its summit glaciers. It is reasonable to predict that the Cascades will see additional eruptions, although it is impossible to predict where and when they will occur and their magnitude. The eruption of Mount St. Helens was very small compared with other known eruptions from similar types of volcanoes.

Figure 4–28 Crater Lake in Oregon. (Courtesy of Crater Lake National Park Administration.)

Rift Zones

As two lithospheric plates separate at a rift boundary, soft, hot asthenosphere rises to fill the gap left by the spreading plates (Fig. 4–29). As the asthenosphere rises below the rift, pressure relief melting forms vast quantities of basalt magma. Most of the world's rift boundaries are in the ocean basins, where they form mid-oceanic ridges. It is this mechanism that is responsible for the fact that basalt makes up most of the oceanic crust.

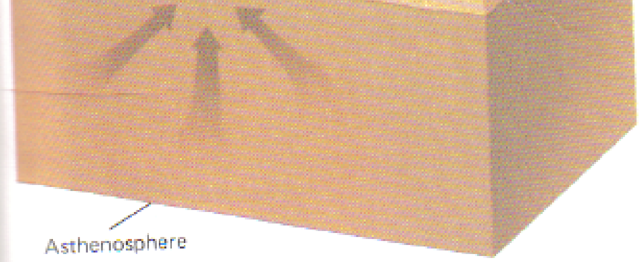
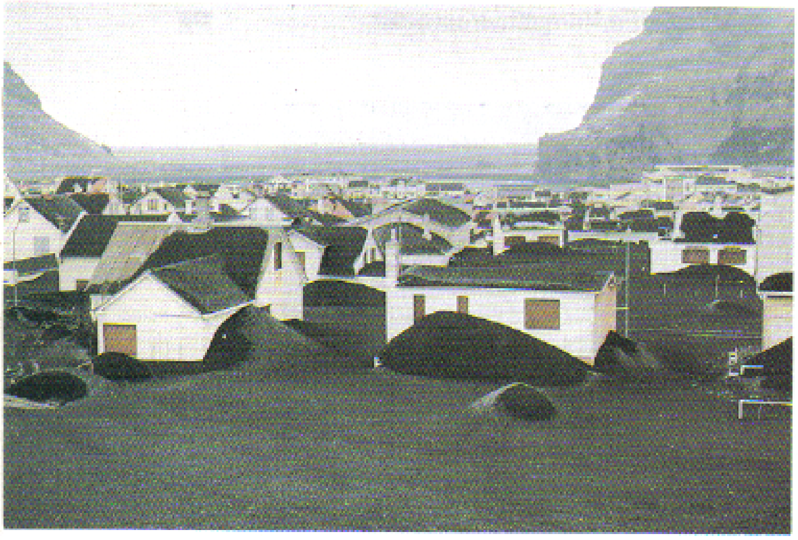


Figure 4–29 At a rift zone, pressure relief melting occurs where hot asthenosphere rises to fill the gap left by separation of two spreading plates.

Volcanic Activity at Oceanic Rift Zones

The island of Iceland in the North Atlantic Ocean is about the size of Virginia and supports a population of a quarter of a million people. It lies directly over the Mid-Atlantic ridge and therefore right on a rift boundary. The island was formed by repeated basaltic volcanism originating from the Mid-Atlantic ridge. Iceland has experienced numerous eruptions since its settlement by Vikings, prior to A.D. 1000. Some of the eruptions have covered villages with ash and cinders. Although some destruction occurs, human injury and death as a result of volcanic activity have been rare. Hot springs and hot rock resulting from recent volcanism are used to generate electrical power for the island, and the spectacular volcanic scenery is a major tourist attraction.



Ash from a volcanic eruption nearly buried the town of Heimay in Iceland. (Courtesy of James Andanson—Sygma.)

Hot Spots

The third environment in which magma commonly forms is known as a **hot spot**. Although not nearly as much magma forms at hot spots as in the other two environments, some interesting and important geological activity occurs at hot spots. Subduction zones and rift zones occur at plate boundaries. In contrast, a hot spot is a volcanic center directly above a rising plume of hot, plastic mantle rock. As this **mantle plume** rises, pressure relief melting forms basalt magma that rises to the Earth's surface.

Volcanic Activity at Oceanic Hot Spots

If a mantle plume occurs in the asthenosphere beneath oceanic crust, eruption above the mantle plume builds submarine volcanoes and volcanic islands (Fig. 4–30). Because lithospheric plates move over the relatively stationary asthenosphere, a hot spot may generate magma continuously as a plate migrates past the location of the hot spot. In this way a chain of volcanic islands may form.

The island of Hawaii is composed of several overlapping shield volcanoes formed above a mantle hot spot. The youngest, Kilauea, frequently erupts basaltic lava, commonly for periods of weeks or months. As in Iceland, lava flows occasionally destroy homes and agricultural land, but they rarely cause injury or death because eruptions are relatively gentle and the flows advance slowly enough that people can evacuate threatened areas. Because the eruptions are relatively safe, at least from a distance, and because they continue for long periods of time, tourists flock to the island to see real volcanic eruptions.

The Yellowstone volcanic field lies above a hot spot, similar to the hot spot beneath the Hawaiian Islands. Why do oceanic hot spots lead to basalt magmas that erupt fluidly and nonviolently, whereas continental hot spots yield violent volcanoes of granitic character? Both types of hot spots probably start with formation of basaltic magma in the upper mantle. However, beneath a continent, rising basaltic magma intrudes the base of the granitic continental crust, which melts at a temperature a few hundred degrees lower than that of basalt magma. Therefore, the basalt magma melts the lower continental crust, producing granitic magma that mixes with the rising basalt. The magma becomes increasingly granite-like in composition as it continues to rise because it melts and incorporates more continental crust. It then may rise toward the surface to erupt violently.

Figure 4–30 Cross-section of a portion of the Earth showing a volcanic island chain forming above a hot spot and mantle plume.

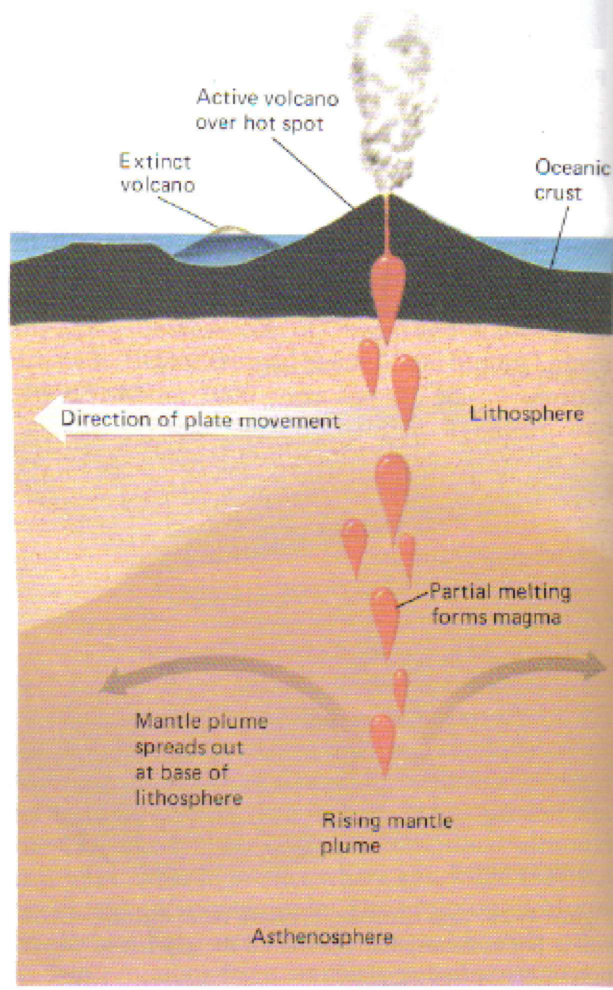


Table 4–2. Some Notable Volcanic Disasters Since the Year A.D. 1000 Involving 5000 or More Fatalities

			Primary Cause of Death and Number of Deaths				
Volcano	*Country*	*Year*	*Pyroclastic Flow*	*Debris Flow*	*Lava Flow*	*Posteruption Starvation*	*Tsunami*
Kelut	Indonesia	1586		10,000			
Vesuvius	Italy	1631			18,000		
Etna	Italy	1669			10,000		
Lakagigar	Iceland	1783				9,340	
Unzen	Japan	1792					15,190
Tambora	Indonesia	1815	12,000			80,000	
Krakatoa	Indonesia	1883					36,420
Pelée	Martinique	1902	29,000				
Santa Maria	Guatemala	1902	6,000				
Kelut	Indonesia	1919		5,110			
Nevada del Ruiz	Colombia	1985		>22,000			

In environments like Yellowstone, basalt flows commonly occur with the much larger volumes of ash-flow tuffs and related rocks because some of the basalt formed in the mantle rises to the surface with the granitic magma.

Continental rift zones commonly produce a mixture of explosive granitic magmas and more gently behaved basaltic flows for the same reasons that continental hot spots do. Melting in the mantle forms basalt magma which melts lower granitic continental crust as it rises. The two different types of magma then rise to erupt in the rift zone.

4.6 Volcanoes and Human Settlements

Volcanic eruptions have led to significant loss of life and destruction of property throughout history. The most destructive eruptions have been of the type described in the previous section, in which gas-charged magma explodes from the upper zones of a shallow magma chamber to form an ash flow. When Mount St. Helens erupted in 1980, it exploded with the force of 500 atomic bombs of the size used on Hiroshima in World War II. Nearly 1 cubic kilometer of rock and ash were ejected, forests were leveled, and despite adequate warning that an eruption was imminent, 63 people were killed. Yet compared with other volcanic eruptions in recent geological history, Mount St. Helens was a small eruption. Table 4–2 summarizes the major known volcanic disasters since A.D. 1000.

Mount Pelée

On May 2, 1902, the coastal town of St. Pierre on the Caribbean Island of Martinique was completely destroyed by an ash flow that erupted from the nearby volcano of Mount Pelée. All but two of the 28,000 residents of the town died nearly instantaneously as an 800°C cloud of gas and volcanic ash

Smouldering ruins of St. Pierre, May 14, 1902, following the May 8 eruption of Mount Pelée. (Courtesy of the Institute of Geological Sciences, London.)