22 Hotspots and Mantle Plumes

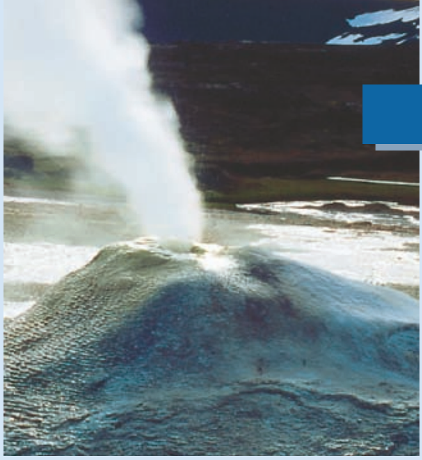
Earth's tectonic system is dominated by geologic processes that occur at the margins of large plates of lithosphere, and our main focus has been on dynamics of these plate boundaries. But plate interiors are not entirely quiet. Several currently active volcanic systems, such as Hawaii and Yellowstone National Park, are far from plate boundaries. Moreover, many large flood basalt provinces, such as those in the Pacific Northwest or central Siberia, have no explanation in simple plate margin dynamics.

Instead, these "hotspots" are believed to be surface manifestations of mantle plumes—long, narrow columns of hot material that flow upward from deep in the mantle—and appear to be independent of plate movements. Apparently, this type of convection stirs the mantle from deep below the shallow zone that feeds the midocean ridges. Thus, mantle plumes provide new information about the inaccessibly deep portions of our planet.

Iceland sits astride the Mid-Atlantic Ridge, and yet it also shows strong evidence for an underlying mantle plume. The hotspot is manifest by geophysical and geochemical studies, but more visibly by numerous geysers, boiling mud pots, and hot springs, such as the one shown in the panorama above. This is a steam eruption at a geothermal field at Hveravellir in central Iceland. More than anything else, these mantle plumes reveal themselves as tremendous thermal anomalies. Not only is water heated to the point that it can flash to steam and create a geyser, but even solid rock may reach its melting point and become partially molten. The magnificent geothermal activity in this area lies within an active volcanic zone that erupts basalt or rhyolite every few years, sometimes spreading ash over much of the North Atlantic Ocean. The most voluminous eruption seen by humans occurred here in 1783. In several areas, molten magma still resides in chambers just a few kilometers below some of the world's most spectacular scenery.

In this chapter, we discuss hotspots and the mantle plumes that appear to lie below them as large and important geologic systems. We will examine the major effects of mantle plumes that ascend beneath the ocean basins and then turn our attention to those that rise beneath the continents. We will also explore what causes plumes to move upward and why they are intimately related to intraplate volcanoes, earthquakes, and broad swells and basins.

Photograph by Ragnar Sigurdsson/Stone.



MAJOR CONCEPTS

1. Mantle plumes appear to be long columns of hot, less dense solids that ascend from deep in the mantle. Mantle plumes create hotspots with high heat flow, volcanism, and broad crustal swells.
2. A plume evolves in two stages. When a plume starts, it develops a large, bulbous head that rises through the mantle. As the head deforms against the strong lithosphere, crustal uplift and voluminous volcanism occur. The second stage is marked by the effects of a still rising but narrow tail.
3. Basaltic magma is created because of decompression of the rising hot plume. Magmas formed in mantle plumes are distinctive and show hints of being partially derived from ancient subducted slabs that descended deep into the mantle.
4. A starting plume that rises beneath the ocean floor produces a large plateau of flood basalt on the seafloor. Subsequently, a narrow chain of volcanic islands forms above the tail of the plume, revealing the direction of plate motion.
5. If a plume develops beneath a continent, it may cause regional uplift and eruption of continental flood basalts. Rhyolitic caldera systems develop when continental crust is partially melted by hot basaltic magma from the plume. Continental rifting and the development of an ocean basin may follow.
6. Plumes may affect the climate system and Earth's magnetic field.

HOTSPOTS AND MANTLE PLUMES

Mantle plumes appear to be long, nearly vertical columns of hot, upwelling materials that buoyantly rise from deep in the mantle. At the surface, plumes are marked by hotspots with high heat flow, volcanic activity, and broad crustal swells.

The first ideas about hotspots and mantle plumes emerged in 1963, from geologic observations of the Hawaiian Islands. It was well known that Hawaii, the largest of the islands, had active volcanoes, few strong earthquakes, and extremely high heat flow. The linear chain of volcanoes lies on a broad rise in the middle of the Pacific Ocean floor.

Significantly, geologists noted an absence of tectonic contraction to form belts of folded strata on Hawaii. Even strong extension is missing, although narrow rift zones emanate from the summits of the **shield volcanoes** and feed lava flows. In addition, it was discovered that the volcanoes on the islands are progressively older toward the northwest (Figure 22.1). For example, the island of Hawaii consists of several still-active shield volcanoes. The volcanoes on Maui, an island about 80 km to the northwest, are barely extinct. Farther to the northwest, the chain of islands becomes still older, and many volcanoes are deeply eroded; some are submerged below sea level.

Mantle Plume

Other linear chains of volcanic islands and seamounts in the Pacific, Atlantic, and Indian oceans show similar trends: An active or young volcano is at one end of the chain, and the series of volcanoes becomes progressively older toward the other end (Figure 22.2). For these reasons, the volcanically active parts of these chains came to be called **hotspots.** We are not completely sure, but the simple idea of **mantle plumes** rising as narrow columns from the deep interior explains many such features and has become a generally accepted part of global tectonic theory. Hotspots appear to be the surface expression of mantle plumes.

Evidence for Mantle Plumes

It must be emphasized that mantle plumes have not been observed directly. But the indirect evidence for their existence is substantial:

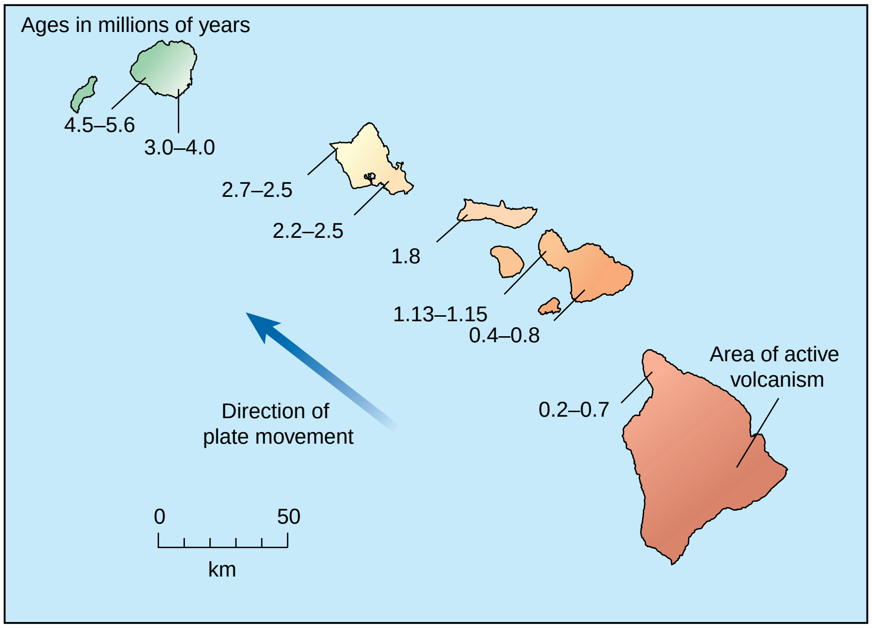


FIGURE 22.1 The volcanic islands of Hawaii are progressively older and more eroded to the northwest. Active volcanoes erupt periodically on the southeasternmost island. A linear chain of seamounts extends even farther to the northwest. Ages of volcanic rocks are given in millions of years before present.

1. Locally, zones of high heat flow and associated volcanism (hotspots) occur far from plate boundaries.
2. These hotspots do not drift with the plates. They are almost stationary, suggesting that they are rooted deep in the mantle far below the moving lithosphere.
3. Geochemical studies show that the basalts erupted from hotspot volcanoes are different from those that come from the upper mantle at divergent plate boundaries. The evidence suggests that the lavas are derived from deep in the mantle, below the asthenosphere (see p. 641).

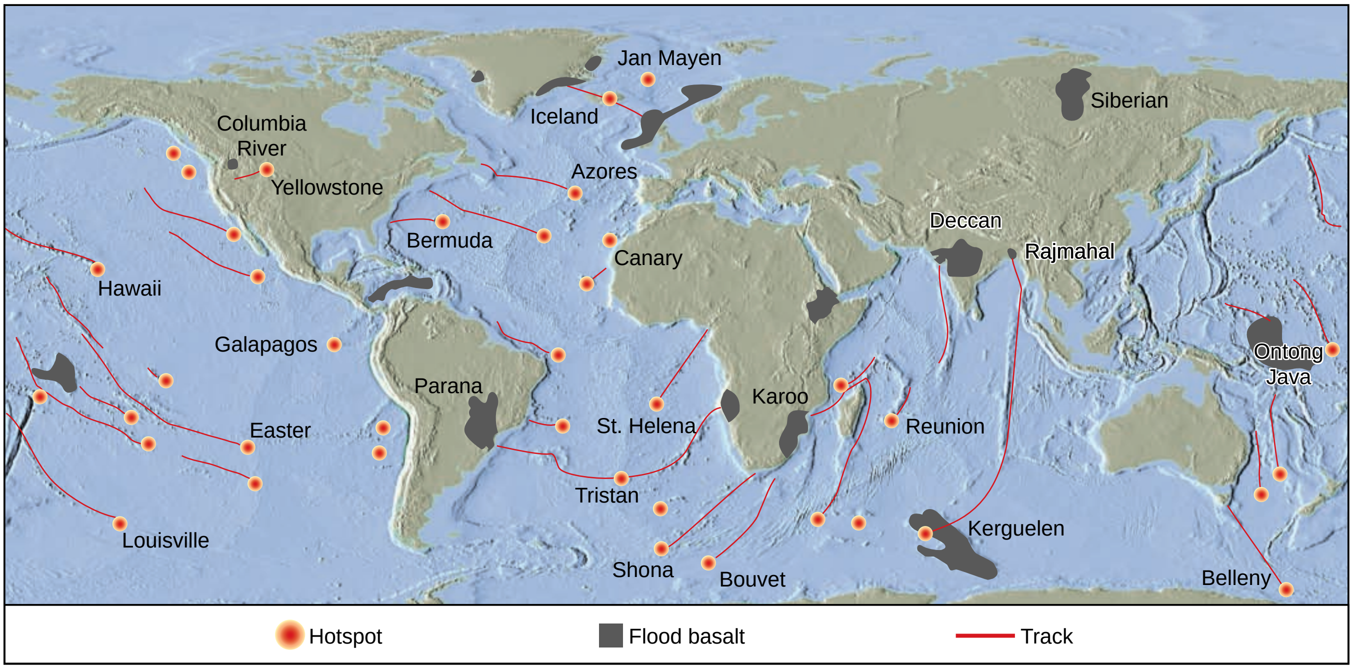


FIGURE 22.2 Hotspots, oceanic plateaus, and continental flood basalts related to mantle plumes are shown on this map. Basaltic volcanism in the ocean basins has formed hundreds of islands, seamounts, and plateaus. Flood basalts, shield volcanoes, and large rhyolitic calderas may form above plumes that lie beneath the continents. Ancient flood basalt provinces (gray) are connected to currently active hotspots by linear chains of seamounts (red lines). For example, the currently active volcanoes on the island of Tristan da Cunha in the South Atlantic mark the site of a hotspot whose initiation erupted flood basalts in South America and Africa approximately 125 million years ago. In the North Atlantic, two flood basalt provinces, 65 million years old, are linked to a plume beneath Iceland. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

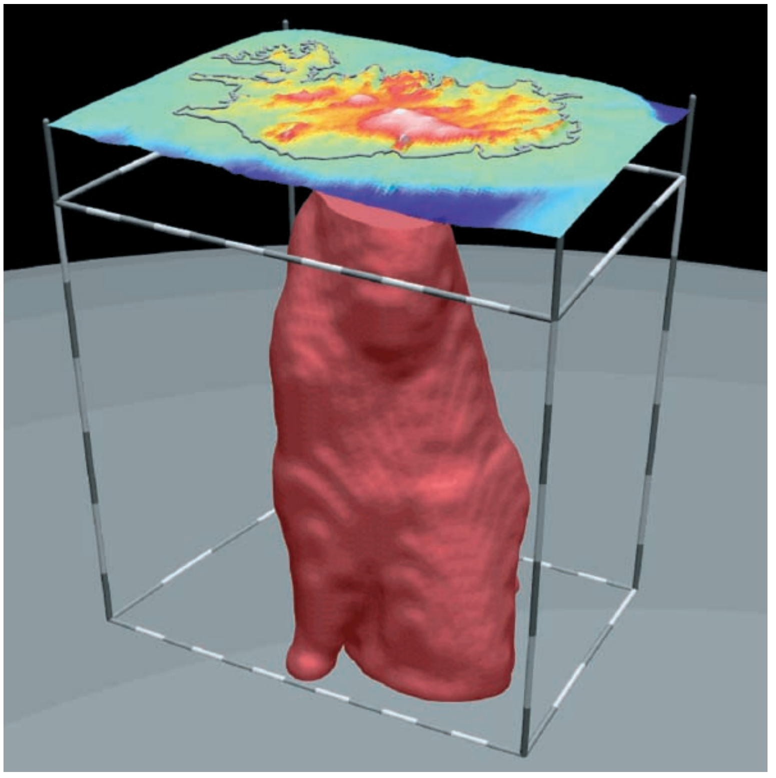


FIGURE 22.3 A mantle plume beneath Iceland is revealed by anomalously low seismic wave velocities in a cylindrical mass below the island. The low seismic wave velocities show that the plume has a higher temperature than the surrounding mantle. The plume extends to at least 400 km depth and has a diameter of about 300 km. *(Courtesy of C. Wolfe and S. Solomon)*

4. Oceanic islands at hotspots are associated with large topographic swells. This association is evidence for an extra source of mantle-derived heat to expand the lithosphere.
5. Perhaps the most convincing evidence for mantle plumes comes from recent advances in seismic studies of Earth's interior. Tomographic images of the mantle beneath Iceland reveal that a narrow column of material with low seismic wave velocities extends to at least 400 km beneath the island (Figure 22.3). Other investigations suggest it extends even deeper, to at least 700 km. The plume has a diameter of about 300 km. High temperatures of the material in the plume probably cause the low seismic wave velocities. In fact, the plume may be as much as 200°C warmer than the surrounding mantle. Further refinements and higher resolution images are revealing more about the precise shapes and depths of mantle plumes.

What is the evidence for the existence of mantle plumes?

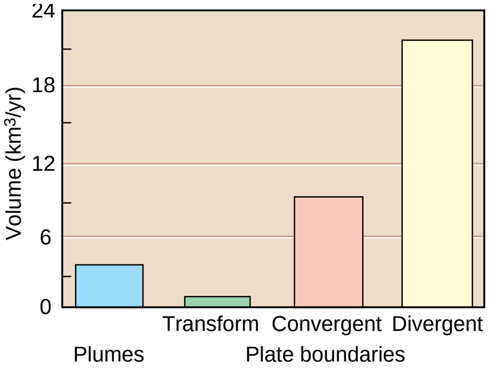
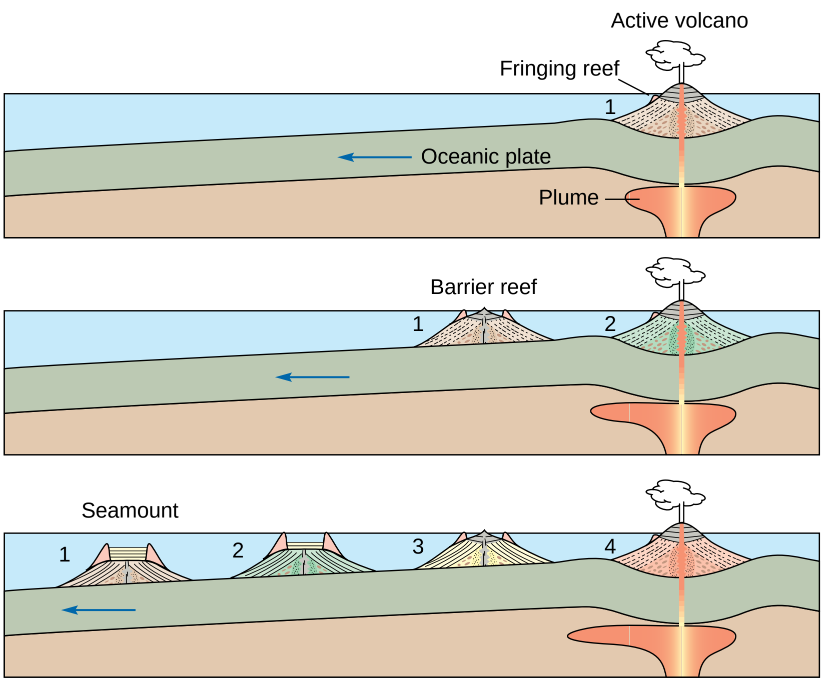


FIGURE 22.4 The volume of magma produced from mantle plumes is much smaller than that produced at divergent or convergent plate boundaries.

Characteristics of Hotspots and Mantle Plumes

The volume of volcanic rock produced at mantle plumes is small compared to that produced along divergent and convergent plate boundaries (Figure 22.4). Most intraplate volcanoes lie on the floor of the South Pacific, which is dotted by many submarine volcanoes and volcanic islands (Figure 22.2). At first glance, the distribution of intraplate volcanoes may seem random. But upon further inspection, linear trends or chains become apparent, especially in the Pacific Ocean (see the maps on the inside covers).

Volcanism over a mantle plume produces a submarine volcano, which can grow into an island. Steps in this process are shown in Figure 22.5. If the plume's position in the mantle does not change for a long time, the moving lithosphere carries the active volcano beyond its magma source. This volcano then becomes dormant, and a new one forms in its place over the fixed plume. A continuation of this process builds one volcano after another, producing a linear chain of volcanoes parallel to the direction of plate motion.



(A) A volcanic island forms above a more-or-less stationary mantle plume. As the volcano grows, its base subsides because of the added weight of the basalt. The volcano forms on top of a broad swell in the lithosphere caused by the heat carried in the plume.

(B) As the plate moves, the first volcano is carried away from the source of magma and stops growing. The island then gradually erodes to sea level. Meanwhile, over the plume, a new volcanic island forms.

(C) Continued plate movement produces a chain of islands. Reefs can grow to form an atoll. As the plate cools and subsides, the volcano may drop below sea level.

FIGURE 22.5 **A linear chain of volcanic islands** and seamounts results from plate movement above a mantle plume. The string of volcanoes produced reveals the path of the moving plate.

From the evidence provided by studies of hotspots, it appears that mantle plumes may have a variety of shapes and sizes. They may consist of hot mantle material rising as blobs rather than in a continuous streak. For the most part, mantle plumes can be envisioned as long, slender columns of hot rock that originate deep inside Earth's mantle (Figure 22.6). They rise slowly toward the surface, arching the overlying lithosphere, forming volcanoes and plutons, and causing small, shallow earthquakes. Some plumes may have diameters of as much as 1000 km, but most are only several hundred kilometers across. The material in the plume appears to rise at rates of perhaps 2 m/yr. Plumes rise under continents and oceans alike, and they occur in the center of plates and along some midoceanic ridges. The extra heat they bring to the lithosphere commonly produces domes up to 1000 km in diameter, with uplift ranging from 1 to 2 km at the center of the dome.

What generates a mantle plume?

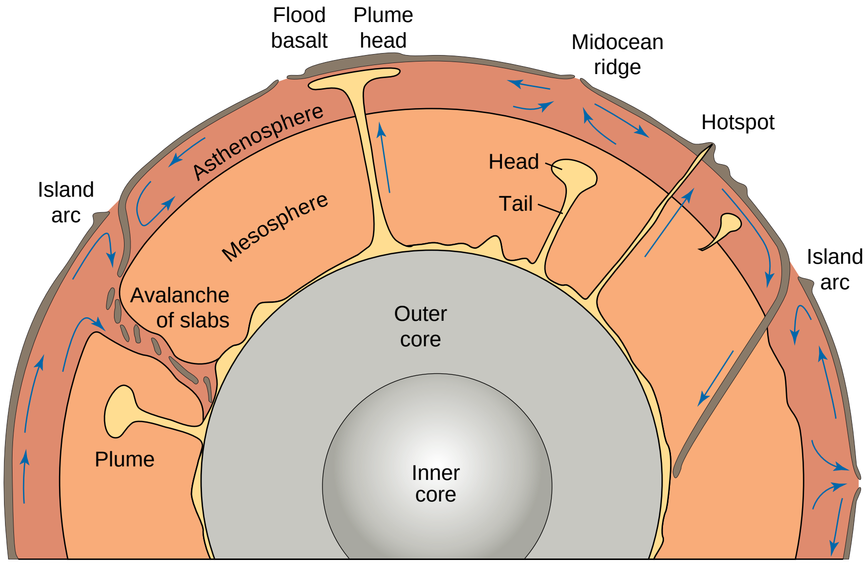


FIGURE 22.6 **Plumes rise from the core-mantle boundary,** according to current theory, and are an important type of mantle convection. Some mantle material in the hot boundary layer between the mantle and core becomes hot, and therefore more buoyant, and rises upward in a cylindrical plume. A new plume starts with a large head, behind which is a slender tail. When the plume reaches the cold, rigid lithosphere, it flattens and spreads outward. Flood basalts may erupt from the plume head. Hotspot islands may form from the narrower, long-lived tail. Oceanic crust subducted deep into the mantle at some ancient subduction zone (right) may be part of the source material of mantle plume.

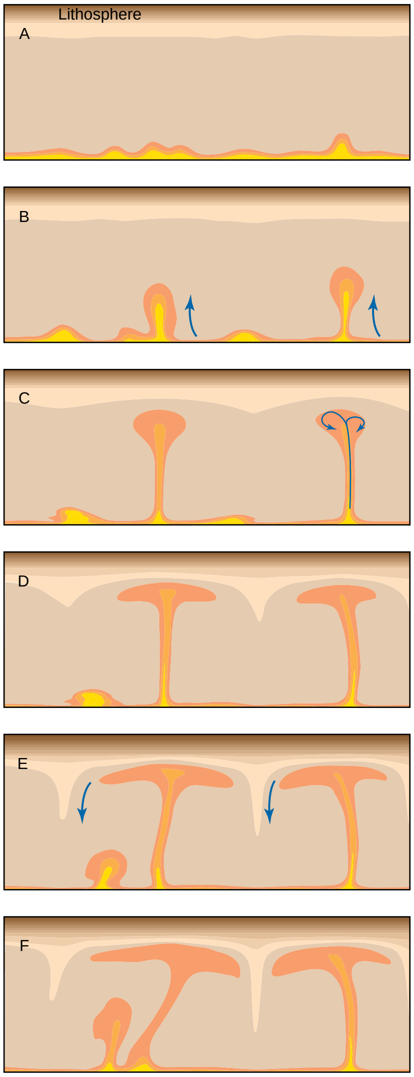


FIGURE 22.7 The development of a mantle plume, shown in these cross sections, is related to the rise of low-density material from deep in the mantle. The colors represent temperature, with yellow hottest and brown the coolest. **(A)** As a plume rises, its head enlarges and a narrow tail develops **(B, C).** When the plume head hits the base of the lithosphere, it flattens (**D**). Cold, dense material also sinks (tan). Gradually, each plume cools—note the lower temperatures in the central plume—and new plumes develop **(E).** *(After M. A. Richards, 1991)*

Mantle Convection

Some geologists think that mantle plumes originate at depths of at least 700 km and perhaps as deep as 2900 km at the core-mantle boundary. Their positions appear to be relatively stationary, as the lithospheric plates move over them. Plumes are thus independent of the crust's major tectonic elements, which are produced by plate movement. As a result, hotspots provide a reference frame for determining the absolute, rather than the relative, motion of tectonic plates. However, the plume locations are not absolutely immovable. Some appear to wave slightly in the "mantle wind" (Figure 22.7).

The Evolution of Mantle Plumes: Heads and Tails

Like the plate tectonic system, mantle plumes are a type of convection that slowly stirs the mantle. However, plate tectonics and mantle plumes are related to two distinct types of convection. One is the convection involved in plate motion, wherein material rises at divergent plate boundaries and descends at convergent boundaries. The other is the rise of thin columns of material in slender plumes from deep in the mantle. Although plumes clearly transport much less heat than the processes at tectonic plate boundaries, mantle plumes are also largely driven by internal heat. Plumes probably arise from a hot layer at the *base* of the mantle. Because it is so hot, the boundary layer surrounding the molten iron core must have much lower viscosity (100 to 1000 times less) and slightly lower density than the mantle above it. As heat from the fluid iron core flows into this boundary layer, parts of the mantle expand and become less dense. When a small portion becomes lighter than the cooler mantle above it (a difference of about 200°C and 0.1 g/cm^3 may be sufficient), it becomes buoyant and begins to rise. Consequently, small bumps form in the boundary layer (Figure 22.7). These may form **diapirs** that ultimately enlarge and develop into buoyant mantle plumes.

Laboratory experiments suggest that a new **starting plume** ascends through the mantle with a large bulbous **head** fed by a long narrow pipe, or **tail,** that extends to greater depth (Figure 22.7). As a new plume rises through the mantle, resistance to its flow causes the head to rise more slowly than the material in the tail. Consequently, the plume head enlarges as it is fed by material flowing up through the long narrow tail; the rising plume head inflates like a balloon. Enlargement of the head also occurs because material from the surrounding cooler mantle is swept into the rising plume.

Because the plume head grows as it moves through the mantle, a large plume head can develop only if it traverses a large distance. Using this relationship, we can estimate that plumes must rise thousands of kilometers, probably from the core-mantle boundary to the surface—a distance of 2700 km. If this is true, much of the heat lost from the molten metallic core is carried away by mantle plumes. Plumes are probably responsible for about 10% of Earth's total heat loss; plate tectonics accounts for more than 80% of the heat lost from the mantle.

When the head of a starting plume nears the surface and encounters the strong lithosphere, it appears to spread out to form a disk of hot material 1500 to 2500 km across and 100 to 200 km thick (Figure 22.7). This is about the size of most continental **flood basalt** provinces. The rising plume uplifts the surface to form a broad low dome (Figure 22.8). If a plume head has a temperature of 1400°C (about 200°C warmer than normal mantle), the buoyancy force and extra heat of the hot plume can create a broad well hundreds of kilometers across and as much as 1 km high (Figure 22.8). This uplift can cause extension, normal faulting, and rifting of the overlying lithosphere. Moreover, as the plume rises to shallow depths, the reduced pressure allows it to melt partially and to produce basaltic magma. The larger the plume head, the larger the volume of basalt that can form.

Eventually, the plume head dissipates by cooling or mixing with the shallow asthenosphere (Figure 22.8). The rest of the plume's history is dominated by flow through the long tail. In contrast to a plume head, the narrow tail is thought to be only about 300 km in diameter. Uplift, extension, and basaltic magmatism will also be associated with this part of a plume's evolution, but all will be less than during

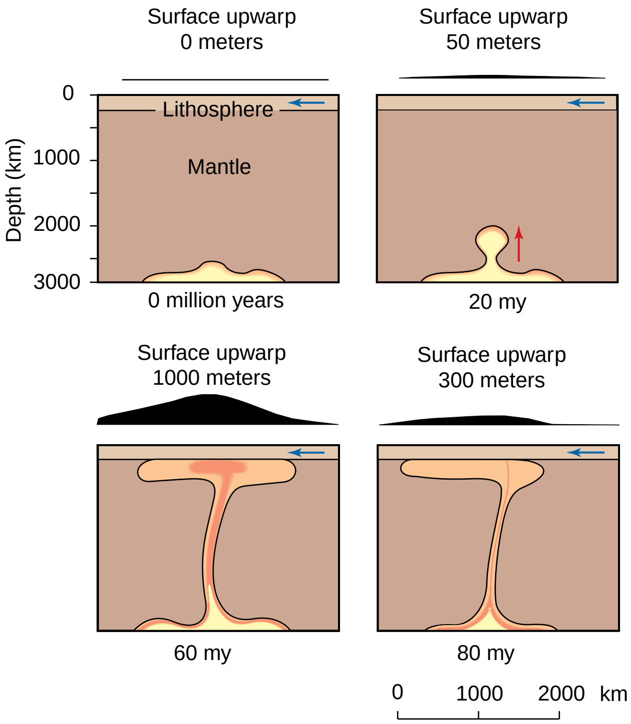


FIGURE 22.8 **A starting plume** has a large head and a narrow tail as shown in these cross sections. Each step shows the size and shape of an evolving mantle plume, along with a profile showing uplift at the surface. The plume's head is enlarged because of entrainment of material from the surrounding mantle and because of its slow movement relative to the material in the tail. Once the head of the plume hits the strong lithosphere, it deforms by flattening into a thinner and wider disk. Uplift of the surface is caused by the buoyancy and heat of the mantle plume. Here, 1 km of uplift occurred over the center of the plume during the first few tens of million years of its history. Gradually, the plate moves and the plume head dissipates, leaving a narrower tail. Eventually, this too disappears.

the starting phase. As the lithosphere moves away from the focus of a plume, it cools, contracts, and subsides. This cooling phase may persist for hundreds of millions of years and may be accompanied by the slow subsidence of the crust and the development of a large sedimentary basin.

Ultimately, the plume itself also loses thermal energy and dies, as new plumes form elsewhere and continue to carry heat from the interior to the surface. A typical life span may be about 100 million years. In short, mantle plumes are temporary features that form and ultimately fade and die.

Plates and plumes are complementary, each involved in a different form of mantle convection. Plumes probably come from a hot boundary layer at the *base* of the mantle, whereas tectonic plates are the cool boundary layer at the *top* of the mantle. As the core loses heat, part of the overlying mantle becomes buoyant and rises in a plume. In contrast, as plates cool, they become denser than the underlying mantle and sink. Thus, in addition to the plate tectonic system, there is also a plume tectonic system. It involves mostly vertical movements of the lithosphere accompanied by volcanism. These processes are superimposed on the constantly moving tectonic plates.

How does the shape of a plume change as it rises through the mantle?

MAKING MAGMA IN MANTLE PLUMES

Basaltic magma is generated in a rising mantle plume by decompression melting. Magmas formed in mantle plumes are distinctive and show hints that they are partially derived from vestiges of ancient slabs subducted deep into the mantle. In continental settings, rhyolite and granite may form above a mantle plume by partial melting of the crust or by fractional crystallization of basalt.

The various components of a magma system can be compared to those of a river system. Each magma system has a *source* of magma, a *path* along which the magma is transported, and a final site of *emplacement* where the magma erupts as a lava flow or where the magma crystallizes to form a pluton. Understanding the magma source—where, how, and why it is generated—is key to understanding and predicting the behavior of the entire magma system.

The source of magma in a rising plume is probably related to melting caused by a drop in pressure (decompression) as the hot material rises to shallow depth (Figure 22.9). This mechanism is very similar to that which yields basalt magma at midoceanic ridges. **Decompression melting** must be a common phenomenon in the mantle because the melting point of peridotite, the most common rock in the upper mantle, decreases slightly as pressure decreases (Figure 22.9). When low-density, solid mantle moves upward in a plume, the pressure is reduced faster than the plume can lose its heat and reach equilibrium with its surroundings. The arrow in Figure 22.9 shows one possible pressure-temperature path for peridotite rising in a plume. Although the rising material in the plume may cool slightly, it still crosses the partial melting curve, when it reaches depths of less than 100 km or so. Consequently, part of the peridotite in the plume melts and forms basaltic magma. This basaltic melt is even less dense than the solids in the plume, so it moves upward into the crust, filling dikes, sills, and other magma chambers. Here, the new magma may mix with other magma, cool to form solid plutons, or move farther upward and erupt, usually as a quiet lava flow that forms part of a shield volcano.

Is there a difference between basalts erupted at midoceanic ridges and those erupted on oceanic islands?

Detailed studies of the compositions of basalts related to mantle plumes lead to a startling conclusion. These basalts may be derived from part of the mantle contaminated by ancient oceanic crust, including oceanic basalt and sediment. Here we have a quandary. If the geophysical evidence is correct, plumes originate from great depths, perhaps as deep as the core-mantle boundary. So, how did crustal materials including sediment get into the deep mantle? Could the sources of plumes be the graveyards for subducted oceanic lithosphere (Figure 22.6)?

Oceanic crust, with its basalt and its marine sediment, undergoes a significant density increase during subduction when garnet and other dense high-pressure minerals form. Perhaps the density increase allows the oceanic crust to travel all the way to the core boundary, like a rock sinking slowly in thick mud. There, it can subduct no further, because the core is much denser. So the subducted lithosphere may reside there for millions of years and mix with mantle rocks already at the boundary. If this mixture becomes expanded by heat escaping from the iron core, it may rise slowly back toward the surface and eventually melt to create basalt magma.

Such a conclusion provides the final element for the vast recycling system that is Planet Earth. Partial melts of the shallow mantle rise buoyantly and then erupt at a midocean ridge. The crust created at the ridge becomes buried by deep-marine sediment before it subducts back into the mantle. On the way down, it is metamorphosed, dehydrated, and incompletely mixed with mantle rocks. Eventually, the oceanic lithosphere may reach the core-mantle boundary. There it

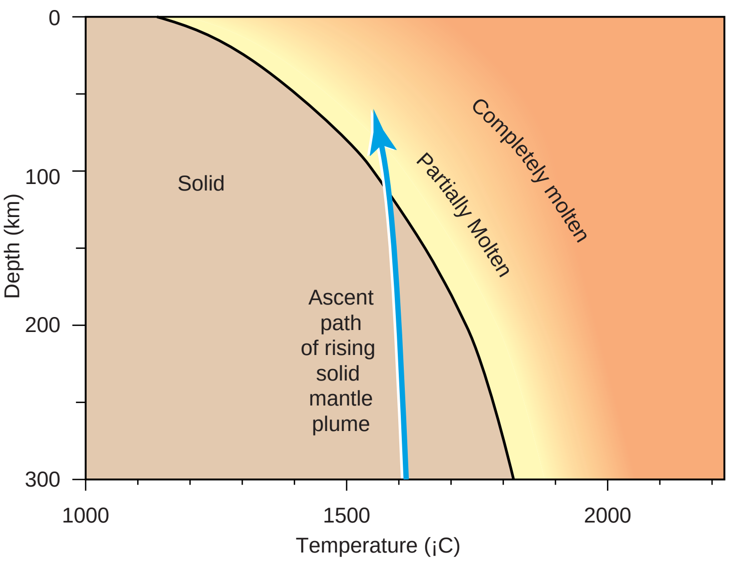


FIGURE 22.9 Magma in a rising mantle plume is produced as a result of decompression melting. The black line marks the temperature at which melting begins for mantle peridotite. The blue arrow shows the pressure and temperature path followed by a rising plume. Basaltic magma is produced when conditions in the plume cross the melting curve at a shallow depth. The partial melt can be extracted and rises to erupt as an ocean island or continental flood basalt.

STATE OF THE ART *X-Ray Fluorescence Spectrometry*

As you read this chapter, you may wonder exactly how lavas that erupt above mantle plumes are different from those that erupt at midocean ridges or at island arcs. To find out, the lava flows may be studied using *X-ray fluorescence spectrometry*—a widely used technique to find the elemental composition of rocks.

Inside an X-ray fluorescence spectrometer, powerful X rays are beamed onto a specially prepared sample of rock. In turn, "secondary" X rays are released from all the atoms in the rock as electrons move from shell to shell. These secondary X rays have wavelengths that are characteristic of each element. Thus, a silicon atom will yield X rays that are different from those emitted by iron or by rubidium. In addition, the strength of the silicon X rays is directly proportional to the amount of silicon in the specimen. The various wavelengths of X rays are separated from each other by diffraction as they pass through specially designed crystals. The intensity of each X-ray wavelength is then measured and converted to an element concentration by comparison with X-ray intensities from rocks of known composition.

(Courtesy of Bruker AXS, Inc.)

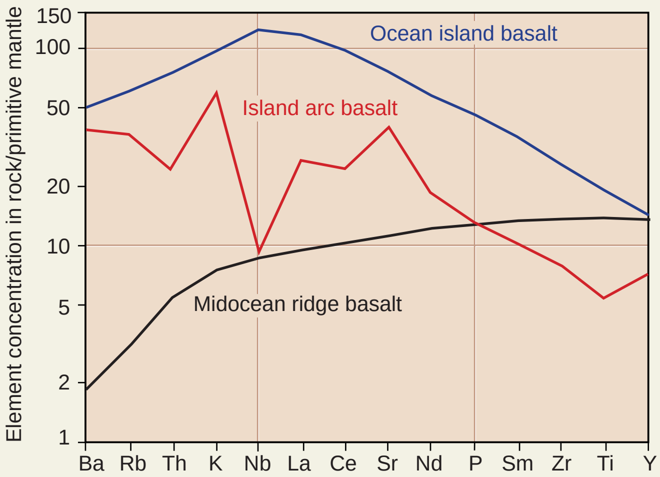
Composition of Basalts from Different Settings

	Midocean Ridge	Island Arc	Ocean Island
Major oxides in weight percent			
SiO_2	50.7	49.2	49.2
Al_2O_3	15.5	15.3	12.8
Fe_2O_3	10.6	9.9	12.5
Trace elements in parts per million			
Rb	1	14	25
Nb	9	1	50
La	3	10	35
Nd	9	1	50
Zr	85	50	220

Chemical analyses of basalt lavas from three different settings are shown in the table. There are only small differences in the major element concentrations, but large differences in the trace element concentrations in the three basalts.

Geochemists have devised many graphical ways to compare such data. One of the most useful is to divide the element concentrations in a rock by those estimated for Earth's primitive mantle. On this kind of graph (sometimes called a spider diagram), the differences among the basalts are obvious. Midocean ridge basalts have relatively smooth patterns but are poor in the elements plotted on the left. Basalts from island arcs have higher concentrations of these elements and decided depletions in two highly charged elements—niobium (Nb) and titanium (Ti). Ocean island basalts, erupted above mantle plumes, have higher concentrations of most of the trace elements, and the curve actually peaks at Nb.

Now that we can see the differences, what do they mean? The differences probably show that the mantle sources of these basalts differ widely from one another. For example, the source of midocean ridge basalts has been depleted in these trace elements over eons by the extraction of continental crust from the mantle. Island arc basalts are enriched in elements (such as Ba—barium, Rb—rubidium, and K—potassium) that are soluble in water and poor in elements (such as Nb) that are not soluble. The soluble elements are carried into magmas when a subducting slab dehydrates (Chapter 21). Finally, ocean island basalts have sources like midocean ridge basalts, but smaller amounts of melting have enriched the trace elements in the partial melts. Careful examination of the oceanic island patterns also suggests that some subducted oceanic crust lies in the plume source. In this way, the compositions of rocks erupted at the surface reveal much about Earth's deep interior.



resides until heat lost from the core makes it buoy back to the surface again, but this time it rises as a part of a long narrow plume rather than sinking as a stiff sheet (Figure 22.6).

MANTLE PLUMES BENEATH THE OCEAN FLOOR

A starting plume may yield flood basalt flows that erupt on the ocean floor and form a large oceanic plateau. As the lithospheric plate continues to move over the plume, a narrow chain of volcanic seamounts forms, with the active volcanoes lying directly over the tail of the plume. If a plume is centered on a midoceanic ridge, an elongate volcanic plateau forms.

Many mantle plumes rise to Earth's surface beneath the ocean basins. Each of these plumes has a discrete history, with a distinct beginning and an end. What, then, is produced when a new plume with its large head rises beneath an ocean basin? And what happens as the long-lived plume tail evolves? Some oceanic plumes are even centered on midocean ridges, creating an exceptionally rich mixture of volcanic and tectonic features. In the sections that follow, we will examine each of these three types of oceanic volcanism: a starting plume, volcanism related to a tail, and a plume on a midocean ridge.

How are mantle plumes expressed on the ocean floor?

Starting Plumes: Oceanic Plateaus and Flood Basalts

The first type of oceanic volcanism produces distinctive underwater landforms. Scattered across the ocean floor are several broad plateaus that rise thousands of meters above their surroundings (Figure 22.2). These **oceanic plateaus** are not easily explored, and consequently, little is known about them. However, oceanic plateaus may form by some of the most spectacular volcanic events on the planet.

The largest oceanic plateau is the Ontong-Java Plateau (Figure 22.10); it is two-thirds the size of Australia. A coral-capped bit of the plateau rises above sea level to form the Ontong-Java atoll, the largest atoll in the world. The surrounding region of the equatorial western Pacific is underlain by oceanic crust that is 25 to 43 km thick—as much as five times thicker than typical oceanic crust. The thick crust is apparently made of about 36 million cubic kilometers of basalt lava flows, enough to cover the entire conterminous United States with a layer 5 m thick. The lavas buried older oceanic crust, with its magnetic stripes, which originally formed at an oceanic ridge. There appear to be no large shield volcanoes or calderas on the plateau. Instead, lava must have erupted from long fissures on the ocean floor, probably as flood basalts, quite unlike the small eruptions that occur at a midocean ridge. If these oceanic flood lavas are similar to those found on the continents, individual lava flows may have been hundreds of kilometers long.

How does the Ontong-Java Plateau differ from an oceanic ridge?

The paleomagnetic character of the lavas on the plateau and a few recently acquired radiometric ages indicate that the Ontong-Java Plateau formed in at least two episodes at about 120 million years ago and about 90 million years ago; during the Cretaceous Period). Much of the plateau was probably created in less than 3 million years. If that estimate is correct, the vents on the Ontong-Java Plateau must have erupted between 15 and 20 km^3 of lava each year. That amount is comparable to the volume of new crust formed by the entire oceanic ridge system in a year, and it dwarfs the 1980 Mount St. Helens eruption of less than 1 km^3 of volcanic rock.

From a geologic perspective, such a rapid outpouring of such a huge volume of lava is truly remarkable. The entire submarine landscape of this large area was changed in only a few million years. Most geologic processes that affect such large

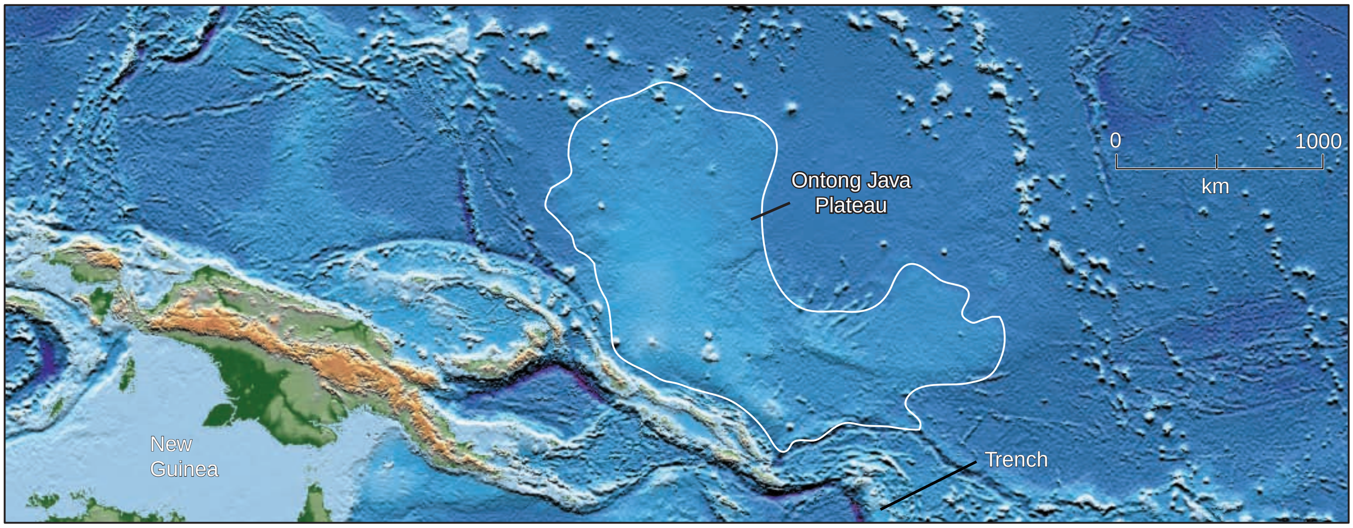


FIGURE 22.10 **The Ontong-Java Plateau** is probably a huge accumulation of submarine flood lavas erupted during the Cretaceous. The plateau rises several kilometers above the surrounding abyssal depths and is underlain by crust that may be 40 km thick, about five times thicker than normal oceanic crust. Oceanic plateaus are probably related to eruptions from the enlarged head of a new plume. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

regions take tens of millions of years to accomplish such changes. For example, the Rocky Mountains have been rising for more than 40 million years, and the Andes have been building for at least 30 million years.

Such a vast oceanic plateau may represent a spasm of igneous activity related to the initiation of a new mantle plume. As the enlarged plume head rose beneath the ocean floor, partial melting produced huge volumes of basaltic lava that erupted over a geologically short period of time. Eventually, the heat from the plume head was lost through this volcanism, and the amount of partial melting declined. Oceanic lithosphere continued to move over the plume tail, and a **hotspot track** formed. The Louisville hotspot (Figure 22.2) is the most likely current location of the plume that fed the Ontong-Java oceanic plateau.

Plume-Tail Volcanism: Hotspot Island Chains

A second type of oceanic volcanism produces hotspot island chains. Presently, most intraplate volcanism is dominated by the construction of large shield volcanoes over plume tails. Most eruptions are relatively quiet flows of basaltic lava from vents at a volcano's summit or on its flanks. Large collapse calderas are common at the summits of these shield volcanoes. In addition, heat from the plume and the weight of the volcano drive a variety of vertical tectonic processes. Hotspot volcanic systems can be explored by referring to the Hawaiian island chain.

How does a mantle plume produce a chain of volcanic islands?

The Hawaiian Plume. Hawaii is the best known example of volcanic activity above the still-rising tail of a mantle plume beneath oceanic lithosphere (Figure 22.11). Hawaii is the active area of a series of otherwise extinct volcanoes stretching across the Pacific seafloor to the Aleutian Trench (Figure 22.12). The lava that has erupted from the hotspot is more than enough to cover the entire state of California with a layer 1.5 km thick. Most of the volcanoes are below sea level now. The islands northwest of Hawaii are all deeply eroded extinct volcanoes.

The island of Hawaii consists of five major volcanoes, each built up by innumerable eruptions. The largest active volcano on Earth, Mauna Loa, dominates the big island of Hawaii. It rises 9000 m above the ocean floor (Figure 22.13). This large shield volcano was built by repeated eruptions of lava during the past million years, and it is still active. Many recent flows can be seen along Mauna Loa's flanks, extending as dark lines from a series of fissures, or **rift zones,** along the crest

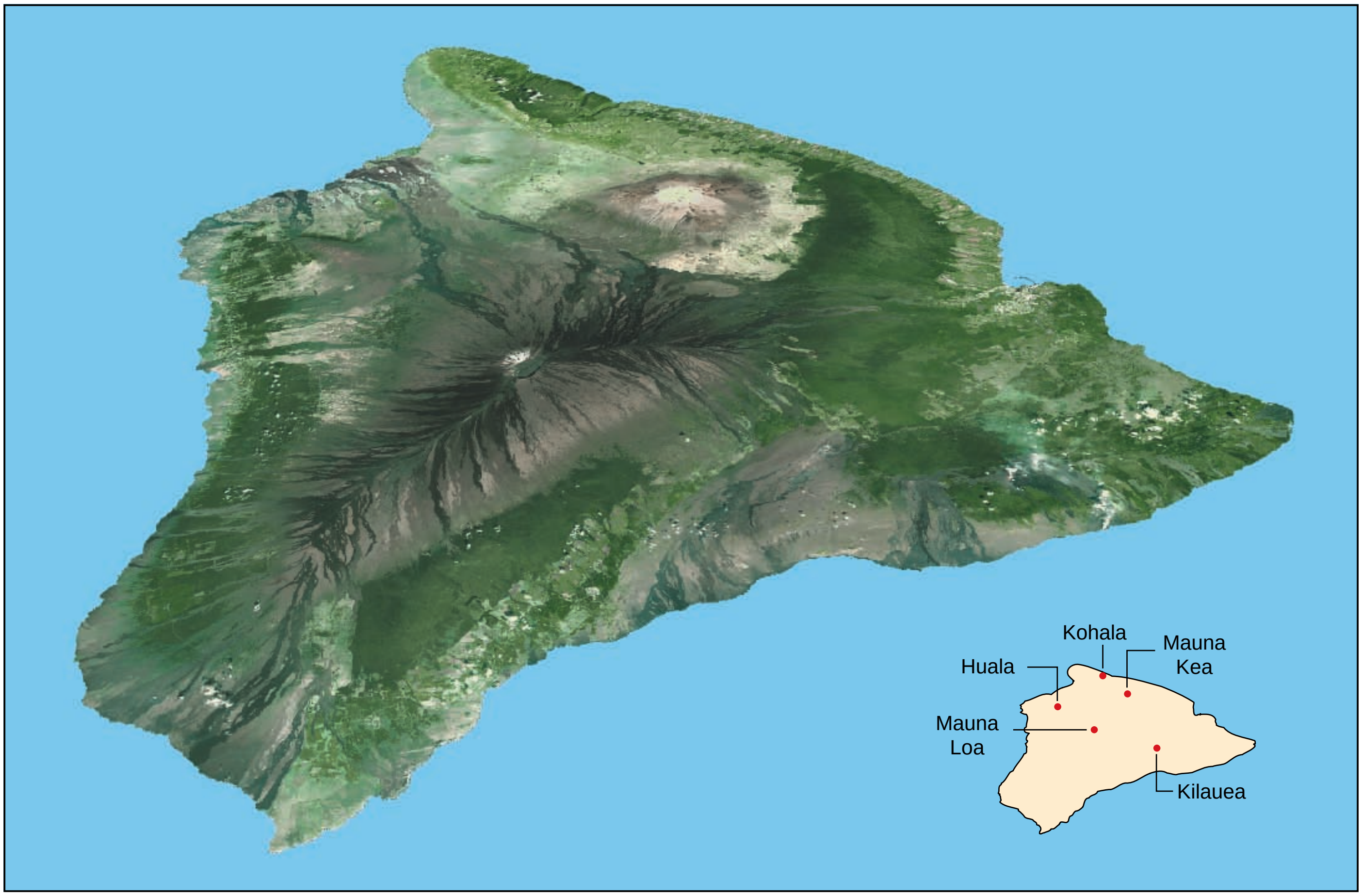


FIGURE 22.11 **The island of Hawaii** as seen from space. Two old eroded volcanoes form the northern (top) part of the island. Mauna Loa is the large volcano in the foreground; it has erupted many times in the past 150 years. The individual flows appear as thin dark lines extending from fissures that emanate from a summit caldera. Kilauea (right) is the youngest of the volcanoes that has reached sea level. Its most recent eruptions began in 1983. *(Copyright SPOT IMAGE/CNES. Data manipulation by Oliver Chadwick and Steven Adams of JPL. Photo Researchers, Inc.)*

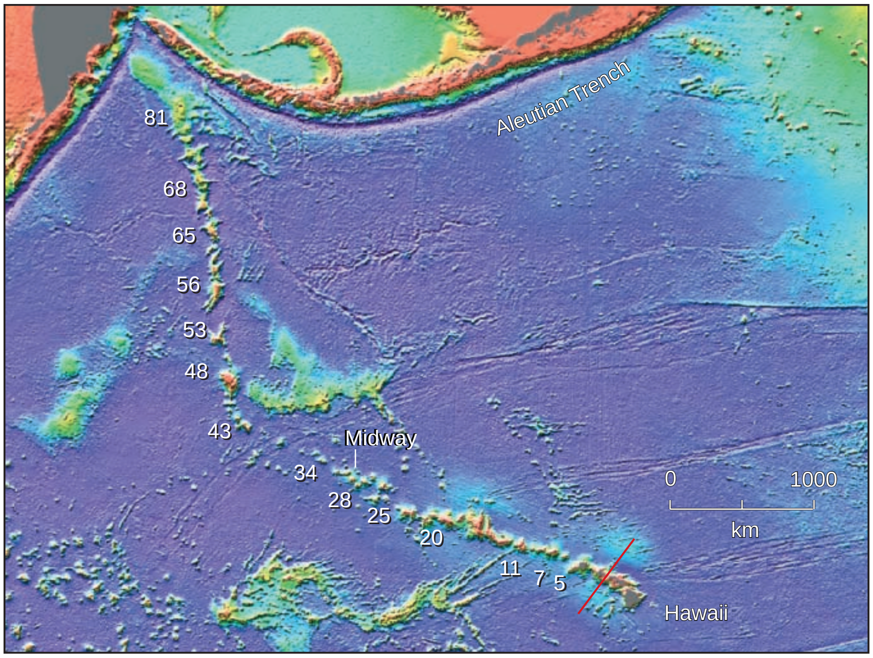
of a ridge (Figure 22.11). The oval caldera (Figure 4.11) formed by the repeated collapse of Mauna Loa's summit when dense intrusions sank under their own weight or as magma withdrew from subterranean chambers.

Southeast of Mauna Loa is the younger Kilauea volcano, where young lava flows erupt primarily from rift zones. An eruption along the East Rift Zone has continued almost without pause since 1986. As a result, an extensive lava field and a small shield volcano have formed, and tube-fed flows extend from the vent to the sea. Kilauea is growing higher, and the island is growing larger on its margin. Farther southeast is an even younger submarine shield volcano, Loihi (Figure 22.13). It, too, is an active volcano and will one day rise to the surface as it progressively grows higher by repeated eruption and intrusion.

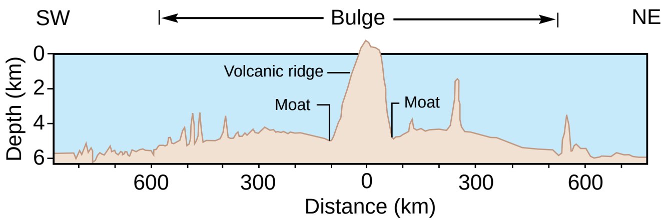
Hawaiian Islands

The volcanoes of Hawaii are shaped like huge rounded plateaus. The classic shield shape of Hawaiian volcanoes describes only that part of the volcano above sea level. They are much flatter above sea level than below (see Figure 11.15). The shape of the entire volcano is complex because subaerial lavas and submarine flows behave differently. Subaerial lavas are more fluid and form gently inclined slopes, whereas submarine lavas do not flow as freely as those on land. They are quenched rapidly by the cold seawater and some also become granulated as they erupt into the cold seawater. These factors cause submarine lava to pile up and produce steeper slopes.

These steeper submarine slopes are susceptible to gravitational failure and mass movement. Vast landslides steepen the slopes of the submarine portions of the volcanoes, as noted in Chapter 11. Most of the submarine flanks of Mauna Loa and Kilauea are actually huge landslide scars (Figure 22.13). The landslides



(A) The volcanic islands and seamounts form the most obvious part of the long chain. A bend in the chain marks a change in the direction of plate movement, which is presently to the northwest. An elongate rise marks the hotspot trail; it is highest near the plume beneath Hawaii and is progressively lower toward the northwest. The narrow trough or moat that lies on both flanks of the island is due to subsidence from the weight of the volcano. Numbers are ages in millions of years for volcanic rocks along the seamount chain. *(Base map from D. T. Sandwell and W. H. F. Smith, Scripps Institution of Oceanography, University of California at San Diego)*



(B) This cross section shows the volcanoes sitting on a broad bulge caused by heating from the underlying mantle plume. On either side, a narrow moat or trough has formed because the weight of the volcanic islands bends the Pacific plate downward.

FIGURE 22.12 **The topography of the Hawaiian-Emperor Island chain** shows the critical elements of the evolution of a hotspot chain.

range from slow-moving slumps bounded by curved faults to fast-moving debris avalanches. At the surface, landslides are marked by high scarps separated by flat benches. In fact, entire volcanoes are being ripped apart by their own weight (Figure 22.14). The active volcanoes are spreading seaward away from the molten or plastic cores of their rift zones. This extension is driven by gravity and is one cause of the rift zones. In turn, the rift zones become sites for intrusion of magma that causes further spreading of the island. These giant submarine landslides pose a hazard to people who live on other islands as well. Catastrophic failure of a giant debris avalanche could cause a tsunami to sweep across the Pacific basin.

The hot plume tail beneath Hawaii has also created a large swell in the oceanic lithosphere (Figure 22.12). This broad uplift is probably caused by the plume's buoyancy and by heating from the mantle plume. The swell is about 1500 km across, more than 4000 km long, and nearly 1 km high. It is elongated along the track of the hotspot and drops gently to the northeast where the lithosphere cooled and contracted after it passed the plume. The high volcanic ridge caps the swell and rises another 5 km or so to the ocean surface.

Why do we believe the island of Hawaii is located above a mantle plume?

So great is the weight of these volcanoes that a narrow depression or moat lies at their base (Figure 22.12). Moreover, because of the load, the islands are slowly sinking by making isostatic adjustments. The island of Hawaii is sinking about 3.5 mm/yr; Maui is sinking 2.2 mm/yr. Farther up the island chain and made of older inactive volcanoes, Oahu is sinking even more slowly. Large submergence rates for the island of Hawaii make it difficult for coral reefs to grow around its shorelines, whereas on the older, more slowly sinking islands of Maui and Oahu, organic reefs flourish in the clear warm water. Consequently, white sand beaches like those of Oahu, derived from the breakup of the coral, are absent on Hawaii.

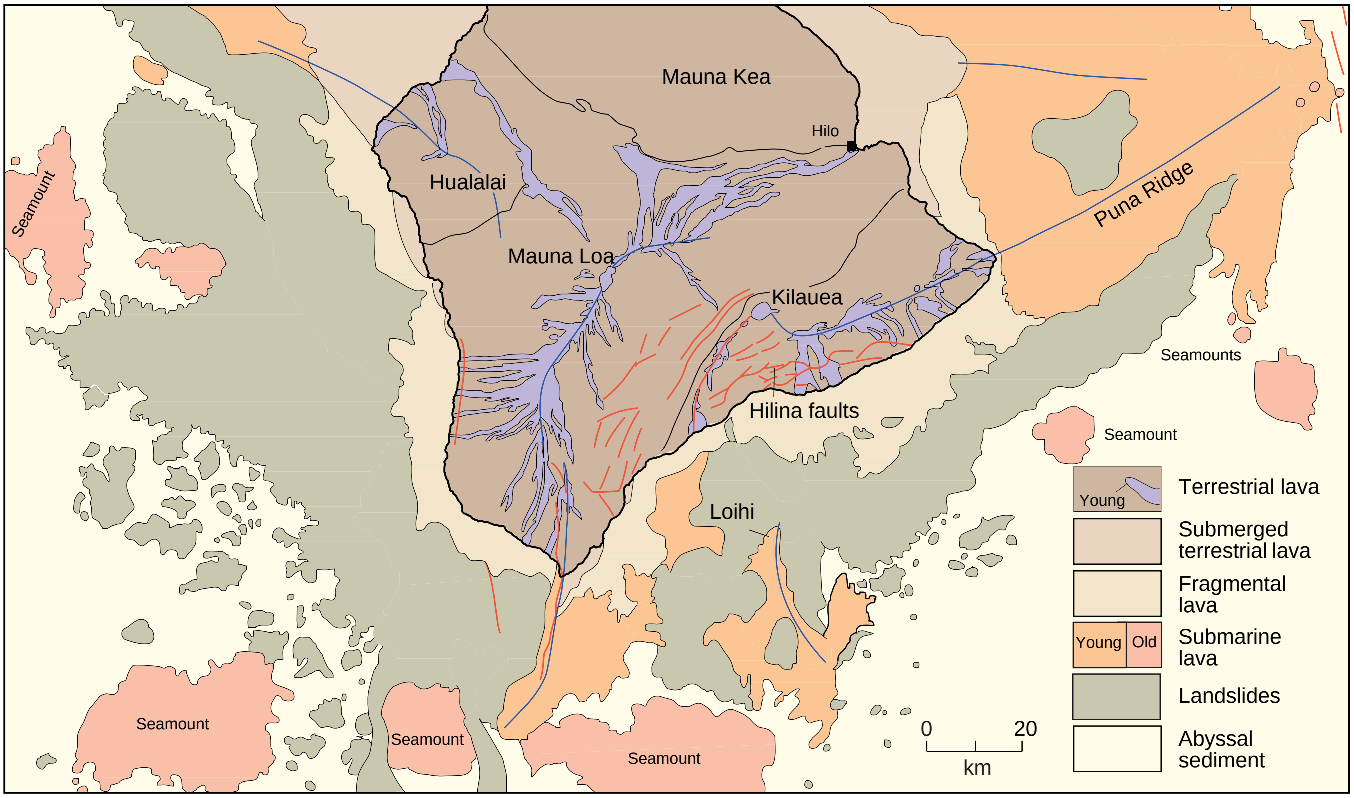


FIGURE 22.13 **The island of Hawaii** consists of several volcanoes that rise from the floor of the Pacific. They include Mauna Loa, the tallest volcano on Earth, and Loihi, a submarine volcano still growing toward the surface. The map shows the importance of eruptions from narrow rift zones in the building of Mauna Loa and Kilauea. The arcuate shape of Loihi is also controlled by submarine eruptions from rift zones. Note that huge landslides have slipped from the submerged flanks of the volcanoes. Normal faults on the island and some rift zones are controlled by movement of these landslides. *(Courtesy of J. G. Moore, U.S. Geological Survey, and W. Chadwick, Oregon State University)*

Hawaiian Earthquakes. Earthquakes in Hawaii (Figure 22.15) are typical of those that form above mantle plumes. Since no plate boundary is involved, earthquakes are relatively small and infrequent. The most common earthquakes are shallow and are related to the movement of magma or to slumping along the landslide-bounding faults. They typically have magnitudes of less than 4.5 and depths of less than 10 km. Another smaller family of deeper earthquakes arises in the mantle. The largest and most recent of this type was a magnitude-6.2 tremor on the island of Hawaii in 1973, occurring about 40 km deep. The earthquake caused about $5.6 million in damage and injured 11 people.

What causes these deeper earthquakes if no plate interactions are involved? Most of the deeper ones probably release strain built up by the enormous load of the volcanoes on the lithosphere. As the volcanoes grow, they add ever more weight to the lithosphere, bending it downward. Consequently, the earthquakes are most common beneath the actively growing part of the volcano chain. The older parts of the hotspot chain are seismically inactive.

Hawaiian Volcanism. Like other oceanic hotspots, Hawaii's volcanic rocks are largely basalt. Silica-rich rocks, such as andesite and rhyolite, are extremely rare. Magmas formed by partial melting of the mantle are overwhelmingly basaltic and poor in volatiles, such as water vapor, compared with those formed in subduction zones. The absence of silicic continental crust beneath the island chain may partly explain the lack of rhyolite: There are no granitic rocks to assimilate and enrich the magmas in silica.

Eruptions on Hawaiian volcanoes are relatively quiet and predictable but, nonetheless destructive. During the most recent eruptions of the Kilauea volcano, destruction of homes, buildings, and roads cost millions of dollars. Most eruptions

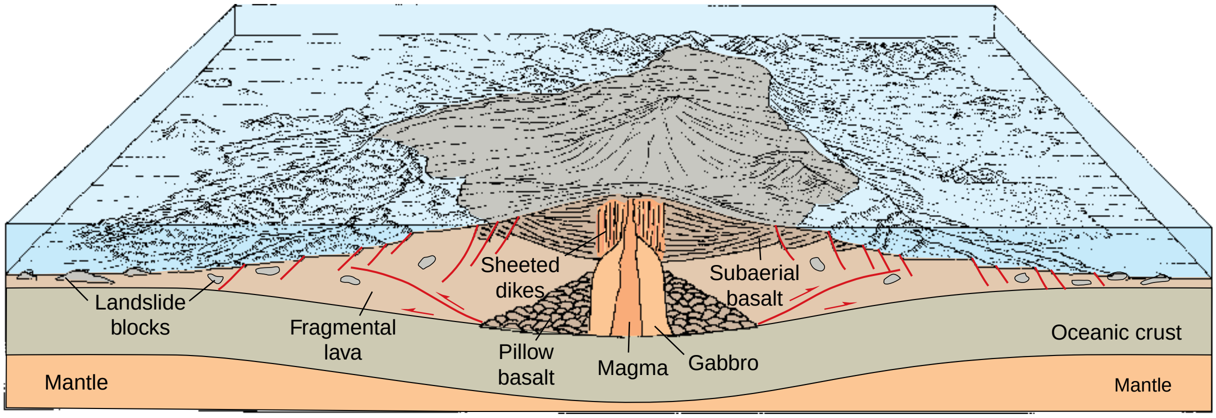


FIGURE 22.14 **Magma system at an oceanic mantle plume,** as deduced from geologic, earthquake, and geochemical studies. After forming in the mantle, basalt magma rises buoyantly through dikes into small magma chambers, where it mixes with magma still present from earlier episodes of intrusion. The magma in the chamber cools and crystallizes to form gabbro along the walls. The movement of large slump blocks rips the volcano apart. Magma fills these rift zones and may erupt to form pillow basalt or fragmental lava under water or, if the volcano is high enough, subaerial lavas above the water. The weight of the volcano causes the underlying oceanic crust to subside.

start by the opening of a short, narrow fissure, only a meter or so wide, that rapidly lengthens to as much as several kilometers. Along the rift, lava erupts as a series of fountains and locally forms a nearly continuous "curtain of fire." The eruptions usually focus on one point on the fissure, where a cinder cone or low shield volcano subsequently develops. Individual flows are usually only tens of kilometers long and eruption rates are much slower than those inferred for flood basalts. Small earthquakes accompany the eruptions because the volcano inflates and deflates as magma is intruded into or flows out of the volcano. During a long eruptive episode, activity may shift up and down the rift system as lava breaks out at different places. Where the lava flows enter the sea, small yet dangerous explosions may occur. Occasionally, the summits of the volcanoes have collapsed to form small calderas several kilometers across.

Volcanic gases, consisting mostly of water and carbon dioxide but including noxious sulfurous gases as well, may mix with humid air to form a type of volcanic smog. However, Hawaiian eruptions are usually too weak to inject aerosols into the atmosphere and affect the climate.

Evolution of Seamounts and Islands. The volcanic islands and **seamounts** scattered across the ocean floors are the largest volcanic edifices on the planet. The factors that control their evolution are quite unlike those for composite volcanoes at convergent plate margins or the lava fields erupted from fissures at divergent plate margins. Most of the volcanic activity that forms the islands and seamounts occurs under water, so the temperature and pressure conditions are quite different from the conditions where subaerial extrusions occur. Also, a submarine volcano is not subjected to contemporaneous stream erosion as it grows. The following summarizes our understanding of the origin of these volcanoes (Figure 22.16).

Magma extracted from a mantle plume moves upward through the lithosphere, eventually reaching the ocean floor. It rises through the brittle crust along fractures or dikes, extruding not only through a central summit vent, but also from fissures or rifts on the flanks. Therefore, a seamount grows upward and outward by extrusion of lava over various parts of its surface (Figure 22.16A). Magma also flows nearly horizontally through the rift zones as it moves from a summit magma chamber to the volcano's flanks. Thus, intrusive dikes make up a large fraction of the total volume of the shield volcano. Gabbro crystallized in small magma chambers also must constitute an important part of the interior. These three types of rock—submarine lavas, dikes, and gabbro—make up most of the volcano (Figure 22.14).

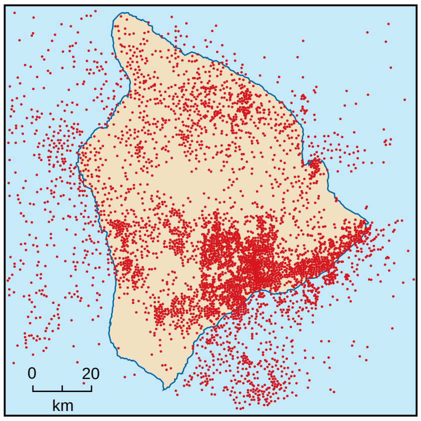
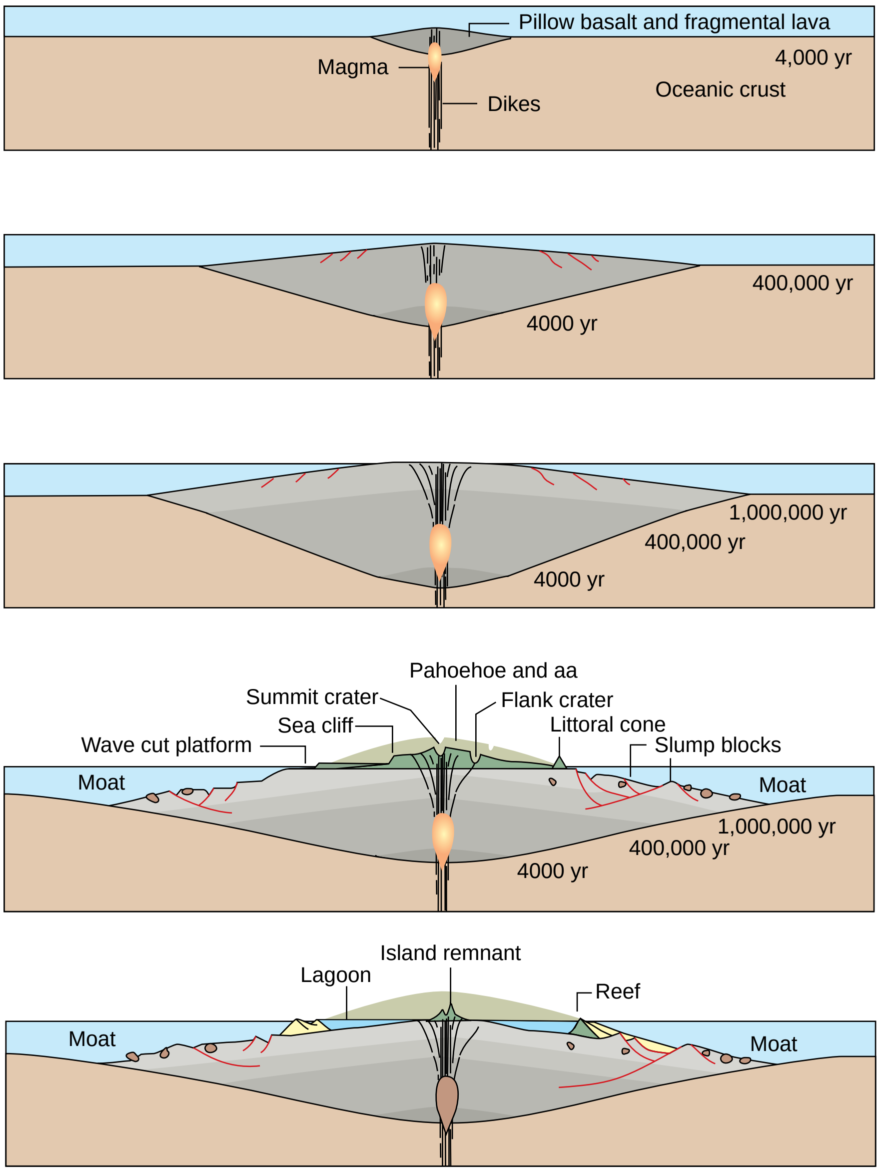


FIGURE 22.15 **Shallow earthquakes** are common in volcanic islands above mantle plumes. Earthquake epicenters for Hawaii are shown here. Most of the earthquakes are related to the movement of magma or to slippage on faults related to large landslides. A few deeper earthquakes are caused by bending of the lithosphere under the weight of the volcanoes.

During the evolution of a large submarine volcano, isostatic balance requires the base of the volcano to subside while its top grows upward. The compensating root is about twice as thick as the overlying mass. Thus, a basaltic volcano with a relief of 3 km must have grown upward 9 km because its base simultaneously had to subside 6 km. Figure 22.16A–C shows the subsidence and growth of a typical seamount during the first million years of its evolution.

How does a volcanic island change with time?

Other factors are important in the growth of islands and seamounts. Submarine lavas erupt in two very different forms. *Pillow lava* might be considered the subaqueous equivalent of *pahoehoe.* Cold seawater chills the lava so rapidly that a crust forms instantly. Each flow advances in a complex multitude of repeatedly budding pillows. Another type of flow leaves beds of *tuff,* fragmented glassy material formed by the explosion and granulation of hot lava when it hits cold seawater. In addition, the abundance of vesicles, and consequently the density of the lava, is directly related to water pressure. At depths of about 1000 m, vesicles form only about 5% of the rock, whereas at depths of 100 m they may form as much as 40%. Consequently, basalt extruded at oceanic depths is denser than basalt extruded on land.



(A) The first 4000 years of eruption makes a volcano 1000 m high, but it has only 0.4% of its ultimate volume. Because of subsidence, its volume is much greater than its height suggests. Pillow lava and fragmental lava dominate.

(B) After 400,000 years, the seamount is 4000 m high, and it has about 40% of its ultimate volume. The volcano also grows by diking and by crystallization of small plutons. The volcano spreads under its own weight.

(C) After about 1 million years, the volcano reaches sea level, and erosion joins subaerial eruptions. A typical shield volcano develops, with gentle slopes, rift zones, and a summit caldera.

(D) Summit and flank eruptions continue to build the shield volcano above sea level, but wave action and erosion begin to overwhelm the construction phase. Wave-cut platforms and sea cliffs enlarge, slump blocks develop, and stream erosion is vigorous.

(E) Within a few million years after the volcano drifts beyond the hotspot, erosion develops a wave-cut platform. Subsidence follows, as the volcano drifts beyond the uparched area above the mantle plume. In tropical areas, coral reefs may develop a flat limestone cap on the eroded volcano.

FIGURE 22.16 The evolution of a hypothetical submarine volcano related to an oceanic hotspot. Most volcanoes in the Pacific drift away from their source plume in fewer than a million years.

Every volcano is subject to the force of gravity, and submarine mass movement can be quite spectacular on seamounts and islands. As magma works its way upward, the volcano swells and radial cracks may develop. In addition, the very weight of the volcano itself begins to tear its fabric apart (Figure 22.16D; Figure 22.14). The fractures may become faults and a large block may slump downward. This movement leaves a gigantic scar near the shoreline. The great Hilina fault scarp on the southern slopes of Hawaii's Kilauea volcano is believed to be such a slump scar (Figure 22.13). Mapping the topography of submarine volcanoes shows that the slump blocks are vast, with scars 30 to 40 km wide and slump deposits covering areas of more than 10,000 km^2 (Figure 11.15).

Eventually, some submarine volcanoes reach sea level, where coastal processes combine to influence the volcanic eruptions (Figure 22.16D). When lava, with a temperature of about 1100°C, erupts on land and then hits cold seawater, it explodes by creating clouds of expanding steam, and the lava shatters into fragments. This unconsolidated material, which is easily eroded and reworked by waves, is deposited along the shore to form a broad platform. Waves can erode this sea-quenched lava with remarkable speed: Wave-cut platforms more than 3 km wide have been eroded in less than 250,000 years. This is roughly equivalent to the extreme rate of erosion in the Himalaya Mountains, where, on average, a layer of rock a meter thick is removed every thousand years. Thus, for a seamount to grow and become an island, rates of extrusion must be greater than rates of erosion.

Once a volcano rises above sea level (Figure 22.16D), pahoehoe and aa flows dominate. The volcano grows rapidly, as lava is extruded from summit and flank eruptions. A steep-sided circular caldera may form near the summit.

The magma supply is gradually cut off when the volcano is carried away from the relatively fixed hotspot (Figure 22.16E). The volcano becomes deeply eroded by streams, waves, and sometimes glaciers. Its summit is soon eroded away and a broad, flat platform forms near sea level. As the volcano moves farther from the uparched hotspot, it subsides below sea level. Once the summit subsides to 200 m below sea level, it remains essentially unchanged by erosion. In tropical regions, however, the growth of coral reefs may add an important structure to the volcanic edifice. As we saw in Chapter 15, a reef typically begins as a fringe around a young volcano, evolving into a barrier reef and eventually into an atoll. This reef material forms a limestone platform capping the top of the eroded basaltic volcano.

Ultimately, the eroded volcano is transported to a subduction zone, where it is either consumed along with the oceanic crust into the mantle or accreted onto a continental margin. After a trip of thousands of kilometers, the seamounts of the Hawaiian-Emperor chain are currently being consumed by subduction down the Aleutian Trench north of Japan. If an oceanic plateau ever formed above the starting Hawaiian plume, it has been long since subducted.

Plumes at Midocean Ridges

The third type of oceanic volcanism shows that not all plumes lie stranded in the middle of oceanic plates. For reasons discussed below, some plumes lie directly beneath divergent plate boundaries. At least six plumes lie on or near the Mid-Atlantic Ridge. From north to south, they are Jan Mayen, Iceland, Azores, Tristan da Cunha, Shona, and Bouvet (Figure 22.2). Iceland is the best known, so we discuss it to illustrate the characteristics of plumes that are centered on midocean ridges.

The Iceland Plume. Iceland lies at the intersection of the north-trending, seismically active Mid-Atlantic Ridge and the seismically inactive Greenland-Faeroe ridge or plateau. If you look at the seafloor map on the inside cover, you might wonder why Iceland is the only great island along a midoceanic ridge. The answer is that more is involved beneath Iceland than a simple divergent plate boundary. The east-trending plateau is a hotspot trail that has been torn asunder at the spreading ridge and carried away on two separate plates.

If not for the mantle plume that lies beneath Iceland, this area would be an obscure, submerged part of the global ridge system. Instead, it is a zone of compromises and contrasts. The compositionally distinctive sources of basalts erupted at midoceanic ridges are mixed deep in the mantle with those typical of plumes, yielding an intermediate mixture. These hybrid basalts erupt along the Mid-Atlantic Ridge axis as much as 200 km north and south of Iceland.

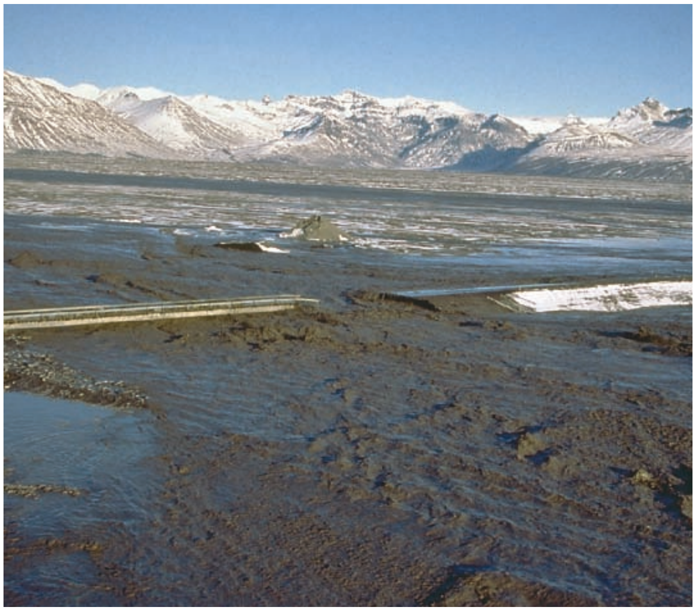
What evidence indicates a plume exists beneath Iceland?

Volcanism on Iceland, caused by the plume, formed basaltic crust more than 30 km thick, four times thicker than typical oceanic crust. Locally, this thick crust has partially melted near new injections of hot basalt, creating rhyolitic magma. In other volcanic centers, mantle-derived basalts have experienced fractional crystallization to create rhyolite. As you know, rhyolite is extremely rare at normal midocean ridges. Because of diverse magmas and a unique tectonic setting, volcanic eruptions on Iceland have created flood basalts, shield volcanoes, fissure eruptions, composite volcanoes, rhyolite domes, and ash flow calderas—a variety of volcanic features quite unlike those at a normal midoceanic ridge!

In addition to these subaerial eruptions, submarine and subglacial eruptions are both common. In the fall of 1996, a small fissure eruption beneath the Vatnajôkull ice cap (see Figure 14.21) melted much of the overlying ice. Some eruptions broke through the ice when hot magma contacted ice-cold water, exploding and showering the ice cap with black basaltic ash (Figure 22.17). After about a month, enough water accumulated to float the glacier off its floor. Water catastrophically burst from the base of the glacier and inundated the outwash plain. Bridges were destroyed as the floods drained the subglacial meltwater. House-sized blocks of ice were ripped from the glacier and tumbled down the plain to the ocean.

The Iceland Ridge began to form about 60 million years ago, when Greenland was rifted away from Europe to open the North Atlantic Ocean (Figure 22.18). Rifting was apparently assisted by the development of a new mantle plume. Large continental flood basalt provinces in Greenland and the northern British Isles mark the position of the starting plume when the continents were still attached (Figure 22.2). Gradually, an open ocean developed between the two continents. Rising high from the seafloor between the continents, active volcanoes on

(A) The overlying ice collapsed into the subglacial lake. Eventually, explosions caused by the contact of hot basalt with the cold water sent low plumes of basaltic ash over the glacier. *(Steve Winter/NGS Image Collection)*



(B) About 1 month after the eruption started, the meltwater burst from the base of the glacier and flooded the outwash plain of the glacier, carrying large blocks of ice and destroying bridges like this one. *(F. Torbjornsson/ Morgunbladid/Gamma-Liaison, Inc.)*

FIGURE 22.17 **Eruption of basalt beneath a glacier on Iceland** caused the base of the glacier to melt.

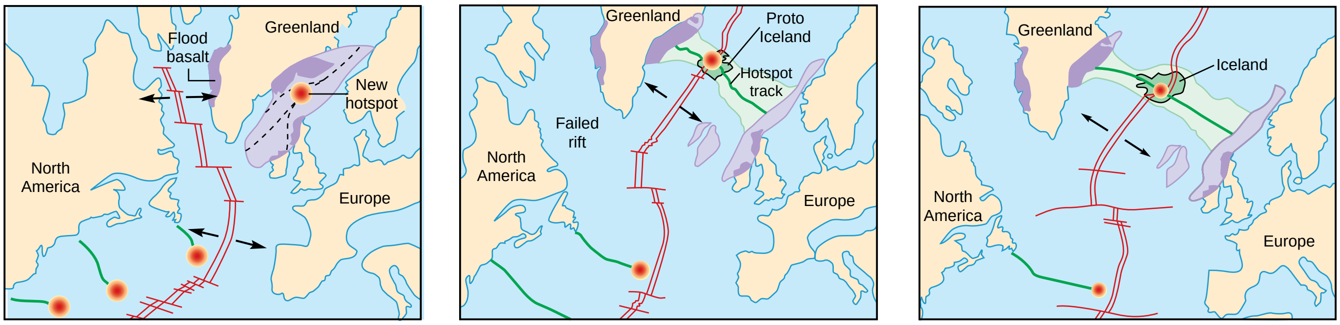
proto-Iceland continued to form above the still-rising tail of the plume. The volcanoes and lava flows were aggressively eroded by streams, glaciers, and waves, keeping much of the island near sea level. Moreover, because the Iceland plume is centered on a ridge, the volcanoes eventually drifted away from the ridge axis and became inactive. As the newly formed lithosphere moved away from the ridge and cooled, it subsided to make the long plateau that links Greenland to the Faeroe Islands. Unlike a spreading ridge, this ridge lacks active volcanoes and has no earthquakes.

At some ridge-centered mantle plumes, a “sudden” shift in the position of the ridge—a so-called **ridge jump**—may isolate a plume tail on one side of the ridge. Half the hotspot trail is stranded on the other side and ceases to grow. For example, the plume beneath the Azores was once on the Mid-Atlantic Ridge but is now east of the ridge (Figure 22.2). The Tristan da Cunha plume is also on the opposite side of the ridge from half of its hotspot trail. A ridge jump may explain why the Ninetyeast Ridge lies north of the Indian Ocean ridge and its parental plume is now centered beneath Kerguelen Island, south of the ridge (Figure 22.2). The ridge apparently drifted off the plume about 37 million years ago.

MANTLE PLUMES BENEATH CONTINENTS

If a plume develops beneath a continent, it may cause regional uplift and eruption of flood basalt from fissures and rhyolite from calderas. Continental crust is not strongly deformed above a mantle plume, but the lithosphere bends to form broad swells and troughs; this bending may trigger shallow earthquakes. Sometimes, continental rifting and the development of an ocean basin may follow the development of a new plume.

The vast sheets of basaltic lavas—continental flood basalts—that cover large areas of the continents have puzzled geologists for more than a century. Their origins were not explained by any aspect of plate tectonic theory, and they remained a major geologic mystery until it was suggested that they might be caused by mantle plumes. Magmatic systems above subcontinental plumes are quite different from oceanic hotspots in composition, eruption and intrusion style, and the nature of the volcanic deposits. The reasons are that (1) the continental crust is thicker and less dense than oceanic crust; (2) the continents’ silica-rich rocks may become assimilated and change the magma’s composition; and (3) continental crust responds to stress quite differently than oceanic crust does.



(A) 60 million years ago. A new mantle plume rose to create a large continental flood basalt province on the margins of what are now Europe and Greenland.

(B) 30 million years ago. Greenland rifted away from Europe and a midocean ridge formed. Volcanoes formed above the plume, but drifted away to make the aseismic ridge (green) between Greenland and Europe.

(C) Today, Greenland and Europe are far apart and volcanically active Iceland sits astride the Mid-Atlantic Ridge. It is being rifted apart, but it is still underlain by an active mantle plume.

FIGURE 22.18 **The history of Iceland** stretches back 60 million years and involves a mantle plume and a midocean ridge.

The Yellowstone Plume

Yellowstone National Park, in northwestern Wyoming, is best known for its spectacular scenery—hot springs, geysers, deep canyons—and abundant wildlife. However, the rocks tell an even more dramatic story. Three huge volcanic calderas form the heart of Yellowstone. From these, more than 8500 km^3 of rhyolite ash-flow tuff erupted over the past few millions of years, including some of the largest ash-flow tuffs known. The most recent major eruption occurred only 620,000 years ago, and its ash buried parts of every state west of the Mississippi River (Figure 22.19). It is the heat from this still-active volcanic system that drives the flow and eruption of groundwater as thermal springs and geysers.

Southwest of Yellowstone, the Snake River Plain is a depression 800 km long and 80 km wide, slicing across north-trending mountain ranges (Figure 22.20). The plain descends from 2500 m at the margin of Yellowstone Park to 1200 m in southwestern Idaho. The Snake River Plain is covered by small basalt lava flows and is dotted with small shield volcanoes, some as young as 2000 years old (see Figure 4.10). The basaltic lava flows cap thick accumulations of rhyolite ash-flow tuff, similar to tuffs at the surface in Yellowstone, but much older. The rhyolites below the Snake River Plain become systematically older with distance from Yellowstone, as old as 16 million years in northern Nevada. Even farther southwest, a narrow rift slices through northern Nevada. It is filled with basaltic and rhyolitic lavas and associated sediments that show that it formed 16 or 17 million years ago (Figure 22.21).

What is the evidence that Yellowstone overlies a mantle plume?

North of this rift, the great flood basalts of the Columbia River Plateau cover an area of nearly 5 million square kilometers in Washington and Oregon. These flood basalts have a cumulative thickness between 1 and 2 km (Figure 22.22), with individual flows up to 100 m thick. This great accumulation of lava was not fed by central eruptions from a single volcano. Instead, the lavas were extruded through many fissures. Such continental flood basalts may erode into plateaus of layered basalt and are therefore also known as **plateau basalts.** Vast **dike swarms** now mark the fissures through which the lava extruded. The largest eruptions occurred about 17 million years ago from long fissure vents along Idaho's western border; these parallel the rift in northern Nevada. Some basalt lavas flowed all the way to the Pacific Ocean, in some cases as much as 500 km.

How are these volcanic and tectonic features related? One hypothesis holds that all are related to a mantle plume that presently lies beneath Yellowstone. According to this theory, about 17 million years ago a mantle plume rose beneath what is now the common border of Idaho, Oregon, and Nevada. The enlarged head of this starting plume fed the Columbia River flood basalts. Eruption rates were very high and some lava flows were exceptionally long. Simultaneously, uplift accompanied by extension created the rift through northern Nevada (Figure 22.21).

As the North American plate moved southwestward (at about 3.5 cm/yr) over the plume's tail, a trail of huge rhyolite calderas formed sequentially atop a broad crustal swell across southern Idaho (Figure 22.21). Each rhyolite caldera was much like the currently active Yellowstone caldera. Rhyolite magma was probably formed by partial melting of a mixture of old continental crust and young basalt. The basalt had been intruded to form dikes and sills above the plume. Large granite plutons crystallized beneath the calderas. In the wake of the plume, the lithosphere cooled, contracted, and subsided, and was covered by younger basaltic lavas forming the broad depression that is the Snake River Plain (Figure 22.20). The eruption rates and volumes of basalt on the Snake River Plain were much smaller than on the Columbia River Plateau. Individual flows are all less than 75 km long, and many are much shorter.

The Snake River Plain is a depression atop a broad arch. The elevated region is about 600 to 1000 km across, comparable in size to oceanic swells related to mantle plumes. The epicenters of earthquakes (up to magnitude 6) form a crescent around the front of the crustal swell (Figure 22.20). These earthquakes are

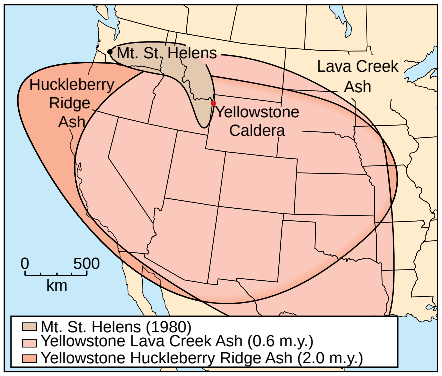


FIGURE 22.19 Rhyolite eruptions from Yellowstone calderas have buried the western United States with ash several times. The last large eruption from this caldera system ejected more than 3000 km^3 of ash as fall and flow deposits. The volume of ash from the devastating eruptions of Mount St. Helens in 1980 is small by comparison: Less than 1 km^3 of magma was erupted.

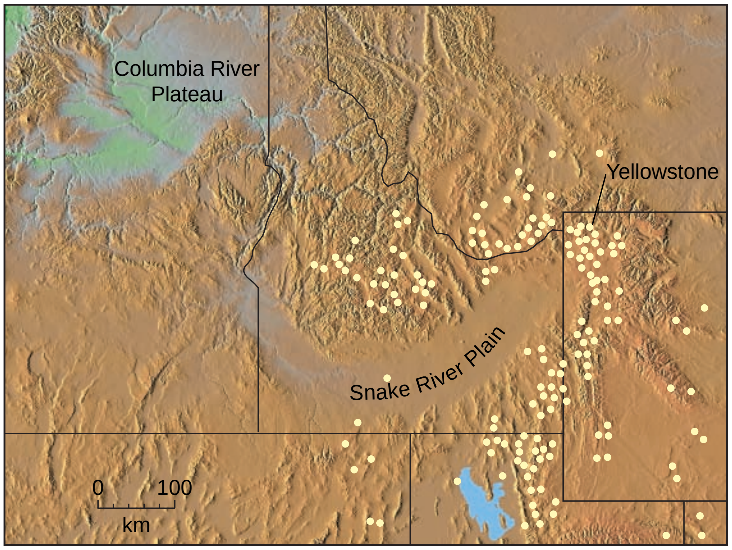


FIGURE 22.20 The Snake River Plain and Yellowstone calderas form a dramatic scar across the mountainous terrain of the western United States. During the last 17 million years (late Cenozoic), silicic volcanism swept across the region as North America moved westward over a nearly stationary mantle plume. Later eruptions of basalt formed small shield volcanoes and fissure-fed flows. The huge Yellowstone caldera marks the present site of the Yellowstone plume. A string of rhyolite calderas like the Yellowstone caldera lies underneath the Snake River Plain to the west. Earthquake locations (dots) are superimposed. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

related to normal faults and crustal extension. Some shallow earthquakes in Yellowstone may also be related to magma movement below the surface.

Interpretations of gravity variations across the Yellowstone Plateau and the Snake River Plain reveal much about the subsurface structure (Figure 22.23). A large gravity low marks the Yellowstone caldera, because it is partly filled by low-density ash and lava and large bodies of hot rock and rhyolitic magma. In addition, seismic wave velocities are anomalously low beneath the caldera. Most likely the low velocities are caused by this hot (probably still molten) rock just below the caldera. In contrast, the Snake River Plain is marked by a gravity high, probably caused by dense basalts at the surface and the accumulation of basalt dikes and sills in the lower and middle crust. No still-molten magma chambers have been discovered beneath the Snake River Plain.

The fundamental cause of the huge geologic anomaly at Yellowstone is the focused flow of heat from the mantle (Figure 22.23), probably from a rising mantle plume. Heat from the plume, probably transferred to the crust by basalt magmas, has (1) uplifted the entire region, (2) caused a multitude of shallow earthquakes, (3) created many separate basalt and rhyolite magma systems of different ages, and, consequently, (4) dramatically modified the structure and composition of the lithosphere. Measurements of the heat flow (2000 mW/m^2) in Yellowstone show

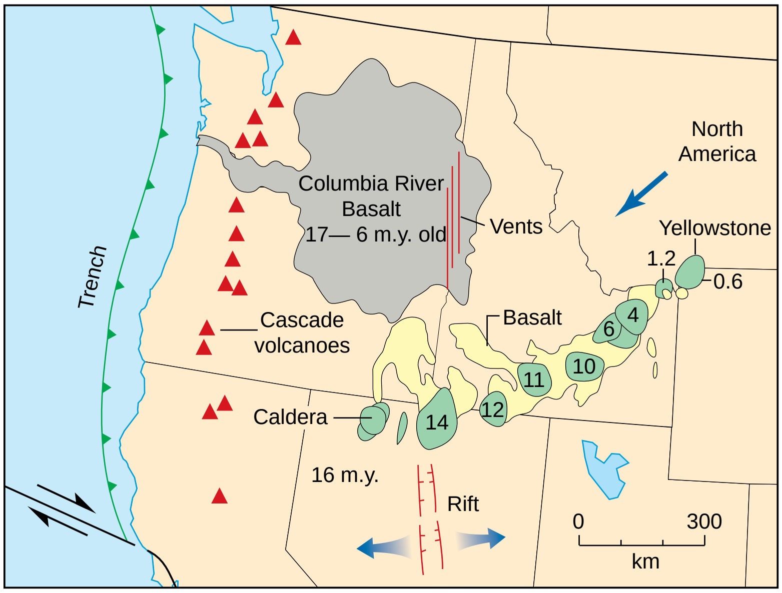


FIGURE 22.21 The Cenozoic features of the northwestern United States may be related to the development of the Yellowstone mantle plume. About 16 million years ago, rhyolite calderas formed near the common borders of Oregon, Idaho, and Nevada, where the plume was probably centered. A narrow rift developed in central Nevada. Simultaneously, the eruption of flood basalts from long fissures on the Idaho border formed the Columbia River Plateau. As the plume head dissipated and North America moved over the plume tail, rhyolite calderas formed in a narrow strip across the Snake River Plain of southern Idaho (the numbers in the calderas are ages in millions of years ago). Later, small eruptions of basalt covered the Snake River Plain. Today, the Yellowstone hotspot lies beneath Yellowstone National Park, where large rhyolite eruptions blanketed much of the region.

FIGURE 22.22 Flood basalts of the Columbia Plateau formed between 17 and 6 million years ago. Locally, several lava flows are stacked one upon the other. Erosion that formed the Channeled Scablands of Washington has exposed this sequence of flows. Individual flows may be more than 100 m thick and as long as 500 km. They provide important information about the style of volcanic activity above mantle plumes.

that it is about 30 times the continental average. The total thermal energy released at Yellowstone in one year is 5% of that released from the entire rest of the western United States. Heat flow across the Snake River Plain in the wake of the plume is still high, but it dwindles to normal heat flow near the Oregon border. Northeast of the plume, where its geologic effects are not yet manifest, the heat flow is much lower (Figure 22.23).

Continental Rifting, Flood Basalts, and Mantle Plumes

Many geological observations suggest genetic links among continental rifts, flood basalts, and mantle plumes. Many episodes of continental rifting have been preceded by crustal uplift and the outpouring of huge volumes of continental flood basalt. Is there any explanation for this relationship?

As discussed earlier in this chapter, a plume begins as a small bump on an internal boundary layer that rises and develops a very large mushroom-shaped plume head and a narrow tail (Figure 22.7). The plume head may be several thousand kilometers across. As the plume head encounters the overlying rigid lithosphere, its ascent slows, and it flattens against the strong, rigid lithosphere. Heat and buoyancy from the plume may cause the overlying lithosphere to dome and weaken. As a result, it may stretch and ultimately rift. While this is happening, copious continental flood basalt may erupt over a short period and spread over large areas. Unlike the slow, steady eruption of basalt at midoceanic ridges, the eruption of lava generated from starting plumes is rapid and episodic.

The connection between a flood-basalt province, continental rifting, and a hotspot track is exemplified by the opening of the southern Atlantic Ocean (Figure 22.2). The flood basalt provinces lie along the present-day continental margins, but they originally extruded above mantle plumes that later developed rifts and seafloor spreading. About 125 million years ago, when South America and Africa were still connected (see Figure 19.38), huge eruptions formed the Etendeka flood basalt province of southern Africa and the Parana basalts of South America. In southern Brazil and adjacent Paraguay, more than 1 million cubic kilometers of basalt were extruded in about 10 million years.

This volcanic episode probably marked the arrival of the head of a new plume at the base of the lithosphere. Rifting of the continent started at about the same time, and the rift grew northward and southward from the site of the plume-related volcanism. Because of rifting, South America slowly slipped away from Africa. The oceanic lithosphere of the southern Atlantic basin formed in the wakes of these two continental fragments. A hotspot near the midoceanic ridge left a narrow track of seamounts on each side of the ridge. The modern volcanic island of Tristan da Cunha lies over the current location of this plume (Figure 22.2). Volcanism along the hotspot trace was much less voluminous than during the initial stage and apparently records the continued rise of mantle material in the tail of the plume.

Elsewhere, several major plumes have risen beneath continental crust during the past 250 million years, creating flood basalt provinces and continental rifts. An example is the vast basalt flood that formed India's Deccan Plateau (1 to 2 million cubic kilometers) as India rifted away from Africa. In North Africa the floods of basalt in the Ethiopian plateaus extruded as the Red Sea Rift developed. Precambrian flood basalts that were probably caused when an aborted rift developed are found in the Lake Superior area of northern Michigan (see p. 569). Continental flood basalts are, therefore, important records of the role played by mantle plumes in initiating divergent plate boundaries.

Plumes alone, however, probably cannot cause continents to break apart. The Siberian flood basalts (Figure 22.2) of the latest Paleozoic age are some of the greatest outpourings of lava the world has known, but the continent did not break up. Likewise, the Yellowstone plume may have aided in the extensional disruption of western North America, but it did not cause complete rifting and the creation of new seafloor. In situations where the plate motions are already suitably established, the additional stress generated by uplift above a plume, or the lowered viscosity it creates in the mantle, may be sufficient to let rifting proceed when it otherwise might not. In addition, the presence of the plume may cause an already active rift to shift over the center of the plume.

Is there a relationship between continental rifting and mantle plumes?

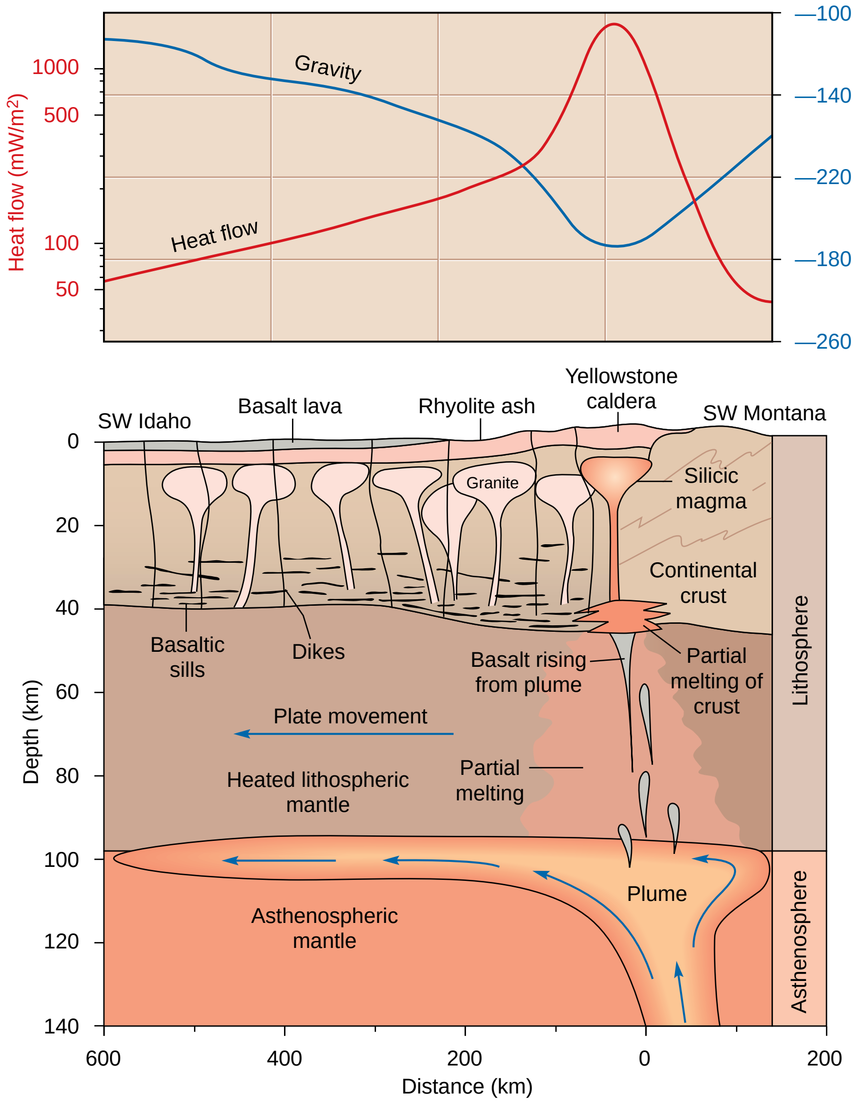


FIGURE 22.23 High heat flow and topography are associated with the Yellowstone plume. The Snake River Plain is a zone of subsidence formed in the wake of the plume. Gravity studies help geologists construct a cross section through the region. Rock densities are given in grams per cubic centimeter and are lowest in the region of the mantle affected by the passage over the plume. Crustal density beneath the Snake River Plain may be higher because of the intrusion of dense basaltic dikes and sills.

PLUMES, CLIMATE CHANGE, AND EXTINCTIONS

Mantle plumes may affect Earth's climate system and magnetic field.

From the foregoing, it should be clear that, like the theory of plate tectonics, the model of a mantle plume is a simple but powerful concept. It explains much of the geologic activity in the central parts of plates that never seemed to fit a simple interpretation of plate tectonics. Volcanic islands, rifts in continents, flood basalts, and continental calderas find explanations in the mantle plume model. Recently, mantle plumes have been used to explain another class of phenomena, including climate change, mass extinctions, and even changes in Earth's magnetic field.

Hypothetically, the effects of mantle plumes may extend far beyond the limits of the flood basalts and rhyolite ash that periodically pour from them. For example, the volcanic activity associated with a starting plume, either beneath a continent or on an ocean basin, occurs in a short, dramatic episode. These spasms of volcanic activity and rapid extrusion of lava may change the composition and circulation of the oceans and the atmosphere. During eruptions, huge volumes of volcanic aerosols and gases, including carbon dioxide (a greenhouse gas), are released.

What effect could a mantle plume have on climate?

Because a series of plumes developed during the latter part of the Mesozoic Era (particularly in the Pacific Ocean, such as the one that developed the Ontong-Java Plateau), some scientists have speculated that enough carbon dioxide was released to raise global temperatures by several degrees. Thus, the warmth that typified the Cretaceous may have had its roots deep in the mantle. Some of the environmental adjustments may have contributed to mass extinctions, including the one in which dinosaurs vanished.

The Deccan flood basalts of India erupted at the boundary between the Cretaceous and Tertiary Periods—marked by extinctions that included dinosaurs and many other species. The Siberian flood basalts have also been correlated with extinctions at the very end of the Paleozoic. These environmental shifts may have helped promote the origin of new species. These provocative hypotheses need further investigation; perhaps within your lifetime we shall establish the cause of these great extinctions.

A secondary result of the release of carbon dioxide from mantle plumes may have been the deposition of organic carbon in marine sediments, especially as black carbon-rich shales and as beds of coal. Plants can convert carbon dioxide into organic carbon molecules and release oxygen gas into the atmosphere. If the carbon is locked in sediments, the atmosphere may eventually become enriched in oxygen. Some paleontologists suggest that oxygen contents higher than those in today's atmosphere were important for the evolution of anomalously large animals, such as dinosaurs in the Mesozoic and large insects in portions of the Paleozoic. Some scientists contend that such high oxygen contents may have been produced during times of enhanced plume development. The excessive carbon dioxide from the mantle could have released oxygen by the mechanism described above.

Hotspots and Mantle Plumes

Another effect of mantle plumes may also have an example in the Cretaceous, a period when several large plumes formed. A significant decrease in the number of reversals in the polarity of the magnetic field marks this part of Earth's history. Magnetic field reversals are probably related to changes in the convective pattern in the metallic outer core. If large amounts of heat are drained from the core during the development of several mantle plumes during a short interval, the convection patterns in the core might be changed. These changes might have diminished the number of field reversals, perhaps by slowing convection in the core.

KEY TERMS

decompression melting (p. 640)
diapir (p. 638)
dike swarm (p. 652)
flood basalt (p. 638)
hotspot (p. 634)
hotspot track (p. 643)
mantle plume (p. 634)
oceanic plateau (p. 642)
plateau basalt (p. 652)
plume head (p. 638)
plume tail (p. 638)
ridge jump (p. 651)
rift zone (p. 643)
seamount (p. 647)
shield volcano (p. 634)
starting plume (p. 638)

REVIEW QUESTIONS

1. What type of volcanic activity occurs within the central parts of tectonic plates, beyond the active plate margins?
2. Explain the origin of chains of volcanic islands and seamounts.
3. Outline the evidence that suggests that mantle plumes are real.
4. What causes a mantle plume to rise?
5. Describe the probable shape and size of a mantle plume. Does the shape of the plume change during its history?
6. How is the production of magma in a mantle plume similar to its production at a divergent plate boundary? If magma is produced in similar ways under the two conditions, why does it have different compositions? How are its sources different?
7. Compare the size, composition, and structure of a typical subduction-related volcano with those of a plume-related volcano.
8. What causes the large topographic swell that surrounds an active ocean island volcano?
9. What does the study of flood basalt provinces tell us about volcanic systems that are related to mantle plumes?
10. Compare the style of volcanism related to a starting plume with that related to a plume tail.
11. What kinds of earthquakes are related to mantle plumes?
12. If Iceland is part of the oceanic ridge system, why is it so much higher than the rest of the Mid-Atlantic Ridge? Does this situation occur anywhere else?
13. What evidence is there that Yellowstone National Park is underlain by an active mantle plume? How does it differ from the Hawaiian mantle plume?
14. Why is rhyolite more common above continental plumes than above oceanic plumes?
15. Compare the possible contrasts between the dominant modes of convection in the upper and in the lower mantle.
16. What represents a more universal type of mantle convection, plumes or plate tectonics?
17. If a starting plume rises 2 m/yr, how long will it take to rise from the core-mantle boundary to the base of the lithosphere?
18. How could a mantle plume affect Earth's global climate?

ADDITIONAL READINGS

Condie, K. C. 2001. *Mantle Plumes and Their Record in Earth History.* New York: Cambridge University Press.

Duncan, R. A., and M. A. Richards. 1991. Hotspots, mantle plumes, flood basalts, and true polar wander. *Reviews of Geophysics* **29:**31–50.

Hill, R. I., I. H. Campbell, G. F. Davies, and R. W. Griffiths. 1992. Mantle plumes and continental tectonics. *Science* **256:**186–193.

Larson, R. L. 1995. The mid-Cretaceous superplume episode. *Scientific American* **272**(2):82–86.

Smith, R. L., and L. W. Braille. 1994. The Yellowstone hotspot. *Journal of Volcanology and Geothermal Research* **61:**121–127.

MULTIMEDIA TOOLS

Earth's Dynamic Systems Website

The Companion Website at **www.prenhall.com/hamblin** provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources

Earth's Dynamic Systems CD

Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animations of the formation of the Hawaiian islands
- Computer models of plume convection
- Guided tour to Earth's hotspots and mantle plumes
- A direct link to the Companion Website