• Volcanoes in Human History

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The Far-Reaching Effects of Major Eruptions

Jelle Zeilinga de Boer

and

Donald Theodore Sanders

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To Joe Webb Peoples—
teacher, mentor, and friend to both authors

• Contents

• Foreword

MOST PEOPLE seldom think about volcanoes or the role they have played in human history. That is because most of us do not live where volcanoes are erupting. They are not part of our everyday lives.

But if you lived near Mount St. Helens when it exploded in 1980, you will not soon forget its tremendous eruptive power. In Iceland, which sits astride the Mid-Atlantic Ridge, volcanoes dominate people's lives and their mythology. Those who live on the Icelandic island of Heimaey literally have an active volcano in their backyards. Residents of Reykjavik, the country's capital, have their homes heated by water that circulates through hot lava.

Active volcanoes remind us that the earth is a living, breathing organism, making our planet unique compared with its sister planets Mercury, Venus, and Mars. In addition to having an immediate effect upon those of us who live near them, volcanoes, in the long term, can profoundly affect our very psyches.

The authors of this book, Jelle Zeilinga de Boer and Donald Theodore Sanders, examine the relationship between volcanoes and human history through nine case histories. These chilling examples show the profound impact volcanic eruptions have had upon humans. The incredible story has taken centuries to unfold. It will surely continue to evolve.

Robert D. Ballard
Institute for Exploration, Mystic, Connecticut

• Preface

THERE IS A WIDESPREAD PERCEPTION that the sciences and the humanities are incompatible, that they have little or nothing in common. What do history, the arts, and great literature have to do with physics, chemistry, biology—or earth science? In 1959 the British scholar C. P. Snow analyzed that question in his widely read book *The Two Cultures.*[1] Snow attributed the apparent incompatibility to misinterpretation and lack of understanding on both sides, and in his book he attempts to reconcile the "two cultures."

The notion that Snow's two cultures are at odds is trenchantly expressed in a novel published in 1983 by the American author Trevanian in a scene where one of the characters warns another, "Beware the attraction of the *pure* sciences. They are pure only in the way an ancient nun is—bloodless, without passion. No, no. Stick to the humanistic studies where, though the truth is more difficult to establish and the proofs are more fragile, yet there is the breath of living man in them."[2]

One of the present authors (Zeilinga de Boer) has attempted to bring the two cultures together at Wesleyan University in his course on geological catastrophes, in which he demonstrates to liberal-arts students that the sciences are not "bloodless," that in the earth sciences in particular, something akin to the "breath of living man" can be seen in such phenomena as volcanic eruptions and earthquakes. In his lectures, Zeilinga de Boer discusses selected geological events, describing their origins while emphasizing the many ways in which the events have affected people, societies, cultures, even history itself. This book, which grew out of those lectures, has as its theme the human dimension of volcanism. The ways in which earthquakes and the humanities are intertwined will be discussed in a later volume.

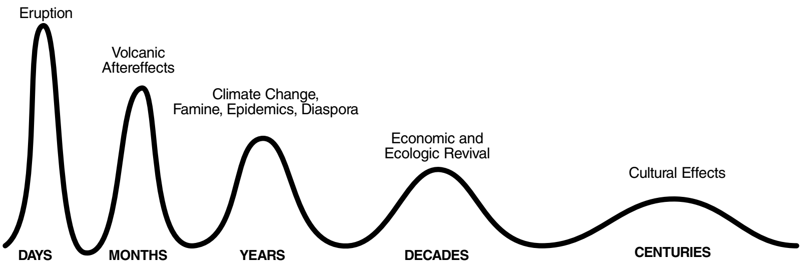
Volcanic eruptions are treated only descriptively in most books, the descriptions concerned mainly with environmental consequences and the number of casualties. Many of these short-lived events, however, have had long-lasting aftereffects. Some eruptions have had global consequences that have lasted for years, decades, centuries, even millennia. Some of the events can be described as catalytic in the sense that their direct aftereffects give rise to other phenomena, whether environmental, economic, or cultural.

Moreover, most books treat only the destructive side of volcanism. But volcanic eruptions, devastating as they may be in the short term, have been of long-lasting benefit to humankind in many ways. Volcanic soils are among the most fertile on earth. Many of our mineral resources are of volcanic origin. Even water, the basic resource without which life could not exist on our planet, ultimately is created by volcanic activity within the earth. All these aspects of volcanism—destructive as well as beneficial—are discussed in the chapters that follow.

In this book we explore nine volcanic eruptions. In each case we briefly discuss the geological setting in terms of plate tectonics—the theory that virtually rigid segments of the earth's crust move about over a less rigid layer and collide, and that the collisions give rise to earthquakes and volcanic activity. Then we discuss the aftereffects of the eruption—its consequences—in human terms.

By describing not only the immediate physical effects of volcanism but also the long-term aftereffects, we demonstrate the inherent connections that exist between the earth sciences and the humanities. Some eruptions have changed societies. Some have been followed by famine and disease, or by political changes either peaceful or violent. Others, of truly ancient origin, have passed into mythology or are reflected today in religious beliefs and practices. Some have achieved cultural immortality in the arts or in literature—in paintings, poems, great books, operas, motion pictures, even architecture.

Volcanism is the surface manifestation of a living earth. We can think of a volcanic eruption as the plucking of a long, tight-stretched string representing time: when the string is plucked it vibrates. During the eruption, at the point of origin, where a great deal of energy is being released, the vibrations will have high amplitudes and short wavelengths. The vibrations will be powerful, but each will last only a moment. Farther along on the string, with the passage of time, the amplitudes will decrease and the wavelengths increase. That is to say, the aftereffects will become less intense and they will last longer, as shown in the figure below.



The "vibrating string" showing the long duration of interdisciplinary effects that can follow a volcanic eruption.

For example in 1815, Tambora, a volcano in Indonesia, exploded in the greatest eruption known to history. It killed perhaps 70,000 people outright. Regionally the catastrophe devastated forests and croplands, producing famine and disease. Around the world there were major changes in the weather as dust and aerosols from the eruption, carried by high-altitude winds, circled the globe and dimmed the sun's rays. In Europe, prolonged inclement weather caused crop failures and food riots, and in 1816 North America suffered the infamous "year without a summer." The European weather inspired Lord Byron's gloomy poem "Darkness" and Mary Shelley's immortal novel *Frankenstein,* which continues to attract readers and moviegoers almost two centuries later. Tambora's string vibrates to this day.

By discussing Tambora's "vibrating string," and eight others, we hope to draw interest both to the tectonic origin of specific volcanic eruptions and to their interdisciplinary consequences. When most of those eruptions occurred, the earth was sparsely populated. Today the human population exceeds 6 billion. The geological events discussed here are not unique. Similar events will occur in the future, and their effects will be magnified by the population density of our crowded planet. It is crucial that we understand the origin of volcanism as well as the devastation it can cause, and the aftereffects, for good or ill, that can linger for years, even decades, to come.

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Special thanks go to Michael Ross, whose telephone call in 1994 led, more or less directly, to the authors' collaboration. And of course we thank Edward Knappman of New England Publishing Associates, who agreed to represent us, provided invaluable guidance, and on our behalf contacted Princeton University Press.

More personally we wish to thank Felicité de Boer, Joan Boutelle, and Katherine Sanders for their support and help in so many ways.

• Table of Conversions

1 centimeter = 0.39 inch
1 meter = 3.28 feet
1 kilometer = 0.62 mile
1 square meter = 10.76 square feet
1 square kilometer = 0.39 square mile
1 hectare = 2.47 acres
1 cubic meter = 35.31 cubic feet
1 cubic kilometer = 0.24 cubic mile
$9/5 \times$ degrees Celsius + 32 = degrees Fahrenheit

• Volcanoes in Human History

1 • Volcanism: Origins and Consequences

Giant smoking volcanoes
stand in a row
like the pipes of a cosmic organ
through which the mighty breath of the earth
blows its roaring music

Robert Scholten

WHEN OUR ANCESTORS realized that their world was not a flat disk resting on the back of a giant turtle—that instead, the earth is a spheroid whirling through space in orbit around the sun—they began to comprehend the nature of the planet that is our home. Over many centuries, scientists pieced together a great deal of information about the earth—the materials of which it is composed, the atmosphere surrounding it, the infinite variety of landforms on its surface, the kinds of rocks that are exposed there.

Eventually, by studying earthquake waves and the time they take to pass through the earth, scientists deduced that our planet has a dense, at least partly molten core at its center and that the core is overlain by a thick layer of less dense material, which they named the mantle. Above the mantle is the thin, rocky crust upon which we live. We might say that the earth resembles an apple in some respects. If an apple is sliced in two, the cross section reveals a small, circular "core" (where the seeds are), a thick "mantle" (the edible flesh), and a "crust" (the very thin skin). The relative proportions of those parts of an apple are not unlike the proportions of the main parts of the earth.

Like our understanding of the structure of the earth, our understanding of volcanoes slowly emerged from beliefs conceived in ignorance. Well into the European Middle Ages, many people thought of volcanoes, with their fiery summits and unearthly roarings, as entrances to the underworld, the hellish world of suffering sinners. In the early 1300s, the Italian poet Dante Alighieri captured the prevailing views of that time in his masterpiece, the *Divine Comedy,* an allegorical, three-part portrayal of a journey, first into hell, the realm of eternal punishment, then into purgatory, where there is hope for the soul's salvation, and ultimately into paradise, where the soul returns to God. Dante's hell is a fiery cavity that reaches to the center of the earth, where the devil dwells. What more obvious interconnection could there be between the devil's subterranean realm and the external world of the living than a volcano?

Forces of destruction, sources of bounty

With the maturing of the geological sciences, of course, such beliefs faded into fantasy. But the association of volcanoes with suffering and disaster remained, for volcanoes, after all, can be, and often are, deadly and destructive.* During the past 400 years, perhaps a quarter of a million people have been killed as a direct result of volcanic eruptions. Indirect aftereffects, such as famine and disease, may well have tripled that number.

*The term *volcano* can be defined in different ways. The dictionary definition includes any opening in the earth's crust through which molten lava, volcanic ash, and gases are ejected. The term can also refer to a mountain formed by the materials ejected from such an opening. Strictly, then, a volcano can be anything from a vent or fissure in the earth to a mountain with a height measured in kilometers. In this book, for simplicity, we reserve the term for volcanic mountains.

Volcanic lava flows consume everything in their path. Volcanoes also can cause landslides and mudflows that rapidly travel long distances, wreaking havoc. Volcanic dust and aerosols in the atmosphere can shield the earth from sunlight and the sun's warmth, disastrously altering weather patterns, sometimes for years. French poet Max Gérard eloquently sums up this calamitous side of volcanism:

> Here is Wotan's brazier,
> Vulcan's furnace,
> the forge of Cyclops,
> Satan's pyre!
> Here is the first panting,
> the birth of matter,
> here the Gods are stoking
> the superstition of men,
> here the times are coming
> of violence and damnation![1]

But paradoxically there are many beneficial aspects of volcanism, and they are crucially important to our lives. Over the eons, volcanic eruptions have emitted vast amounts of water vapor, bringing to the surface the fluid that is essential to life. Much of the water vapor in any given eruption may come from volcanically heated groundwater—recycled rain and snow in the zone of saturation below the surface of the ground. But many scientists believe that all the water on earth—whether in clouds, mountain streams, rivers, lakes, or oceans—was originally vented into the atmosphere by volcanoes. According to that theory, water originated as dissociated hydrogen and oxygen atoms deep in the earth's mantle. Volcanism is responsible, too, for creating many of the minerals in the earth—minerals in the ores that give us copper, lead, zinc, and other metals required for industry and modern technology.

Volcanic eruptions also bring nutrients to the earth's soils. The potassium and phosphorus needed by plants are contained in the ash produced by many eruptions. The weathering of volcanic rocks also releases such nutrients. Therefore volcanism supports plant life and is ultimately responsible, in many regions, for agricultural abundance. Hundreds of millions of people live quietly on the flanks of volcanoes or in nearby lowlands, farming the fertile soils. Thus, though volcanoes are destructive during short periods of eruption, they bring us many essential benefits during the long periods between eruptions. This all-important, and often neglected, dual view of volcanism is vividly illustrated in Figure 1-1, which shows a volcano erupting and bringing death and destruction while, at the same time, producing a cornucopia overflowing with the good things of life. Again quoting Max Gérard,

> It burns so as to re-create,
> the glow of fire becomes an embrace . . .
> that destroys and rebuilds, tears and will mend, burns
> and will make green again.[2]

Products of volcanism

The products of volcanic eruptions—lava, gases, and fragmental materials such as ash—all ultimately derive from molten rock, called *magma,* that originates within the earth. Because magma is hot and fluid and contains dissolved gases, it is less dense than solid rock and tends to work its way upward through fissures in the earth's crust. Lava is magma that has erupted at the surface. The term *lava* applies both to the molten material and to the rock that forms after magma has cooled and hardened. Rapid cooling, which leaves little time for mineral crystals to form, produces fine-grained rock.

We often think of volcanic rocks as being black, or at least dark gray, creating dismal, colorless landscapes. Most lava flows are indeed drab and dark, but some, depending on their chemical composition, create landscapes that are vibrant with color. In 1924 after Gilbert Grosvenor, a founder of the National Geographic Society, climbed Mauna Loa, the largest volcano on the island of Hawaii, he reported traversing "a lumpy, rolling sheet of colored glass, extending as far as the eye could reach, glistening at times with the radiance of countless jewels,

FIGURE 1-1. The dual nature of volcanism. Volcanic eruptions cause death and destruction. But equally important in the long run, they provide fertile soils, hence bountiful harvests, as well as a wide range of mineral resources. Engraving by Nicollet after a design by Fragonard. Private collection.

sparkling with the brilliance of diamonds and rubies and sapphires or softly glowing like black opals and iridescent pearls."[3]

The gases released in volcanic eruptions comprise mostly water vapor, along with lesser volumes of carbon dioxide, sulfur dioxide, and other gases. Indeed, it is thought that volcanism was responsible for creating the planet's atmosphere when the earth was young. The oxygen we breathe came later, after the evolution of life-forms capable of photosynthesis, which uses sunlight to transform carbon dioxide and water into organic matter, releasing oxygen as a by-product.

Many of the materials ejected during eruptions are fragments of rock, either solidified bits of magma or pieces of preexisting rock torn from the conduit that feeds the volcano. Such materials are called *pyroclastic,* from the Greek *pyro* (fire) and *klastos* (broken). Sometimes clouds of such fragmental material, along with hot volcanic gases, form devastating pyroclastic flows, which, because of their weight, hug the ground and race down mountainsides at express-train speed, destroying everything in their path. Typically they separate into three parts:

- Dense material—fragments of fresh magma, pumice, and older volcanic rock ripped from the conduit or from the flanks of the volcano—that hugs the ground.
- Fiery, gaseous surges containing droplets of fresh magma. Many surges form at the head of the flow or along its sides, and they move much faster than the dense material.
- Clouds of volcanic dust that form buoyant plumes rising thousands of meters into the air.

Life cycles of volcanoes

Volcanoes have life cycles much as animals and plants do. On the morning of February 20, 1943, a Mexican farmer named Dionisio Pulido had the unpleasant experience of witnessing the birth of a volcano in his cornfield, about 320 kilometers west of Mexico City. What had been a slight depression in the field became a gaping fissure that emitted clouds of sulfurous smoke accompanied by loud hissing noises. By the next morning, Señor Pulido's cornfield was occupied by a cinder cone more than 10 meters high. Within a week the volcano, named Paricutín after a nearby village, had attained a height of 170 meters, and within a year it had reached 370 meters. Within nine years, Paricutín had produced voluminous lava flows that destroyed several towns and had grown to an elevation of 2,272 meters. Then the volcano went into repose.

In 1980 the Japanese author Shusaku Endo wrote a novel entitled *Volcano* in which the protagonist recalls how a university professor, Dr. Koriyama, eloquently described such a cycle: "A volcano resembles human life. In youth it gives rein to passions, and burns with fire. It spurts out lava. But when it has grown old, it assumes the burden of past evil deeds, and it turns quiet as a grave."[4] The fictional Dr. Koriyama might well have added that upon aging, volcanoes also lose much of their beauty. Young volcanoes typically form sleek, symmetrical cones. Old volcanoes have ragged, time-worn summits and flanks scarred by erosion.

Volcanoes erupt spasmodically, each eruption possibly including several pulses. Such activity can last from a few weeks to several years. Some volcanoes become quiescent, or dormant, for hundreds or even thousands of years but then are reactivated when a new upwelling of magma rises through the volcano's conduit. But all volcanoes eventually grow old and "die," or become extinct. Most have short life spans in geological terms—only one or two million years, often less. Volcanic fissures typically have even shorter life spans. Some of the magma that fills a fissure inevitably cools and solidifies there, forming a tabular body of rock called a *dike.* Any new pulses of magma normally intrude along a margin of the dike or through new fissures adjacent to it.

Volcanoes typically are crowned by eruption craters. During the largest eruptions, however, molten rock may not be able to rise from within the earth fast enough to replace the ejected magma, and as a result, the upper part of the volcano collapses inward. The result is not just a crater but a much larger depression called a *caldera* (Spanish for *caldron*): some calderas can be tens of kilometers in diameter. An example is the misnamed Crater Lake in southwestern Oregon. The lake occupies a caldera (not a crater) almost 10 kilometers across and about 600 meters deep. It was created about 6,000 years ago, when an ancient volcano known as Mount Mazama exploded.

Within Crater Lake lies Wizard Island, a small volcano, now extinct, that was born sometime after the caldera was formed—evidence that even apparently "dead" volcanoes can be reborn. A recent example of such rebirth occurred in 1927, when a volcano named Anak Krakatau appeared in the Sunda Strait between Java and Sumatra. Its birthplace was a submerged caldera that had been formed in 1883, when a volcanic island named Krakatau exploded in one of the great eruptions of history. Fittingly, the Indonesian name Anak Krakatau means "child of Krakatau."

Plate tectonics

In the 1960s geologists began to understand that the outer part of the earth is made up of individual rigid plates, some very large, others small, which slowly move over a ductile, or plastic, interior layer (Figure 1-2). The movement of these tectonic (structural) plates, at a rate typically measured in centimeters per year, is responsible for most volcanoes and earthquakes. This is the theory of plate tectonics, which revolutionized the science of geology by providing a single, unifying concept that helps explain most geological processes and features.

The earth's rigid outer shell includes the rocky crust and a thin layer of the uppermost part of the mantle. Together they form what geologists call the *lithosphere,* from the Greek *lithos* (stone). The ductile layer of mantle material over which segments of the lithosphere move is called the *asthenosphere,* from the Greek *asthenos* (weak).

The lithosphere segments—that is, the tectonic plates—are in motion presumably because of slowly moving convection currents within the mantle. The currents are believed to be driven by heat from the earth's core, much as convection currents are created in a pot of water heated on a stove. Hot water, being less dense than cold water, rises to the surface, where it cools, becomes more dense, and therefore returns to

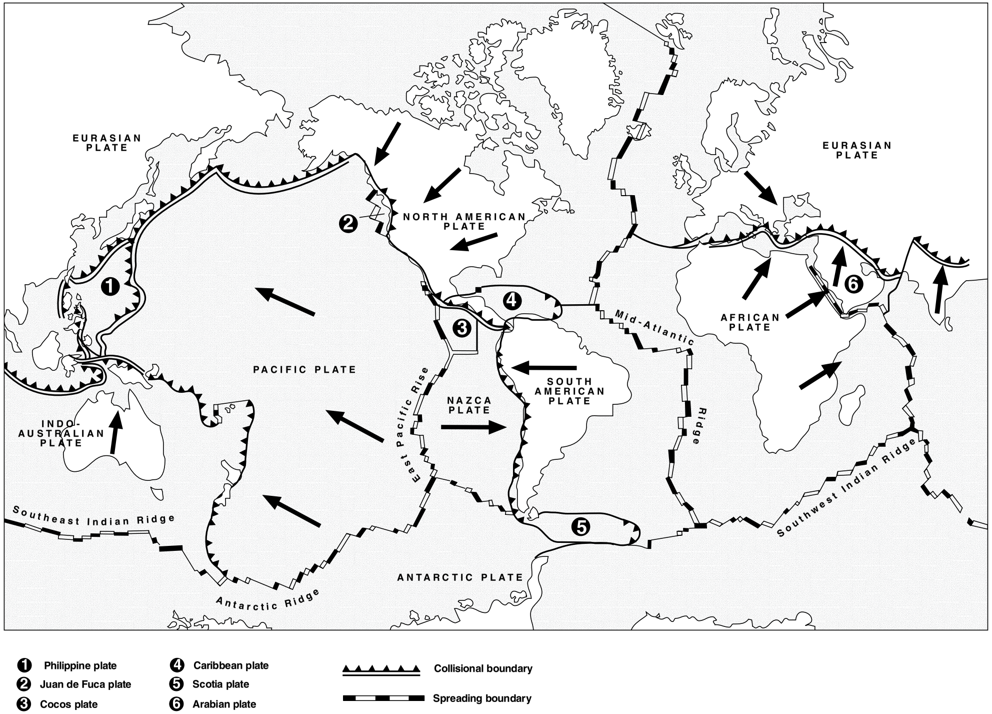

FIGURE 1-2. Configuration of the earth's tectonic plates, showing the collisional boundaries between converging plates and the spreading boundaries between diverging plates. The arrows indicate the present directions of plate motion. The black triangles at the collisional boundaries show the direction in which one plate is being subducted beneath another.

the bottom of the pot. A similar process is believed to be at work, albeit very slowly, within the earth.

As tectonic plates move about the earth's surface, inevitably they collide with one another. When they do, the consequences are profound. At these collisional, or convergent, boundaries, one plate slides beneath the other in a process known as *subduction.* The subducted plate descends into the asthenosphere, where high temperatures and pressures force fluids out of the subducted rock. The hot fluids—mostly steam from water in fractures and from minerals containing hydroxyl groups (comprising one hydrogen atom and one oxygen atom bound together)—rise and react with the rock in the wedge of mantle material above the subducted plate, causing chemical changes that locally reduce melting temperatures (see Figure 1-3). As a result, part of the asthenosphere wedge melts and becomes magma.

Magma formation

Volatile gases are released from the subducted plate as it reaches a depth of about 70 kilometers. By the time it has descended to 200 kilometers all liquids and gases have been squeezed out. Therefore it is between 100 and 150 kilometers that magma is generated. Blobs of magma are believed to rise slowly through the ductile asthenosphere, like air bubbles rising through water, until they reach the bottom of the solid lithosphere above the mantle wedge. There they coalesce into sheets of molten material that is hot enough to melt adjacent parts of the lithosphere.

As new batches of magma arrive, the molten mass eventually generates enough pressure to arch the still-brittle part of the lithosphere above it. Arching of the lithosphere creates fractures that allow magma to rise into the crust, where it forms pockets called *magma chambers* that may have volumes of many cubic kilometers. These chambers expand as more magma rises into them and as the hot magma melts rock formations that enclose them. As long as magma

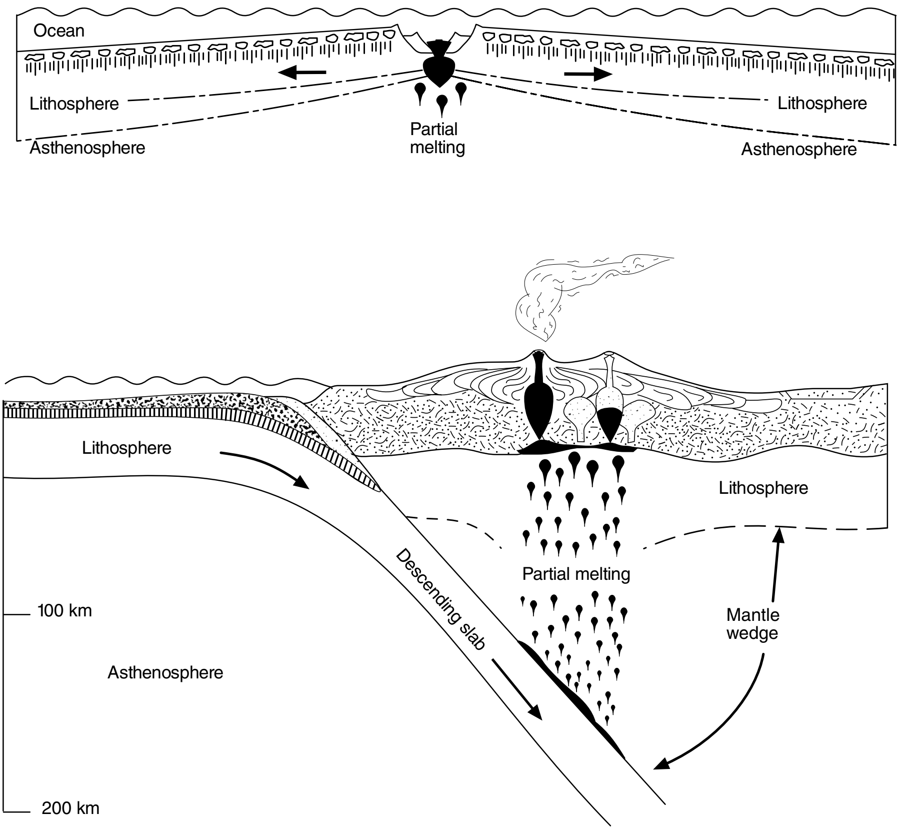

FIGURE 1-3. *Top:* Partial melting of the upper asthenosphere and formation of magma below an oceanic ridge at the boundary between separating plates. *Bottom:* Subduction of an oceanic plate beneath a continental plate and partial melting of the upper asthenosphere.

resides in a chamber, it continues to react with the surrounding rock, and its chemistry changes. It becomes lighter, less dense, and richer in gases, and it also becomes more viscous, or resistant to flow. Magma chambers give rise to volcanoes when increasing pressures force part of the molten mass up through crustal fractures, or conduits, that reach the earth's surface.

Magma can contain as much as 5 percent water by weight. Although not high in absolute terms, such a percentage means that those huge subterranean magma chambers contain enormous quantities of water.* When the molten rock erupts at the surface, the hot, vaporized water rises into the atmosphere as steam. The water eventually returns to the earth as precipitation—rain or snow—which finds its way into cracks in the rocks of the crust or becomes incorporated into certain types of rock-forming minerals. Over millions of years, as tectonic plates collide with other plates and are subducted, those molecules begin another slow rise to the earth's surface. Thus there is a geological water cycle akin to the hydrologic cycle by which moisture falls to earth from atmospheric rain clouds, evaporates, and returns to the atmosphere—except that the geological cycle proceeds at an infinitely slower pace.

The great heights attained by some volcanoes give evidence of the enormous pressures generated by rising magma. In the world's highest volcanoes, Llullaillaco and Cerro Ojos del Salado in the Andes of South America, magma has been pushed to altitudes, respectively, of 6,723 and 6,908 meters above sea level. Moreover, particles of magma in observed eruption columns sometimes reach heights of 30,000 meters or more. Most magma, however, never reaches the earth's surface. As much as 90 percent of the molten rock that enters the lithosphere remains at depth, where eventually it cools and solidifies. Even in cataclysmic eruptions, far more magma remains within the earth than erupts at the surface. Some 74,000 years ago, in what is now Indonesia, a volcano named Toba exploded with a colossal blast that hurled an estimated 3,000 cubic kilometers of pyroclastic material into the atmosphere. But that figure represents less than 10 percent of the volume of material—some 30,000 cubic kilometers—that is estimated to have been left behind in the magma chamber.

*Although for simplicity we use the term *water* here, in reality the "water" consists of dissociated atoms of hydrogen and oxygen, which combine to form water vapor (H_2O) only during an eruption.