# 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

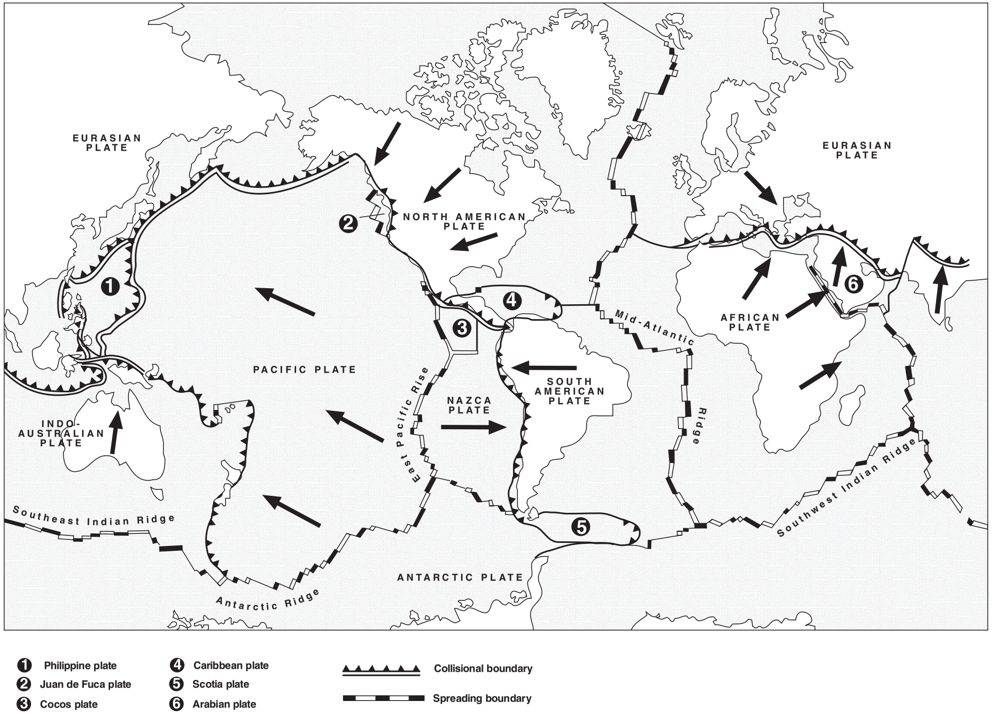


FIGURE 1-2. Configuration of the earth's tectonic plates, showing the collisional boundaries between converging plates and the spreading boundaries between diverging plates. The arrows indicate the present directions of plate motion. The black triangles at the collisional boundaries show the direction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

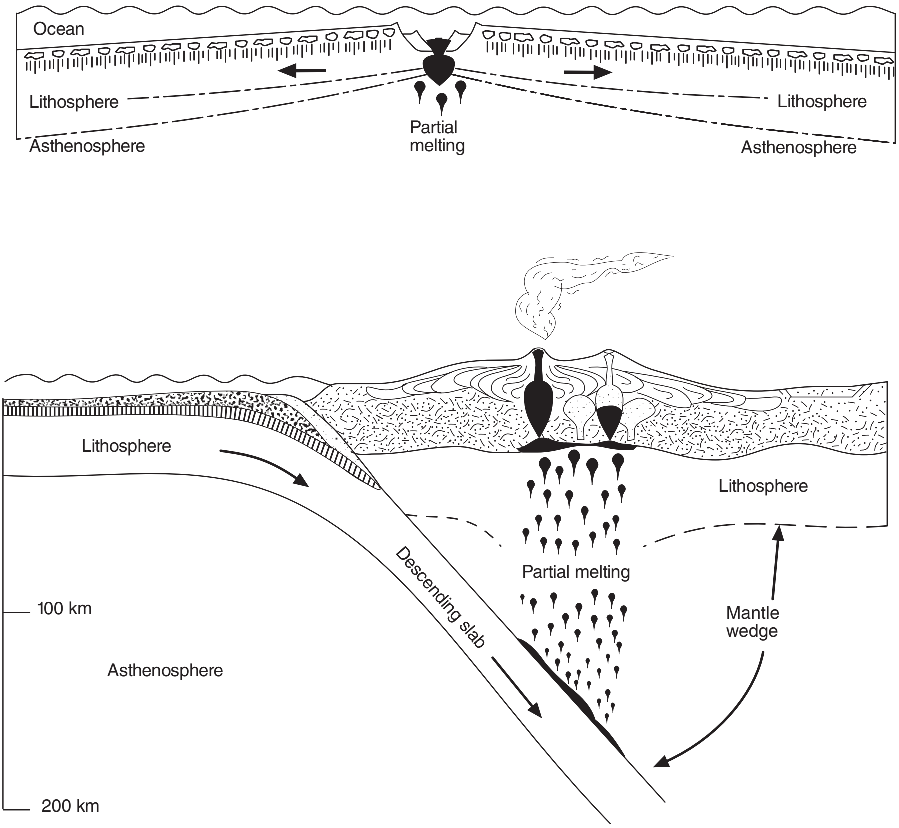


FIGURE 1-3. *Top:* Partial melting of the upper asthenosphere and formation of magma below an oceanic ridge at the boundary between separating plates. *Bottom:* Subduction of an oceanic plate beneath a continental plate and partial melting of the upper asthenosphere.

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.

## *Volcanic arcs*

The angles at which tectonic plates are subducted generally range from 15 to 70 degrees, depending on the buoyancy of the subducting plates. Where subduction angles are shallow, the earth's curvature gives the plate boundary a shape like an arc of a circle, just as the rim of a dent in a rubber ball has a circular shape. Thus when magma generated along such a boundary rises through the overlying plate, it forms a curved row of volcanoes known as a volcanic arc. Volcanic arcs in the ocean form island arcs—for example, Japan and the Aleutian Islands of Alaska.

About 60 percent of the world's volcanoes on land—that is, those that have erupted on continents or, if in the sea, have risen above the surface—are in island arcs in the so-called Ring of Fire, a series of volcanic belts that virtually surround the Pacific Ocean above the plate boundaries shown in Figure 1-2. Another 20 percent of the active land volcanoes are in or near the Mediterranean Sea, where several small plates, or platelets, are colliding with one another. Because most of the earth's land is north of the equator, about two-thirds of the known volcanoes on land are in the Northern Hemisphere. There are more than 1,500 of these volcanoes, as catalogued in 1994 by Tom Simkin and Lee Siebert of the Smithsonian Institution in Washington.[5] More than 3,000 eruptions have been recorded during the past three centuries. Despite the large number of land volcanoes, they produce probably only 15 to 20 percent of the magma that reaches the earth's surface.

## *Oceanic ridges*

For tectonic plates to collide in some places, they must diverge, or spread apart, in other places. Most spreading boundaries are within the earth's ocean basins, where they are marked by underwater ridges or mountain ranges many hundreds of kilometers wide. The Mid-Atlantic Ridge, for example, winds along the floor of the Atlantic Ocean, marking the boundary between the North American and Eurasian plates and between the South American and African plates. The axes of many oceanic ridges, notably the Mid-Atlantic Ridge, are elongated depressions called rift valleys, bounded on either side by faults. Most rift valleys are riddled with fissures, which provide pathways for enormous volumes of magma—probably 75 to 80 percent of the magma that rises to the earth's surface. The weight of overlying water prevents gases dissolved in the magma from escaping rapidly, so deep-sea eruptions are not explosive. The magma solidifies as part of the oceanic lithosphere, forming new crust.

### *Mantle plumes*

Volcanism can also be manifested as plumes of hot mantle material produced by upwellings of heat originating deep in the earth. The magma that rises in plumes can surface through either fissures or volcanic conduits. The plumes can remain active for many millions of years, and they may be hundreds of kilometers in diameter. They create what geologists call *hot spots* on the earth's surface. Iceland lies over a hot spot within the rift zone between the Eurasian and North American plates. The islands of the Hawaiian archipelago, almost in the middle of the Pacific plate, were created as the plate slowly drifted northwestward above a stationary hot spot. Although mantle plumes have produced vast quantities of magma in the past, they are less productive today than other forms of volcanism.

### *Uncorking the champagne*

The eruption of a volcano is often likened to the opening of a bottle of champagne. The dissolved gas (carbon dioxide) in champagne remains in solution as long as the bottle is tightly corked to keep the liquid under high pressure. But the moment the cork is removed and the pressure reduced, the gas separates from the liquid and expands suddenly (creating the "pop"), and champagne flows from the bottle (or erupts, if the bottle is opened carelessly) as a bubbly foam.

In a volcano, of course, the liquid is magma, which contains a variety of gases (mostly water vapor), all under great pressure. Whether a volcano erupts explosively or quietly is a function of the magma's viscosity. Just as highly viscous magma resists flowing, it also resists the separation of dissolved gases—until the magma reaches the earth's surface and the confining pressure is released. Then, as with a bottle of champagne, the gases expand suddenly and the volcano erupts convulsively, shredding the molten magma into myriad droplets that, upon cooling, become pyroclastic fragments.

If the magma has low viscosity and therefore flows readily, the gases are under much less pressure and separate easily from the molten rock. The result can be a relatively quiet eruption: the magma merely oozes from the earth. The viscosity of magma is directly related to its content of silica, or silicon dioxide, a common component of many minerals. The more silica, the higher the viscosity and the more sluggish the magma.

## *The volcanic explosivity index*

To compare the magnitude of volcanic eruptions, geologists have developed a *volcanic explosivity index,* or VEI, similar in principle to the Richter scale for earthquake magnitudes. The index is based mainly on the volume of explosion products (Figure 1-4) and the height of the eruption cloud. Each succeeding category represents a tenfold increase in explosivity, or explosive power, over the next lower category.

Eruptions with VEIs of 0 or 1, like most of those in Hawaii, typically ooze lava with little or no violent activity. Explosive eruptions generally have VEIs of 2 to 5. But especially powerful eruptions like those of Bronze Age Thera in the eastern Mediterranean, Italy's Mount Vesuvius in 79 C.E., and

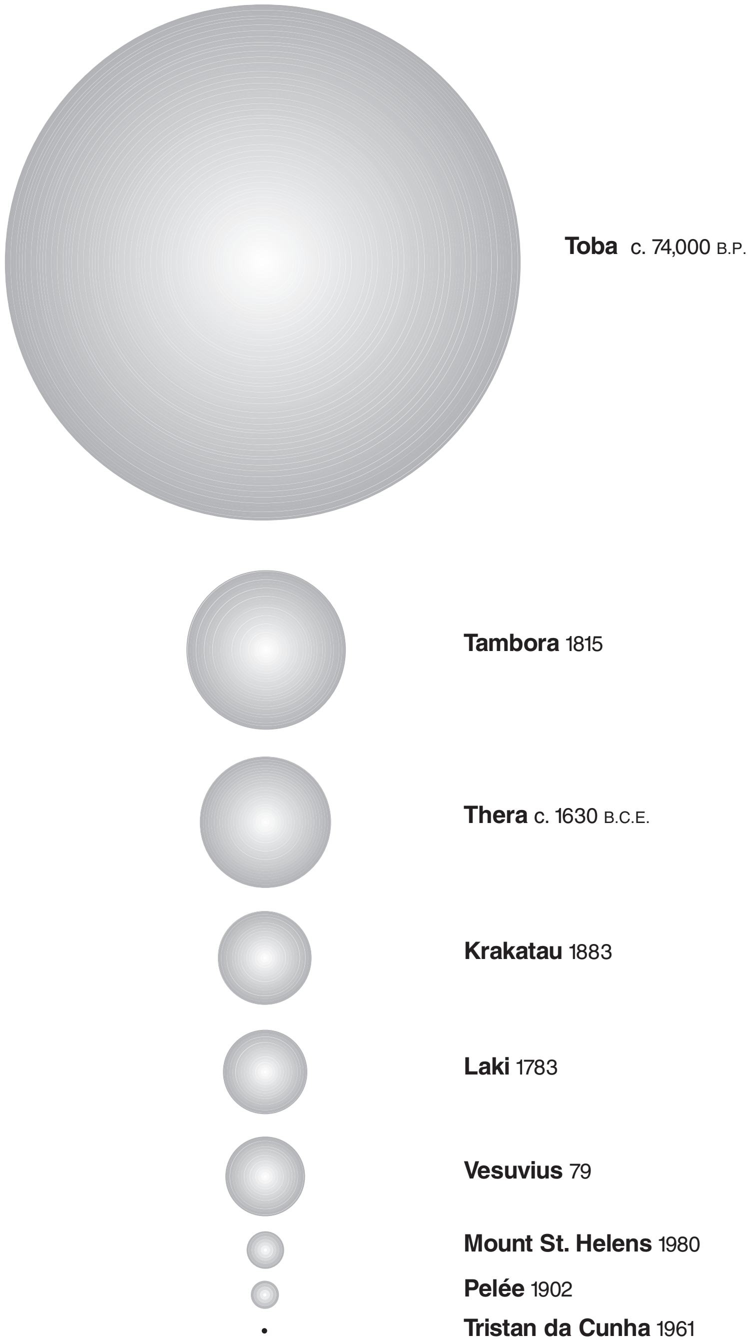


FIGURE 1-4. Schematic comparison of the volumes of volcanic materials emitted during the eruptions discussed in this book.

TABLE 1-1. The major eruptions discussed in this book, in order of increasing VEI

| VOLCANO | LOCATION | YEAR | INTENSITY | VEI |
|---|---|---|---|---|
| Tristan da Cunha | Tristan da Cunha | 1961 | Moderate | 2 |
| Surtsey | Iceland | 1963 | Moderate | 3 |
| Eldfell | Iceland | 1973 | Moderate | 3 |
| Kilauea | Hawaii | c. 1790 | Large | 4 |
| Laki/Grimsvötn | Iceland | 1783 | Large | 4 |
| Pelée | Martinique | 1902 | Large | 4 |
| Mount St. Helens | United States | 1980 | Very large | 5 |
| Vesuvius | Italy | 79 | Huge | 6 |
| Thera | Greece | c. 1620 B.C.E. | Huge | 6 |
| Krakatau | Indonesia | 1883 | Huge | 6 |
| Tambora | Indonesia | 1815 | Colossal | 7 |
| Toba | Indonesia | c. 74,000 B.P. | Humongous | 8 |

NOTE: B.C.E. means "before the commmon era"; B.P. means "before the present." The terms used to describe intensity are those employed by volcanologists. VEI stands for volcanic explosivity index.

Indonesia's Krakatau in 1883 probably had VEIs of 6. Tambora, also in Indonesia, erupted in 1815 with an estimated VEI of 7. And 74,000 years ago the colossal eruption of Toba, mentioned earlier, is thought to have had a VEI of 8 or higher (see Table 1-1).

Low-VEI eruptions are much more frequent than highly explosive eruptions. Volcanic events with VEIs between 0 and 3 may occur every few years somewhere on earth. In contrast, eruptions with VEIs greater than 6 occur at intervals of up to thousands of years.

The volume of material ejected by a single volcanic eruption can be prodigious. Many pictures have been published showing the huge cloud produced by the 1980 eruption of Mount St. Helens in the state of Washington. Impressive as it was, that eruption was but a burp compared with truly great eruptions of the past. In 1883 Krakatau emitted about eight times as much material as Mount St. Helens. The 1815 explosion of

Tambora produced at least thirty times as much material. And Toba is thought to have produced a thousand times as much material as Mount St. Helens, as illustrated in Figure 1-4.

### *Destructive power*

Causes of damage from volcanic eruptions are not restricted to gas emissions, lava flows, pyroclastic flows, and ashfalls. Volcanoes are notoriously unstable mountains. Many rise thousands of meters above surrounding lowlands, with flanks so steep that minor earthquakes can cause massive landslides. Most large volcanoes are high enough that warm, moist air rising up their flanks forms clouds near the summit. Hence such volcanoes are subject to frequent rainstorms or, if high enough, snowstorms. Water-saturated mountain soils, as well as packed snow and glacial ice, are very likely to break loose and become landslides or avalanches. Both are commonly triggered by earthquakes associated with eruptions. Landslides coursing down the valleys of mountain streams often become transformed into mudflows, which can travel great distances at high speed, destroying everything in their path.

Moreover, many volcanic craters accumulate large volumes of water from rainfall or melted ice or snow. During the early stages of an eruption, as hot magma rises toward the surface, that water may become boiling hot. Eventually it may be forced from the crater by upwelling magma, causing hot, boiling mudflows that are terrifying, and fatal, for anyone caught in their path.

Major eruptions can change weather patterns, not only locally but also regionally and even globally. Eruptions with high VEIs pour enormous quantities of dust and sulfur dioxide gas into the atmosphere. The dark dust particles absorb sunlight. The sulfurous gas molecules react with atmospheric water vapor to form tiny droplets, or aerosols, of sulfuric acid. The light-colored aerosols reflect sunlight. Thus such eruptions reduce the amount of heat reaching the earth, and surface temperatures are lowered. Veils of volcanic dust and aerosols can remain in the atmosphere for years. Carried around the world by high-altitude winds, they can have serious long-lasting effects on global weather patterns. Because most land masses, hence most volcanoes on land, are north of the equator, the Northern Hemisphere is especially vulnerable to weather changes related to volcanism.

The destructive power of volcanoes is not limited to periods of eruption. Even extinct volcanoes are potentially dangerous. As they age, the mountains become more and more unstable. Eventually an entire flank, weakened by fractures, might collapse, causing a landslide of prodigious proportions. Or if the flank of a volcano should collapse into the sea, as has happened in the Hawaiian Islands, it would create a giant wave, or *tsunami*. Tsunamis can wreak havoc when they crash ashore on other islands or even on the shores of continents far across the ocean.

In this book we describe nine volcanic eruptions, which varied in the amount of destruction they caused and had effects on humankind, for good or ill, that ranged from local to global in scale. In each chapter, we briefly discuss the geological setting of the event and its immediate consequences. Then, as in our metaphor of the "vibrating string," we emphasize the most significant long-term aspects of each eruption—those aftereffects that have changed lives, societies, and cultures.

## DATING OF VOLCANIC EVENTS

The accurate dating of volcanic events is crucially important in relating them to human endeavors. Most volcanic events that have occurred during historical time are reasonably well dated. The ages of earlier eruptions are less certain, and those events are dated by scientific methods that are still evolving. For example, eruptions that alter weather patterns can affect the growth of trees. Thus the width of annual growth rings can be an indication of aberrant weather, possibly caused by volcanic activity. The sulfuric-acid aerosols that form in the atmosphere after major eruptions eventually settle back to earth, and in glaciated regions they leave traces of acid in annual layers of ice. Thus cores taken from ice caps in Greenland and Antarctica have provided evidence of volcanism.

Although annual tree rings and acidic layers in ice cores can indicate time in terms of years, they cannot always be related to a specific volcanic eruption. But when molten lava cools and solidifies, its component minerals, some of which contain iron, often retain a magnetic orientation parallel to that of the earth's magnetic field at the time when the lava was molten. This phenomenon, called *paleomagnetism,* can be used to correlate the magnetic orientation of the solidified lava with different known directions of the earth's magnetic field in the past. Thus paleomagnetic studies can reveal the approximate time of a specific volcanic eruption.

Another widely used dating method is to measure the amount of radioactivity given off by isotopes of certain chemical elements. The most common of these radiometric methods is to analyze the carbon in an organic substance and determine the amount of carbon-14 relative to the amount of carbon-12, the most common isotope, in a given sample. Cosmic rays entering the earth's atmosphere react with atmospheric gases, and one of those reactions changes nitrogen to carbon-14 and hydrogen. Carbon-14 is radioactive, having a half-life of about 5,730 years. Both carbon-14 and carbon-12 react with oxygen in the atmosphere to form carbon dioxide, which eventually is taken up by living plants. When a tree, for example, dies or is cut down for firewood or lumber—or is killed in a volcanic eruption—it no longer takes in carbon dioxide, and the amount of carbon-14 it contains begins to decrease by radioactive decay. Therefore the ratio of carbon-14 to carbon-12 in a piece of the tree, in ashes from a fire, or in the timbers of a house provides an indication of how long ago the tree died. The lower the ratio, the older the eruption that killed the tree.

The carbon-14 dating method assumes that the rate at which that isotope forms in the atmosphere has remained constant for thousands of years. Although we know the rate has not in fact remained constant, this method is considered quite reliable as long as corrections are applied. Other, even more reliable methods make use of the relative proportions of different isotopes of argon, or of argon and potassium, in the minerals in volcanic rocks. So-called argon-argon and potassium-argon dating methods offer great precision and are especially useful for obtaining much older dates than can be obtained with carbon-14. Newer, less common dating methods are also available for dating volcanic rocks.

Layers of volcanic ash in sedimentary deposits can be dated geologically if we know the age of a deposit, as by identifying fossils of known age or knowing the rate at which overlying sediments were deposited. Moreover, we can use this method to determine the origin of the ash by comparing its chemistry with that of ash from a known volcano.