1 ⟡ BREATH-PIPES AND IGNIVOMOUS MOUNTAINS

Early Concepts of Volcanism

The science of igneous petrology requires three things: igneous rocks, human beings, and an appropriate methodology for the acquisition of knowledge and understanding about the igneous rocks. Magmatic activity and igneous rocks have characterized the crust throughout the 4.5 billion years of Earth history. Despite the existence of a planet that throbs with volcanic activity and that is decorated with innumerable masses of granite and gabbro, rhyolite and basalt, anorthosite and carbonatite, a science of igneous petrology cannot exist in the absence of humans. Anatomically modern humans probably appeared on Earth more than 100,000 years ago. Some of them observed volcanic eruptions, and many of them used igneous rocks such as obsidian. That was certainly the case a few millennia ago when civilizations sprang up in the ancient Near East. Yet the science of igneous petrology finally emerged only when people began to devise systematic ways of observing and thinking about igneous rocks. This book tells the story of how the science that we now call igneous petrology came into being and how it subsequently evolved.

VOLCANOES IN THE WORLD OF THE ANCIENTS

Human beings have long been curious about the behavior and significance of volcanoes, the great "fire-breathing" mountains that instill both terror and awe when they violently spew noxious fumes and flaming rocks. Because some early civilizations were located in regions of vigorous tectonic activity, our distant predecessors had ample opportunity to observe and reflect on volcanic phenomena. Although the ancient peoples dwelling on the vast alluvial plains of the Nile, Tigris, Euphrates, and Indus Rivers had little acquaintance with volcanoes, the citizens of classical Greece and Rome as well as the inhabitants of ancient Israel, living near junctions of tectonic plates, were certainly familiar with volcanism. The interpretations of volcanic phenomena entertained by these civilizations were variously mythological, theological, or naively scientific.

The Old Testament contains a sufficient number of references to "burning sulfur" or "brimstone" (Genesis 19:24; Deuteronomy 29:23; Job 18:15; Psalms 11:6; Isaiah 30:33, 34:9; and Ezekiel 38:22) and to "smoking mountains" (Exodus 19:18, 20:18; Psalms 104:32, 144:5) to suggest that the ancient Israelites were acquainted with volcanic phenomena. Israel's interest in the phenomena of nature, however, was largely theological. The Old Testament writers did not indulge in scientific theorizing about volcanoes, and no other ancient literature indicates the extent to which Hebrew scholars may have speculated about such matters. The book of Genesis envisioned the destruction of the ancient cities of Sodom and Gomorrah by fire and burning sulfur as an event of divine retribution for their unparalleled wickedness. Although the description in the book of Exodus of the giving of the ten commandments at Mount Sinai by Yahweh suggests the possibility of accompanying volcanic activity, the writer of Exodus regarded Yahweh as the one who caused the mountains to smoke and the earth to tremble. Neither Genesis nor Exodus inquired into the nature of smoking mountains or the eruption of burning sulfur in terms of mechanistic explanations or natural causes. More recently, Neev and Emery (1995) suggested that Sodom and Gomorrah were destroyed by an earthquake and that the flaming materials might have been ignited hydrocarbons that had been released from reservoirs by the seismic activity.

In contrast to the monotheistic Hebrews, both the classical Greek and Roman civilizations were steeped in pagan polytheism and its attendant mythology. Volcanic phenomena were, therefore, commonly interpreted in mythological terms. For example, the Roman writer, Publius Vergilius Maro, better known as Virgil (70–19 B.C.), penned a graphic description of the eruption of Mount Etna, the great volcano of Sicily, in his epic *Aeneid*. Although describing terrifying crashes, black clouds smoking with pitch-black eddies, glowing ashes, balls of flame licking the stars, and the violent vomiting of molten rock boiling up from the lowest depths, Virgil (Fairclough, 1994) linked these occurrences to the story about the giant Enceladus (Typhon to the Greeks) being scathed by a thunderbolt of Jupiter and weighed down by the mass of Mount Etna. Every time that the giant shifted from one side to the other, Virgil said, the region moaned, trembled, and veiled the sky in smoke. Virgil also located the entrance to the underworld in the vicinity of Lago Averno (Lake Avernus) in the volcanic terrain known as Campi Phlegraei (the Phlegraean Fields) west of Naples, Italy. The lake occupies a volcanic crater.

The Greeks designated Hephaestus, and later Roman myths designated Vulcan, as the god of fire. Roman poets linked Vulcan's workshop with active volcanoes, allegedly the chimneys of Vulcan's forge. The island of Vulcano, one of the Lipari Islands north of Sicily, received its name because it was considered to be the location of Vulcan's forge. From the Roman god Vulcan and the island Vulcano the name of "volcano" has since been applied to smoking, cinder-erupting, lava-emitting mountains around the world.

Mythological conceptions of volcanoes were not confined to the classical civilizations. More recent volcano myths existed in Tonga, Samoa, Indonesia, Iceland, and among the Aztecs of Mexico. Myths about volcanoes persist in Japan and Hawaii. Many native Hawaiians still envision eruptions of Kilauea as expressions of the wrath of the goddess Pele, who is said to reside in the caldera of Kilauea. They believe that Pele is able to make islands and mountains, melt rocks, and destroy forests.

Despite the mythological overtones in much classical writing about the natural world, some authors did provide explanations for natural phenomena, including volcanoes, in terms of natural, material causes. Several Greek writers made important observations about geological phenomena such as erosion, sedimentation, fossilization, the interchange of land and sea, and earthquakes (Desmond, 1975). In addition, many of the Greek and Roman references to Mount Vesuvius and the Phlegraean Fields in Italy, Mount Etna in Sicily, the Lipari Islands, and Santorini near Crete contain descriptions of landforms and eruptions. In some cases, the writers attempted to explain volcanic behavior in terms of physical causes.

Prior to the eruption of Mount Vesuvius in A.D. 79, Mount Etna, known for its frequent emissions, drew the widest attention. The philosopher Empedocles of Agrigentum (492–432 B.C.) presumably died by falling into the crater of Mount Etna. Diodorus of Sicily (1st century B.C.) referred to fiery eruptions from Mount Etna that laid waste to regions along the sea (Oldfather, 1933). He wrote that such great torrents of lava were poured forth from Mount Etna that the people known as the Sicani had to move to the western part of Sicily. The geographer Strabo (63 B.C.–A.D. 21) discussed volcanoes in considerable detail. In his *Geography*, he noted that an earlier writer, Poseidonius, had commented that the fields of the Catanaeans were covered to great depth by volcanic ash during eruptions of Mount Etna. Strabo observed that volcanic ash ultimately proved to be beneficial because it rendered the land so fertile (Jones, 1931). When lava solidified, he found that the surface became stony to such a depth that quarrying was necessary to uncover the original land surface. He reported that the melted liquid that pours over the rim of Mount Etna's craters is a "black mud" that flows down the mountain and solidifies to millstone. Strabo provided an extensive description of Mount Etna, which evidently supported a significant summit-climbing trade. He observed that the top of the mountain experienced many changes. The fire concentrated first in one crater, then in another. The mountain sent forth lava on one occasion, flames and fiery smoke on another, and red-hot masses on still another. Strabo conjectured that Sicily was not a piece of land that had broken away from Italy but a landmass that might have been elevated out of the sea because of the volcanic eruptions of Mount Etna. He proposed a similar origin for the Lipari Islands and described other instances of land emerging from the sea by volcanic action.

Many references to Mount Vesuvius and the nearby Phlegraean Fields appear in classical literature written prior to the cataclysm of A.D. 79. Diodorus of Sicily referred to the arrival of Hercules at the Phlegraean plain, so named from the mountain that in old times had erupted in a huge fire as Mount Etna did in Sicily (Oldfather, 1933). Diodorus noted that the mountain was called Vesuvius in his day and that it showed many signs of the fire that raged in ancient times. The Roman architect Vitruvius (d. 25 B.C.) described volcanic products in the vicinity of Mount Vesuvius such as pozzolana and pumice. Vitruvius noted that "in ancient times the tides of heat, swelling and overflowing from under Mount Vesuvius, vomited forth fire from the mountain upon the neighbouring country" (Morgan, 1960, p. 47). As a result, he surmised that "sponge-stone" (Pompeian pumice) had been formed by burning of some other kind of rock. Strabo wrote that the summit of Mount Vesuvius was mostly flat and unfruitful, appeared ash-colored, and had pore-like cavities in soot-colored masses of rock that looked as though they had been eaten out by fire (Jones, 1931). He inferred that the district had once been on fire and that the fire was quenched after the fuel gave out.

Understandably, the cataclysmic eruption of Mount Vesuvius that buried the cities of Pompeii and Herculaneum in A.D. 79 attracted considerable attention. The eruption was described in graphic and dramatic detail by Gaius Plinius Caecilius Secundus, better known as Pliny the Younger (A.D. 61–114), who was only seventeen years old at the time. In a letter to Cornelius Tacitus, Pliny wrote about the death of his uncle, Gaius Plinius Secundus (Pliny the Elder) (A.D. 23–79), the author of the monumental *Natural History*. The younger Pliny wrote prophetically that his uncle died in a catastrophe that was so spectacular that his name would likely live forever (Radice, 1969). He reported that his uncle, the commander of the fleet at Misenum, ordered his ships across the Bay of Naples for a closer look at the developing eruption. Eventually, according to the nephew, the flames and smell of sulfur became so strong that most people took flight and roused Pliny the Elder to stand up. As he was leaning on two slaves, his nephew wrote, he suddenly collapsed, most likely because the dense fumes had choked his breathing. When daylight had returned two days later, the body of Pliny the Elder was found intact, uninjured, fully clothed, and looking asleep rather than dead. In a later letter to Tacitus, Pliny the Younger told of his own escape from the dense black cloud of falling ash. When the darkness finally dispersed, he wrote, the sun was shining much as it does during an eclipse. Pliny admitted to being terrified to see that everything had been buried deep in ashes like snowdrifts. Sigurdsson (1999) has written a detailed account of the famous eruption.

A remarkable aspect of Greco-Roman writing about volcanoes is that at least three rudimentary theories of volcanism were proposed: the exhalation theory originated by Aristotle, the fuel theory of Strabo, Vitruvius, and Seneca, and the organismal-breathing theory of Ovid. The most elaborate of these theories, expounded in *Meteorologica*, was developed by Aristotle (B.C. 384–322) in the context of his general theory of exhalations. He interpreted volcanic eruptions as the end result of the movements of subterranean exhalations (winds) that gave rise to earthquakes. Aristotle cited an eruption in the Lipari Islands as an example. He said that the wind that caused earthquakes on the islands broke out like a hurricane. The earth swelled and rose into a lump with a noise. The swelling finally exploded so that a large amount of wind, cinders, and ash broke forth, smothering the city of Lipara and extending as far as Italy. In this case, Aristotle said, the breaking up of the air into tiny particles caused them to catch fire within the earth (Lee, 1952). T. Lucretius Caro (Lucretius) (c. 99-c. 55 B.C.), a Roman poet, adopted an essentially Aristotelian explanation in his account of the nature of volcanoes in *De Rerum Natura*. Mount Etna, Lucretius suggested, is hollow underneath, and all its caves are filled with wind (Bailey, 1947). When agitated, the wind becomes hot, eventually heating all the rocks and earth that it touches. In time, the agitated wind heats the rocks so much that they emit swift flames. The wind, Lucretius wrote, drives itself through the mountain's jaws carrying heat, scattering ash and smoke with thick murky darkness, and hurling heavy rocks.

Strabo, too, linked volcanic flames with winds. He claimed that the flames at Mount Etna and on the volcanic island of Thermessa (Hiera) were stimulated along with winds. When the winds died away, so, too, did the flames. Strabo, however, also maintained that volcanic eruptions feed on some kind of fuel. He referred to the exhaustion of fuel at Mount Vesuvius and suggested that volcanic fires might be kindled by fuel just as the wind is fueled by evaporation from the sea. Vitruvius was much more explicit about this alternative view. In discussing "pozzolana" he noted that the soil in the vicinity of Mount Vesuvius is hot and full of hot springs. Such a condition would not exist, he claimed, "unless the mountains had beneath them huge fires of burning sulphur or alum or asphalt" (Morgan, 1960, p. 47). Aristotle's exhalation explanation was combined with the fuel theory of Vitruvius by Lucius Annaeus Seneca (c. 2 B.C.–A.D. 65). Seneca suggested in *Naturales Quaestiones* that when subterranean winds rush through underground cavities containing sulfur and other combustible materials, these flammable substances are ignited by friction (Corcoran, 1971).

A third view was suggested by Publius Ovidius Naso (Ovid) (43 B.C.–A.D. 17), the Roman author of the epic poem *Metamorphoses*. Suggesting that Earth is a great organism, he likened volcanic eruptions to the breathing of an animal. Ovid, however, combined the organic theory with Aristotle's exhalation theory and Vitruvius' fuel theory: He asserted that if the earth is like a living animal with many breathing-holes that can exhale flames, then it can close up those holes and open new ones when it shakes itself. Moreover, the friction of pentup winds in caverns driving against the rocks could cause fire. After the winds had spent their force, however, the caverns would cool and the flames would be extinguished. Ovid also said that pitchy substances and yellow sulfur might serve as sustenance for the fires, and when these nourishing substances were exhausted then the fires would die out (Miller, 1977). Sigurdsson (1999) has discussed classical Greek and Roman ideas about volcanoes more thoroughly.

VOLCANISM IN THE MIDDLE AGES

The writers of ancient Greece and Rome provided descriptions of volcanoes and volcanic eruptions, suggested several causes for volcanic activity, and referred to emission products such as lava (ruax), scoria, pozzolana, and ash. In the early centuries of the Christian era, conditions that fostered scholarly thought began to deteriorate. Economic decline and political turmoil plagued the Roman Empire until it fell to barbarian invaders. Contact between the Latin West and Greek East diminished. The early Christian movement, typically popular among the poorer classes and faced with much persecution, had no time for leisurely reflection about the natural world. As Christianity continued to spread, however, it became the dominant cultural force in the western world. While Christianity encouraged literacy and education, particularly through the monastic movement, theological questions absorbed most of the intellectual energy of scholars. Moreover, the church was ambivalent about the knowledge acquired by the pagan Greeks. As historian of science David Lindberg (1992, p. 151) observed in his discussion of the development of science from classical times to the Middle Ages, if the ancient church is compared to the National Science Foundation, it will "prove to have failed abysmally as a supporter of science and natural philosophy." He pointed out, however, that in relation to its contemporaries, "the church was one of the major patrons—perhaps *the* major patron—of scientific learning." Although scientific thought in general and thought about volcanoes in particular stagnated during the first several centuries of the Christian era, some medieval Christian scholars retained an interest in geological matters. These individuals speculated about fossils and the effects of the biblical flood and compiled encyclopedic lists of stony objects (Adams, 1938). So far as we know, however, medieval Christian writers said little that was new about volcanoes, although Albertus Magnus (c. 1200–1280) attempted an experiment to determine whether volcanic action resulted from subterranean steam pressure (Koch, 1966).

Although the Latin West experienced some decline in scholarly activity, knowledge of classical Greek scholarship persisted in the eastern Mediterranean. During the Islamic conquest, much Greek learning was absorbed into that expanding culture, and original scientific activity eventually flourished in the Islamic world. To the extent that Arab writers of the Middle Ages like Ibn

Sina (Avicenna) devoted attention to geological features, they were preoccupied with erosion and sedimentation. Nevertheless, the theory of petrifying juices was developed to explain the formation of some rocks. Much classical literature, preserved by Islamic scholars, was reintroduced into western Christendom during the thirteenth century. In the latter Middle Ages, Christian scholars uncritically accepted much of the science of the classical writers, including the descriptions and theories of volcanoes of Aristotle and Strabo. They added virtually nothing new regarding the nature of volcanoes. Scientific interest in volcanic activity may also have been dormant throughout the Middle Ages because of the linkage of the horrors of hell to volcanic fires in much medieval theology.

VOLCANISM IN THE SIXTEENTH AND SEVENTEENTH CENTURIES

After the Renaissance, even such astute sixteenth-century observers as Bernard Palissy (1510–1590), Conrad Gesner (1516–1565), and Johann Kentmann (1518–1568) added little to the body of knowledge about volcanoes. Georg Bauer (1494–1555), also known as Agricola, wrote at length about rocks and minerals and speculated about the role of fluids in their formation, yet he barely mentioned volcanic activity. In *De Re Metallica* (Bandy and Bandy, 1955), Agricola referred to millstones that were formed from molten rock erupted at burning places. Rivers of such molten rock were noted to flow away as at Mount Etna.

The ascendancy of the mechanical philosophy in the seventeenth century was accompanied, however, by intense interest in the nature, behavior, origin, and history of the entire terrestrial globe, as indicated by the studies of Galileo Galilei (1564–1642) and Isaac Newton (1642–1727) on the place of Earth in the heavens and by the speculations of René Descartes (1596–1650) about the formation of Earth from mechanically interacting particles from vortices in space. Later in the seventeenth century, global histories based on mechanical principles were formulated by Thomas Burnet (1635–1715), William Whiston (1667–1752), and many others (Rappaport, 1997). Several of these global theories were accompanied by illustrations of Earth's interior. Among the scholars participating in the movement to understand and illustrate the globe as a whole was Athanasius Kircher.

Athansius Kircher (1602–1680) was a prolific German Roman Catholic priest of encyclopedic interests who spent most of his career at the Jesuit College of Rome (Reilly, 1974). A polymathic scholar who wrote 44 books, Kircher addressed the subject of volcanoes in a volume, *Mundus Subterraneus*, devoted to understanding Earth as a globe (Kircher, 1664). Kircher had visited both Mount Vesuvius and Mount Etna in 1638 while working on this massive study of underground phenomena. An extract of material on volcanoes from this book appeared five years later as *The Vulcano's or Burning and Fire-vomiting Mountains, Famous in the World: with their Remarkables* (Kircher, 1669). Kircher described Mount Vesuvius and Mount Etna, reviewed known volcanoes, and provided a general theory of volcanic action in terms of subterranean fire. Kircher (1669, p. 3) believed that there are two "Associates, and Agents of Nature," namely, fire and water, agents that "sweetly conspire together in mutual service, with an inviolable friendship and wedlock, for the good of the whole in their several and distinct private-lodgings." The various interactions of the two agents moving through an elaborate system of interconnected subterranean channels and vents were thought to lead to a host of terrestrial phenomena, such as "Minerals, Juyces, Marles, Glebes, and other soyls, with ebullitions, and bublings up of Fountains."

Apart from that point, Kircher's views on volcanoes largely represented an amalgam of the conceptions of Aristotle, Strabo, Vitruvius, and other classical writers. Referring to volcanoes as "ignivomous" or "fire-vomiting" mountains, Kircher (1669, p. 5) claimed that they are "the vent-holes, or breath-pipes of Nature, to give vent to the superfluous choaking fumes and smoaky vapours, which fly upwards." Upon emission of the fumes, the entrance into Earth is made possible for "friendly cherishing Air to revive and ventilate those suffocating flames" which would otherwise "continually shake the foundations of the Ground with intolerable commotions and Earthquakes." As an Aristotelian, Kircher considered volcanoes from the perspective of various causes. The formal cause of the eruptions, he said, is the fire. The material cause is sulfur, salt, niter, and bitumen in the dark recesses of Earth. The instrumental cause, Kircher (1669, pp. 58–59) claimed, is "the Cavernous nature of the place . . . oppressed with Sulphureous Smoak and Soot," and, lastly, the efficient cause consists of "Winds and Blasts," issuing bellows-like from the cavernous interior, stirring the dormant fires, and kindling the matter.

For the most part, studies of volcanoes in the seventeenth and eighteenth centuries, primarily by Italian writers, focused on the volcanoes themselves apart from any consideration of the global context. Mount Vesuvius had experienced some minor events during the Middle Ages, but a violent eruption in 1631 elicited descriptive books from Antonio Santorelli (1632) and Giulio Cesare Recupito (1635). Subsequent eruptions in the late seventeenth and eighteenth centuries resulted in additional studies by Paragallo (1705), Sorrentino (1734), Serao (1738), and della Torre (1755). Giovanni Maria della Torre described white polygonal garnet-like crystals in the lava (leucite) and observed that thick lava from an eruption in 1754 split into pieces when it was raised with a pole. The numerous eruptions of Mount Etna throughout the seventeenth century attracted the interest of Giovanni Alfonso Borelli (1670) and the Englishman Heneage Finch Winchilsea (1669). The eruption on Santorini between 1707 and 1711 made a strong impression on Abbé Anton-Lazzaro

Moro (1687–1764) of Venice. So did an account of the 1538 eruption of the cinder cone, Monte Nuovo, in the Phlegraean Fields. As a result, Moro (1740) attributed virtually all stratified rocks to the elevating effects of volcanic agency.

Despite a growing awareness of the worldwide distribution of volcanoes, the most detailed descriptions of the latter eighteenth century were confined predominantly to Mount Vesuvius and to Iceland. Much information about volcanoes was obtained by academics and government officials and recorded in scientific letters, scientific travelogs, and communications to *Philosophical Transactions of the Royal Society of London* (Rappaport, 1997). Several such reports were sent to *Philosophical Transactions* by Sir William Hamilton (1730–1803), the envoy of Great Britain to the court of Naples (Sleep, 1969; Carozzi, 1972). Hamilton (1772) eventually compiled these letters and reports into a book about Mount Vesuvius, Mount Etna, and other volcanoes.

Hamilton arrived in Naples on November 17, 1764. On June 10, 1766, he wrote to the President of the Royal Society of London that Mount Vesuvius had recently made a large eruption. He reported that nothing terribly interesting other than a lot of smoking had happened on the mountain for several months until late in March 1766, when Mount Vesuvius erupted ash and lava began to boil out of its crater. Hamilton passed a night on the mountain while the eruption proceeded. He approached the mouth of the volcano as closely as he dared and observed that the lava looked like a river of red hot liquid metal. As the eruption proceeded, he said, some English observers who accompanied him got too close and were injured by flying rocks. Hamilton described the development of crust on the cooling lava and the existence of lava tubes.

In a letter of February 3, 1767, he wrote that he had collected various salts, sulfur, lava, and cinders for later analysis. He was amazed to discover that none of the local chemists had ever bothered to analyze any of the eruption products of Mount Vesuvius. On December 29, 1767, Hamilton wrote to the Royal Society that a violent eruption had commenced on October 19, 1767, lasted seven days, and emitted about three times as much lava as had the ten-month-long 1766 eruption. He shipped an extensive collection of eruption products from Mount Vesuvius to the British Museum. Having painstakingly assembled the samples during the past three years, he expressed the hope that some of his learned countrymen might put the collection to use in making some important discoveries about volcanoes.

A couple of years later, Hamilton wrote on October 17, 1769, that after having spent almost five years examining volcanic phenomena all around Naples, including the nearby island of Ischia, he thought it would be a good idea to visit Mount Etna. He reported that on June 24, 1769, he set out with some companions from Catania, Sicily, to climb the mountain. He succeeded in climbing to the edge of the crater where he spent three hours. In a masterpiece of understatement he wrote that "the steep ascent, the keenness of the air, the vapours of the sulphur, and the violence of the wind, which obliged us several times to throw ourselves flat upon our faces to avoid being overturned by it, made this latter part of our expedition rather inconvenient and disagreeable" (Hamilton, 1772, p. 59). On this excursion, Hamilton also spent three days in the Lipari Islands, where he saw Vulcano and observed Stromboli in eruption. Upon his return to Naples, he had the opportunity to watch the excavations of Pompeii at a time when both human and horse skeletons were encountered. He ascertained that the skulls of the dead had been fractured by the falling rocks.

Hamilton speculated that "subterraneous fire" acted as the "great plough" used by nature to overturn the bowels of Earth, thereby exposing fresh fields on which to work. Because of his more than twenty ascents of Mount Vesuvius, his detailed observations of actual eruptions, his descriptions of volcanic products, his collection of specimens, and his letters published in *Philosophical Transactions of the Royal Society of London*, Hamilton became a recognized authority on volcanic eruptions.

Hamilton had plenty of company on top of Mount Vesuvius, including Ferber, Spallanzani, and Breislak. The Swede Johann Jacob Ferber (1743–1790), Professor of Natural History at Mietau, had been educated at Uppsala, Sweden, where Linnaeus, Cronstedt, and Wallerius had systematized the different kingdoms of nature. On his travels throughout Europe during 1771 and 1772, Ferber (1776) climbed to the summit of Mount Vesuvius twice. On one occasion he entered into its crater. Like Della Torre, he reported seeing the garnet-like crystals embedded in the lavas.

The Abbé Lazarro Spallanzani (1729–1799), Professor-Royal of Natural History in the University of Pavia and Superintendent of the Imperial Museum in that city, undertook a tour of Italy and Sicily in 1788 to improve the collections of the museum with the addition of some volcanic products (Dolman, 1975). During six months at Mount Vesuvius, Spallanzani (1798) tried to reach the summit but lava showers and sulfurous gases forced him to retreat so that he was denied the "pleasure" of getting near the edge of the crater. He was successful, however, in coming remarkably close to flowing lava and measuring its velocity. He reported that when he was only five feet from the lava, the "caloric" was sufficiently vehement to encourage him to back away. He measured the velocity of the lava currents by throwing cooled chunks into the flow and observing how long it took them to be carried a specified distance.

Spallanzani lacked sufficient time to measure the temperature of the lava, but he outlined a detailed scheme for how to make such measurements. He also issued a challenge and warning for potential students of volcanoes. "I do not deny," Spallanzani (1798, p. 19) said,

> but that these and other similar experiments are difficult, offensive, and, in some degree, even dangerous; but what experiment can be undertaken perfectly free from inconvenience, and all fear of danger, on mountains which vomit forth fire? I would

> certainly advise the philosopher who wishes always to make his observations entirely at his ease, and without risk, never to visit volcanoes.

Spallanzani knew from firsthand experience what he was talking about, for on one occasion he burned out his shoes. That he repeatedly exposed himself to considerable danger in the interests of a scientific investigation of Mount Vesuvius is confirmed by the fact that many of his gas collection experiments occurred in the Grotta del Cane. He reported that if a dog were brought into this cavern and its nose held to the ground, it would soon begin to breathe with difficulty and die if not speedily removed into the open purer air. Spallanzani measured the chemical composition of volcanic gases of Mount Vesuvius jointly with Scipione Breislak (1750–1826), a priest and teacher at the Military Academy of Naples (Francani, 1970). They determined that the gas consisted of 10 percent "vital air, or oxygenous gas," 40 percent "fixed air, or carbonic acid," and 50 percent "phlogisticated air, or azotic gas" (Spallanzani, 1798, p. 91). Breislak later witnessed the 1794 eruption of Mount Vesuvius and observed the volcanic phenomena of the Phlegraean Fields and Pozzuoli.

One of the most respected geological writers of the era, Déodat Guy Silvain Tancréde Gratet de Dolomieu (1750–1801), was a military officer in the Knights of Malta with a flair for natural history (K. L. Taylor, 1971c). Dolomieu studied the lavas of Mount Etna and many of the recent volcanic fields of Italy and speculated on the nature of lava and the causes of volcanism in a series of articles and travel books.

Iceland, too, had begun to draw the attention of scientific parties. Of particular importance was a 1772 expedition under the supervision of Sir Joseph Banks (1743–1820), a prominent botanist who had participated in the first voyage of Captain James Cook between 1769 and 1771 (Cameron, 1952; Foote, 1970). Banks was accompanied by the natural historian Daniel Carl Solander (1733–1782) and Uno von Troil (1746–1803), later to become Archbishop of Uppsala. Von Troil (1780) published an account of the Icelandic expedition. "There was not one," said von Troil (1780, p. 5) of his enthusiastic and determined party, the first ever to attain the summit of Mount Hekla, "who did not wish to have his cloaths a little singed, only for the sake of seeing Heckla in a blaze." Although they were not rewarded by seeing an eruption, they described eruption products, hot springs, and geysers. Von Troil summarized the historical eruptions of Mount Hekla and surmised that its activity had been more intense than that of either Mount Vesuvius or Mount Etna.

Every late eighteenth-century European natural philosopher knew of the existence of the Mediterranean and Icelandic volcanoes, but reports of volcanoes had come to western Europe from other parts of the world during the past three centuries. European naturalists knew of eruptions in the Azores and the Canary Islands. By the end of the eighteenth century, the exploration of the New World had disclosed the existence of many volcanoes in the West

Indies, Mexico, and along the length of the Andes Mountains in South America, and volcanoes had also been observed by European voyagers in Japan, the Philippines, and the East Indies (Scrope, 1825). Toward the end of the eighteenth century, the Hawaiian volcanoes came to the attention of the western world thanks to the voyages of James Cook. Even if a natural philosopher had never seen an active volcano, he had read accounts of them and undoubtedly had seen many specimens of volcanic products in museum collections. Naturalists of the latter eighteenth century knew very well what lava, scoria, pumice, obsidian, and volcanic ash looked like.

Since the Renaissance, naturalists had also arrived at a moderate consensus on the cause of volcanism. Following the lead of Strabo, Vitruvius, and Seneca rather than Aristotle, writers generally conceived that volcanoes owed their origin to the combustion of some sort of fuel, perhaps coal beds, most likely triggered by the decomposition of pyrite not far below Earth's surface. Although he had closely linked volcanoes to subterranean fire in intimately interconnected passageways, Kircher (1669, p. 59) also regarded the matter of the subterraneous fire as "Sulphur, Bitumen, Pit-Coals, and also Allom, Salt, Nitre, Coaly Earth, and Calcanthum or Vitriol, and such kind of Metals."

Kircher's contemporary, Martin Lister (1638–1712), was one of the premier English natural historians of the seventeenth century (Carr, 1973). Lister (1683) issued a series of three papers in *Philosophical Transactions* in which he espoused pyrite as the cause of thunder and lightning, earthquakes, and volcanic eruptions. He found other potential causes of volcanism wanting. It could not have been the sun, he said, for Mount Hekla, located in an extremely cold climate, was just as active as Mount Etna. Human activity could not have caused eruptions because some volcanoes seem to have fired before the world was populated everywhere. Moreover, eruptions occur at the very tops of vast high mountains, places that are unfit for human habitation. Only pyrite, he said, provided so general and lasting a fuel that could cause lightning, thunder, earthquakes, and volcanoes.

Lister's proposal received experimental support at the hands of the French chemist Nicholas Lémery (1645–1715). Lémery demonstrated experimentally that sufficiently massive, pasty mixtures of water with iron and powdered sulfur, the constituents of pyrite, eventually burst into flame (Hannaway, 1973). Lémery argued that the heat and fire were generated by the violent friction of pointed acid particles of sulfur acting upon particles of iron. This experiment, he concluded, sufficiently demonstrated how fermentations, shocks, and conflagrations occur in the bowels of Earth at places like Mount Vesuvius and Mount Etna (Lémery, 1700). For years thereafter, writers asserted the importance of pyrite decomposition in volcanic action, assuming that Lémery's experiment provided vindication of the hypothesis that pyrite served to fuel volcanic fires.

One such writer was Richard Kirwan (1733–1812), a prominent Irish mineralogist, Inspector General of Mines for Ireland, and long-time President of the Royal Irish Academy (Scott, 1973b). Kirwan (1799) maintained that the heat of lavas originated from the decomposition of water by pyrite. Flame would arise, Kirwan proposed, where heated pyrite had been in contact with heated coal, black wad, or petrol. He envisioned that bituminous, sulfurated masses of stone and earth were gradually softened and liquefied in the process. Moreover, he noted, volcanic ejections never contained any undecomposed pyrite.

More ambivalent, Ferber (1776) asserted that many possible causes of subterraneous inflammations had been demonstrated by experimental philosophy, but he was uncertain whether these causes were ultimately traceable to the interaction of water and pyrite or to the fermentation of calcareous materials produced by acids or waters. He did note, however, that pyrite was reported to be thrown out of volcanoes in small quantities and that sublimated sulfur is very common.

By the end of the eighteenth century, numerous volcanoes had been discovered around the globe; exploration and description of Mediterranean and Icelandic volcanoes had become quite commonplace; some lava and volcanic gas had been chemically analyzed; individual crystals within lava had been noted; the velocity of lava currents had been measured; and a commonly held theory that attributed volcanism to the interaction of decomposing pyrite with carbonaceous matter had emerged. The infant science of volcanology had been born.