Chapter 1

Eruptions, Jargon, and History

Volcanoes assail the senses. They are beautiful in repose and awesome in eruption;
they hiss and roar; they smell of brimstone.
Their heat warms, their fires consume; they are the homes of gods and goddesses.
(Robert Decker 1991)

Volcanic eruptions are the most exciting, awe-inspiring phenomena of all the Earth's dynamic processes, and have always aroused human curiosity and/or fear. Volcanoes, volcanic rocks, and volcanic eruptions come in many varieties, however, and to begin to understand them one must absorb a great amount of terminology and information. We'll get to that material soon enough, but first let's explore what volcanoes are *really* like! The facts and figures in subsequent chapters could prove boring if you lose sight of the fact that each volcano and every piece of volcanic rock that you will ever study was born of fire and fury, and that all volcanic rocks are ultimately derived from underground bodies of incandescent liquid called **magma** – molten rock. Every volcanic mountain or rock that you will ever see or touch once knew terrible smells and sounds that you must close your eyes to imagine.

French volcanologists loosely divide the world's volcanoes into two general types: ***Les volcans rouges*** (red volcanoes) and ***Les volcans gris*** (grey volcanoes). "Red volcanoes" are those volcanoes that are mostly found on mid-oceanic islands and are characterized by **effusive** activity (flowing red lava). The "grey volcanoes," generally found near continental margins or in island chains close to the edges of continents, are characterized by explosive eruptions that cover vast surrounding areas with grey ash. This is a pretty good rough classification for most volcanoes, although there are many that have had both effusive and explosive eruptions throughout their

Volcanoes: Global Perspectives, 1st edition. By John P. Lockwood and Richard W. Hazlett. Published by Blackwell Publishing Ltd.

histories (or during individual eruptions). The volcanic hazards and risks posed by each of these types of eruptions differ greatly, and will be described in detail in later chapters.

We hope that in this chapter you will gain some understanding of the look, smell, and *feel* of erupting volcanoes, and that this will put the material of the subsequent chapters in a more relevant light. To provide this we will describe our personal experiences during eruptions of two volcanoes – one "grey" and one "red." The first narrative will describe events during the large 1982 explosive eruption of Galunggung volcano [99] (Indonesia), and the second will describe some small 1974 effusive eruptions of Kīlauea volcano [15] (Hawai`i). Each eruption was different, and each exemplifies opposites of volcanic behavior. The first eruption had serious economic impact on millions of people, whereas the second ones were primarily of scientific interest to the observers and caused no economic loss.

In this and a few other places, the first person "I" will be used in reference to personal accounts of the authors and identified by our initials, JPL (Lockwood) or RWH (Hazlett).

A "Grey Volcano" in Eruption – Galunggung – 1982

Fine ash was falling in a dim light that afternoon in July 1982, limiting visibility to about a hundred meters outside the Volcanological Survey of Indonesia (VSI) Cikasasah Emergency Observation Post. Light grey ash covered everything in sight and could have been mistaken for snow, were it not for the broken coconut palms and the sweltering tropical heat. The narrow road in front of the VSI Observation Post was clogged with fleeing refugees who, with heads covered with newspapers or plastic bags and faces covered with cloth breathing filters, carried their bundles and baskets quickly down the road (Fig. 1.1). Children carried babies and led water buffalo. An occasional small flatbed truck, almost obscured by its overflowing human cargo, crawled along with the refugees.

The fresh-fallen ash muffled the sounds of footsteps, and the people were silent as they hurried down the road away from danger. The only constant sounds were Muslim prayers, wailed in Arabic over a loudspeaker at a refugee camp on a high, relatively safe ridge 1 km away. Thunder and the dull booming of explosions from the direction of Galunggung's crater 7 km away became louder and more frequent while ash fell more heavily, so I (JPL) turned to go back inside the observation post.

Inside the post, a beehive atmosphere prevailed as technicians busily checked seismographs and shouted out readings to communications specialists in an adjoining room. Their reports were being radioed to Civil Defense Headquarters in the city of Tasikmalaya, 17 km away (Fig. 1.2) and to the VSI Headquarters in Bandung, 75 km to the west: *Tremor vulkanik mulai naik – amplitud duabelas millimeter sekarang – kami mendengar letusan-letusan dari kawah!* ("Volcanic tremor is beginning to increase – the amplitude is now 12 mm – we hear explosions from the crater!") The observation post was set up in a well-built house in the evacuated zone, but extremely fine volcanic dust nonetheless managed to infiltrate cracks and was everywhere. Note-taking was difficult since fine ash continuously settled on the paper and clogged our pens. The dust formed golden halos around the naked light bulbs dangling from the ceiling, and observers all wore cloth masks over their faces to facilitate breathing. We were in the dangerous Red Zone, as close to Galunggung's central crater as possible, where no one but emergency personnel were allowed to stay at night, and the thought nibbled at the edge of my

Fig. 1.1 Refugees from falling ash at midday, outside the Galunggung Volcano Observatory, Cikasasah, Indonesia, August, 1982. USGS photo by J. P. Lockwood.

Fig. 1.2 Location of Galunggung and other major active volcanoes (starred circles) of central Java, Indonesia. Major metropolitan centers (bars) are also indicated.

consciousness – "Do I really want to be here?" That thought never progressed very far, however, since I knew that at that moment I was one of the most fortunate volcanologists anywhere. *Reading* about volcanoes is fine, but *being* at a volcano, especially during an eruption, is the best means to discover new knowledge. I suspected that the next three months at Galunggung were going to include some of the most concentrated learning experiences of my life.

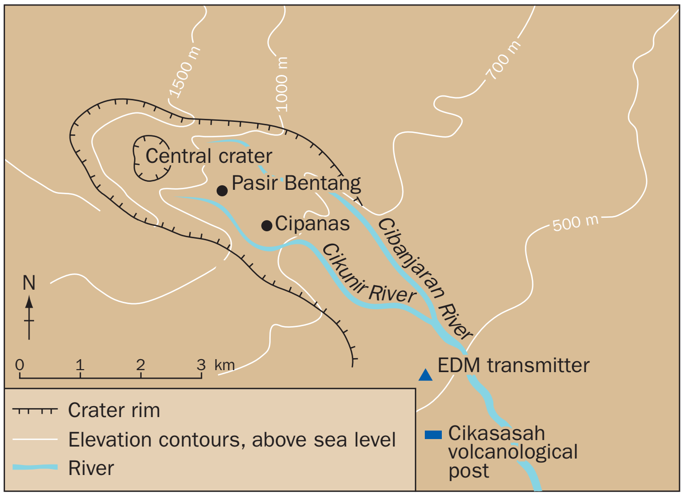

Fig. 1.3 Galunggung volcano, Indonesia. Terrain features and locations of geodetic survey stations during the 1982–3 eruption.

Galunggung is at the center of the most fertile, heavily populated agricultural land in central Java. It is a horseshoe-shaped volcano, whose central portions had been blown out by a catastrophic prehistoric eruption (Fig. 1.3). For many kilometers to the east, the plain is littered with thousands of small hills, each representing a shattered fragment of the volcano's heart. Hard-working farmers had established a productive complex of rice terraces and fish ponds inside Galunggung's amphitheater, an area that was renowned in all Java for its beauty and agricultural efficiency. All was quiet during the early months of 1982, and there had been no activity at the volcano since the formation of a large dome during a small non-explosive eruption within the central crater in 1918. The VSI monitors the volcano on an annual basis, but the previous "check-up" in 1981 had shown nothing anomalous. Galunggung's potential danger was well-known to local authorities, however, as about 4000 people had been killed downstream of the volcano by hot *lahars* (mudflows) in 1822. Legends of devastating prior eruptions abound in the records of the local Tasikmalaya Sultanate.

Residents did not need to be told what to do when a sharp earthquake was felt by Galunggung farmers on the evening of April 4 and snakes reportedly began to emerge from the ground. Those living within and near the central crater around the volcanic dome that had grown there in 1918 quickly began to evacuate. Earthquakes continued that night, and a violent eruption tore apart the center of the crater the next morning. Because the people had fled during the night, no one was killed, though many homes were destroyed. The VSI was alerted, and the first team of volcanologists arrived on April 6. Their portable seismometers showed high levels of earthquake activity, and they recommended an immediate evacuation of all people within the Galunggung "horseshoe." Their warning came none too soon, as a powerful explosion on the evening of April 8 devastated a wider area up to 4 km from the crater and generated highly fluid, incandescent pyroclastic flows which poured about 5 km down the Cibanjaran River, incinerating several small villages. Again, because the people had been warned, there were no casualties. Eventually more than 100,000 residents left their homes for "temporary" refugee camps which had been hurriedly constructed just outside the danger area.

The Galunggung activity continued to increase in violence over the next several months. Explosive eruptions repeatedly sent churning clouds of ash and steam more than 16 km into the sky. Galunggung's activity was noted on international news wires on June 24 when a British Airways 747 with 250 people aboard entered an ash cloud over central Java during an explosive night eruption of the volcano. The jet was flying between Singapore and Perth at 11,300 m when it entered the ash cloud and abruptly lost power in all four engines. After gliding free of the ash, the pilot was able to restart three engines and barely make it back to Jakarta airport for a "blind" emergency landing (the windshields had been frosted by ash abrasion).

These ash clouds deposited their loads over a wide area, and ash fell as far as Jakarta, 190 km away. About 25 million people were affected by "nuisance" ash, which required repeated cleanup. More than 500 million cubic meters of ash eventually blanketed much of west Java. An area of about 10,000 km^2 was covered by ash at least one centimeter deep which clogged irrigation systems, damaged crops, and seriously lowered food production in the heart of central Java's rich farmland. At one point, a half-million people faced serious food shortages that required expensive relief efforts by the Indonesian government.

I (JPL) first learned about the Galunggung eruption in early April, when John Dvorak called the US Geological Survey's (USGS) Hawaiian Volcano Observatory (HVO), after having seen the first explosion from the summit of Merapi volcano, 290 km to the east. John was in Indonesia as a participant in a cooperative program between the USGS and the VSI, supported by the US Agency for International Development (USAID). This program was designed to introduce the VSI to modern volcano monitoring techniques in use at HVO. I was slated for a four-month assignment to Indonesia that summer, and spent the remainder of the spring at HVO preparing equipment for the trip.

My family and I left for Indonesia in July, burdened by an incredible load of tripods and other survey gear. While enroute, we read that yet another jet had been forced down after an encounter with a Galunggung ash cloud. We knew nothing of the seriousness of that episode, however, but were amazed on our flight between Singapore and Jakarta when I looked outside and counted *three* engines on the starboard wing! The pilot was walking down the isle at the time and I asked him what sort of strange airplane this must be with six engines. "No, there are only *five*," he said, "the extra one on the starboard wing is being carried to Jakarta to replace one of the damaged engines on the plane downed by Galunggung."

At the Jakarta airport, we could see the Singapore Airlines 747 parked off to one side with its badly sandblasted windshield and paint. The circumstances were similar to those of the earlier British Airways incident: The plane had flown into an ash cloud at 10,000 m and had lost power in three of its four engines. The disabled jetliner with its 230 terrified passengers had descended to 4000 m before the pilot was able to restore partial power to two engines and limp to Jakarta airport. Examination of the engines later revealed that the Galunggung ash had melted within each and had been deposited as glass on the turbine blades. After this second near-disaster, commercial aircraft re-routed their flights far from Galunggung for the duration of the eruption, and the aviation industry, in close cooperation with volcanologists, began major efforts to educate pilots about volcanic ash hazards (Chapter 14).

Upon our arrival at the VSI headquarters in Bandung, I was told by Dr Adjat Sudradjat, the VSI Director, that because of the mounting economic and social impact of the continuing Galunggung eruption, he would prefer that I not work primarily at Merapi as previously planned, but instead prepare to spend most of my time at Galunggung. I was delighted, and traveled to Galunggung that night.

Two critical questions urgently required answers from the volcanologists at Galunggung: i) When would the eruption stop? (critical information, which would dictate how long Government relief efforts would be required); and ii) Was there any chance that a much larger eruption might occur, and if so, was the evacuated zone large enough – was the city of Tasikmalaya safe? The 1883 eruptions of Krakatau [98] had killed more than 30,000 people in Java, and memories of that tragedy had not been forgotten.

Electronic Distance Measurement (EDM) instruments were some of the most important tools available to us for answering these questions. John Dvorak and his Indonesian colleagues had established a small EDM network in mid-May, and had set up laser reflectors close to the

crater. However, those were destroyed by a violent eruption a few hours after the field party had left the area. Because of continuing eruptive activity, no one was able to visit the crater area for the next few months. The major eruptions occurred every few days, and were incredibly spectacular at night (Fig. 1.4). The continuing eruption was causing major economic impact on Indonesia, however, and there was no way to enjoy the fireworks. The eruption had already devastated a large area of fertile farmland near the volcano, more than 50,000 residents had been evacuated to refugee camps, and the lives of millions of people were being disrupted by widespread ash across central Java. By late July, it was apparent that a larger EDM network, including stations closer to the central crater, was critically needed. This would allow us to estimate the size of the magma reservoir beneath the volcano and thus assess the danger of larger eruptions, as well as to better predict individual eruptive phases. We somehow *had* to establish new stations closer to the crater.

Fig. 1.4 Night view of Galunggung volcano in eruption, September, 1982. This two second exposure indicates the continuous lightning activity associated with the eruption of electrostically charged ash. USGS photo by J. P. Lockwood.

Our EDM equipment consisted of a laser transmitter and special reflectors. The transmitter (or "gun") was set up at one survey point (Fig. 1.5) and the reflectors at another; the

Fig. 1.5 Monitoring inflation of Galunggung volcano between eruptions by EDM from Cikasasah station, 6 km from the rim of crater, where volcanologists have set up a temporary laser reflector. USGS photo by J. P. Lockwood.

precise distance between gun and reflector can then be measured to the accuracy of a few millimeters by computerized comparison of the light signals leaving the gun and the returned light from the reflectors. To establish reflector stations closer to the crater, we had to figure a "safe" time to approach closer. Small explosions were nearly continuous at the crater but the violently explosive, more dangerous eruptions were occurring at intervals of one to seven days. We soon noticed that these larger eruptions were all preceded by a brief period of eruptive quiet, followed by 2–3 hours of gradually increasing activity building up to the most violent explosions. Thus, it looked as if a volcanological team would have time to make a quick visit to the outer rim of the central crater and install EDM reflectors during the pre-eruptive "quiet" period with sufficient time to flee when the eruptive intensity began to increase. Furthermore, a sophisticated seismic monitoring network had just been installed around Galunggung by my HVO colleague Bob Koyanagi and a joint USGS-VSI team so that we would have good information on earthquake activity during our trip to the crater.

Galunggung's crater was clear on the morning of August 7 (Fig. 1.6), and the seismographs showed no activity, so volcanologists Dedy Mulyadi (Indonesia), Maryanne Malingreaux (Belgium) and I decided to set out before the violent eruption we now expected could begin. We loaded our EDM reflector gear into a jeep and were able to drive about halfway to the crater into a world increasingly barren and devoid of life. At the point where the road ended about 4 km from the crater, the only sign of life was an Indonesian entrepreneur who had set up a "store" in the ruins of an ash-crushed building. His only wares were a dozen bottles of soda which he carried to his store each day in the hope of a sale to a rare passerby. We bought three sodas for our packs and hurried on by foot. We soon had to cross the Cikunir River (see Map, Fig. 1.3), a normally small stream that was now a deep gorge cut into fresh volcanic mudflow (lahar) deposits that blanketed the land and villages surrounding the river bed to a depth of

Fig. 1.6 View into Galunggung's prehistoric horseshoe-shaped crater during a lull between major explosive eruptions in August, 1982. The pyroclastic deposits from these eruptions have built up the rim of the inner crater. Note the drooping, broken palm fronds which are a universal trademark of "grey volcano" eruptions anywhere in the tropics, and result from even minor accumulations of volcanic ash. USGS photo by J. P. Lockwood.

Fig. 1.7 Ruins of Cipanas village, three kilometers from the central crater of Galunggung. Volcanic ash (tephra) can accumulate thick enough to collapse roofs in only a few hours, especially when damp and heavy from rainfall. Although typically light grey in color, it can look like fresh-fallen snow when blanketing the countryside. USGS photo by J. P. Lockwood.

more than 10 m. Crossing the river was easy at the time because only a few centimeters of muddy water were present. We knew we had to return before the next lahars were generated, however, or else we could be helplessly stranded on the other side of the Cikunir with no possibility of re-crossing to the safety of our jeep.

We hurried on through areas where only shells of broken homes (Fig. 1.7) gave evidence of the lives of the people who had fled the area. In one of the ruined villages we met a barefoot man, illegally in the Red Zone, who had come on this day to see his rice paddies and the wreckage of his home. He explained that he was being asked by the government to leave Galunggung forever and move to faraway Sumatra to begin a new life with government help. However, he told us that he could never leave his ancestral home and the graves of his forefathers. He had planted the next season's rice crop in a safe area and would transplant the seedlings to his own land whenever the eruption ended. *"Kepan selesai?"* (When will it end?) he asked. We didn't know, and couldn't answer, so we moved on even faster, knowing that the reflectors we carried could help to provide an answer for this man and the hundreds of thousands of others whose lives were being ravaged by Galunggung.

We installed a reflector station above the ruins of Cipanas village, tested it with a measurement from the "gun" 5 km away, and raced on towards the crater, now less than 2 km away. The area we were crossing had once been heavily forested, but all the trees had been incinerated or swept away, and nothing but the desolation of grey ash, pock-marked by volcanic bomb craters, could be seen on all horizons. It was a scene of devastation more complete than in any war zone, except perhaps for the ground zero of Hiroshima. In fact, the cumulative explosive power of Galunggung had already far exceeded the "small" nuclear bombs exploded in 1945.

Suddenly, our radios crackled to life with the message that earthquake flurries had begun anew beneath the crater, indicating the onset of the next eruptive phase. *"Kembali – kembali* *sekarang!"* ("Return – return immediately!") We could see that the visual forewarnings had not yet begun, however, and knew from our previous experience that it was probably still safe, so we ignored the radios and hurried on. Just as we reached a ridge directly below the crater rim at 09:45, we heard small explosions in the crater above us and saw small puffs of steam and ash rising from beyond the crater rim.

We set up our laser reflectors in record time, then called the survey crew back at Cikasasah by radio and asked them to begin the EDM readings – quickly! We were asked to forget the readings and hurry back, but after coming this far we were hardly ready to quit. So, we took the critical temperature readings as the red laser light began to flicker at the gun 6 km away. As the readings seemed to drag on, explosions within the crater became quite loud and angry black "cauliflower" clouds began to boil from the crater. Large blocks of lava up to 0.5 m in diameter were being thrown from the crater, making muffled sounds as they landed in the soft ash a few hundred meters away. The readings were finally finished at 10:10. As we began to pack up our gear, small pyroclastic flows began to pour over the crater rim in our general direction (Fig. 1.8). Our new station was located on a narrow ridge radial to the crater, however, and we felt quite safe – for the moment – as the small ash clouds parted around the ridge and were deflected into the Cikunir River far below. To allay the concerns of our worried colleagues at Cikasasah, we radioed them to say we were on our way back. But we secretly decided to stay just a little while longer, because I knew from the scores of similar phases we had observed previously that we probably had several more minutes of relative safety. In hindsight, it was foolish to tempt fate (many volcanologists have died doing so); but the extra few minutes we remained there were some of the most incredible moments of my life. Times like this are far

Fig. 1.8 EDM reflector at Pasir Bentang station below the erupting crater of Galunggung, Auguat 1982. A small pyroclastic flow is beginning to cascade down the crater wall, and the thin deposits left by similar small Haws are seen behind the reflector tripod. Note the permanent reflector mounted on stake to left. Photo by Dedy Mulyadi.

too busy for written notes. Furthermore, to remove one's eyes from the scene before us would have been a terrible waste of observation time, as well as rather hazardous. Instead, as we did our work, I spoke into a tape recorder, an invaluable tool for times like this. My recorded words, spoken with a rather serene calmness (belied by the background roar of the volcano), follow:

09:53 – Steam and ash clouds have increased in intensity, and at this moment a black cauliflower cloud boils out of the northeast side of the crater looking like the puffing from a giant steam locomotive.

10:00 – The entire crater is now the source of nearly continuous explosions. The roar is deafening and the ash clouds have reached 2 to 3 km above our heads. Blocks begin to fall at the crater's rim and unseen lightning is thundering above.

10:08 – Large angular blocks are falling on the outside of the crater wall above us with loud "whoomp-whoomp-whoomp" sounds. They're really not falling – they are ballistically propelled – shot out laterally by the violent explosions – not "falling" from the clouds. They land as groups in distinct impact areas about 100 × 200 meters in area following particularly loud explosions, and bounce and roll down the slope toward us, but deflect around our ridge and down into the Cikunir gorge.

10:10 – Readings finished. We begin packing up.

10:18 – The eruption continues to increase in violence, and gray-black ash flows are boiling over the crater rim and glide almost silently down slope in our general direction, never coming closer than about 150 m. The lightning becomes very intense in the clouds overhead and the explosions are very loud, almost deafening. The lightning begins to strike the crater rim above us and the black ash clouds have mushroomed above our heads, leaving only the horizon to the east clear. We realize that things could get out of control pretty quickly, and decided to retreat – I don't need to breathe more ash! [The truth is, I had seen the autopsy reports of the Mount St Helens [27] 1980 victims and was thinking about their ash-clogged throats. Would our simple particle masks be adequate for breathing if those ash clouds above collapsed? I have no notes for the next ten minutes as we scrambled down slope toward safety. We passed Cipanas at a run and didn't stop to look back – the roaring behind us was louder and we all must have been thinking that maybe we cut this one a bit too close].

10:28 – (out of breath) [We reach the destroyed village of Lingajadi, 1.4 km from Pasir Bentang – and stop to look back]. *Ash is now falling on the hills directly behind us and Pasir Bentang is completely obscured. We're going to keep on moving.*

10:52 – Reached jeep after crossing Cikunir with no difficulty. We've been in a fine ash fall for the past 10 minutes. The light is fading fast and there is no horizon – visibility about 300 m. The soda salesman had left long ago, and his table and our jeep were already covered by several millimeters of gray ash.

Survival Tips for Field Volcanologists

Whenever feasible, approach eruptive areas from the upwind side. "The smell of sulphur may not be entirely unpleasant to volcanologists (or sinners!)", but we prefer fresh air whenever we have the choice. Small ash eruptions won't hurt you – but the fine ash can wreak havoc on camera gear and visibility, and remember – upwind beats downwind every time!

> *11:15 – As we drive closer to Cikasasah we move through crowds of refugees leading their water buffaloes and carrying baskets of baby fish from the few fish ponds they had kept open.* These people had come from the nearby refugee camps in the morning to clean ash from the roofs of their abandoned homes which would collapse from the weight of ash unless it was removed daily (Chapter 14).
>
> *11:30 – Reached the Cikasasah Observatory!* Our VSI colleagues treat us a bit like ghosts, and as I look at Maryanne I see part of the reason – she smiles and her white teeth make a striking contrast to her otherwise light gray, ash-covered face. The falling ash has stuck to all of our faces and turned us gray too, just like everything around us.

But we had reason to smile. The Pasir Bentang and Cipanas EDM stations were ready, and if they survived this eruption, we'd be able to measure those critical distances in the morning. By 13:35 the ash cloud overhead had totally blocked out the sun's light, and it was *black* at Cikasasah – the blackest black I have ever seen. It really is "impossible to see your hand in front of your face" during heavy ashfall, and my hand bumped into my nose as I gave the old saying a test.

The reflectors we installed *did* survive the eruption, and EDM observations during the ensuing eruptions proved critical to our analysis of Galunggung's underlying magma chamber. We learned that ground deformation did not extend far from the central crater, which showed the magma chamber to be small and not likely to cause larger eruptions. We also learned that inflation of the crater area preceded most eruptions and that deflation accompanied eruptive activity – i.e. survey lines between Cikasasah and the near-crater stations were normally longer *after* eruptions, showing that deflation had occurred. We were thus able to determine when the volcano was inflated and thus more likely to erupt. This gave us a means to predict individual eruptions and enabled the VSI to quantitatively demonstrate the quieting of Galunggung as the underlying magma chamber became less and less active.

The reflectors we established lasted for the next six months of activity and almost miraculously were never destroyed, although large bombs formed impact craters as much as two meters in diameter a few meters from the Pasir Bentang station. Almost two meters of ash was deposited at Pasir Bentang over this period, and the reflectors which were originally established more than a meter *above* ground level were soon *below* that level and had to be dug out after each major eruption (Fig. 1.9). Eventually narrow trenches had to be dug in front of the reflectors to allow "lines of sight" to the EDM gun stations.

The numerous eruptions were especially awe-inspiring at night, and my family and I spent many sublime hours admiring the thunderous eruptive grandeur of Galunggung along with silent groups of emergency workers and refugees.

The Galunggung eruption ended on January 8, 1983, and the refugees, except for the 10,500 who had been permanently moved to Sumatra, returned to the areas where their villages, rice paddies, and fish ponds had once been. The intricately terraced water systems, which had taken hundreds of years to build, were cleaned out and reconstructed within two years. By 1986 everything appeared normal once again. Homes had been rebuilt and the rice paddies were healthy with no sign of the deep ash which had deeply buried them in early 1983. Where had all that ash gone? I found that the incredibly hard-working farmers had simply

Fig. **1.9** R. I. Tilling excavating line-of-sight path for EDM measurements at Pasir Bentang station, Galunggung, October, 1982. The reflectors had to be re-excavated after every tephra fall event – this is the same reflector that had been above ground two months earlier (Fig. 1.8). USGS photo by J. P. Lockwood.

"buried" the ash in their fields. They dug under the ash, removed the fertile and impervious topsoil, and placed it back above ash as much as a meter thick! Mineral nutrients from the underlying ash would now slowly seep upward, making the paddies more fertile than before.

A "Red Volcano" in Eruption – Kīlauea – 1974

BACKGROUND

I (JPL) first saw flowing lava during a brief vacation visit to Hawai`i in 1971, and subsequently began to hope and scheme for an opportunity to work at the USGS's Hawaiian Volcano Observatory (HVO) – located near the summit of Kīlauea, the world's most active volcano. My chance came in January 1974 when my family and I moved to Hawai`i for a HVO tour. There had been a lull in Kīlauea's volcanic activity, however, and I feared that perhaps there would be no eruptions at all during my scheduled two-year HVO assignment. How ungrounded my fears proved to be! 1974 unfolded as one of the most volcanically active years in Kīlauea's recorded history. I was about to learn firsthand that volcanoes are living, breathing entities, and that **magma** (molten rock stored underground) and **lava** (magma that has reached the Earth's surface – whether still molten or long-cooled) are more than geological abstractions! I would soon learn from HVO's talented technical staff how to monitor that magma movement with innovative tools, and would have many opportunities to witness the awe-inspiring moments when magma breached Earth's surface and finally became "lava." I was also to learn about and to gain respect for the tradition of *Pele*, the Hawaiian goddess of fire and volcanoes. Pele was about to produce a set of spectacular eruptions to welcome me to my career in volcanology.

Richard "Rick" Hazlett (RWH), then an undergraduate researcher from Occidental College, also arrived on the HVO staff during that time, and was learning how to track the underground migrations of molten rock and how to forecast volcanic eruptions. His arrival led to an academic career in volcanology that has ever since remained an element of our friendship. We here recount some of our experiences during that exciting time when we were "baptized by fire." First, some background.

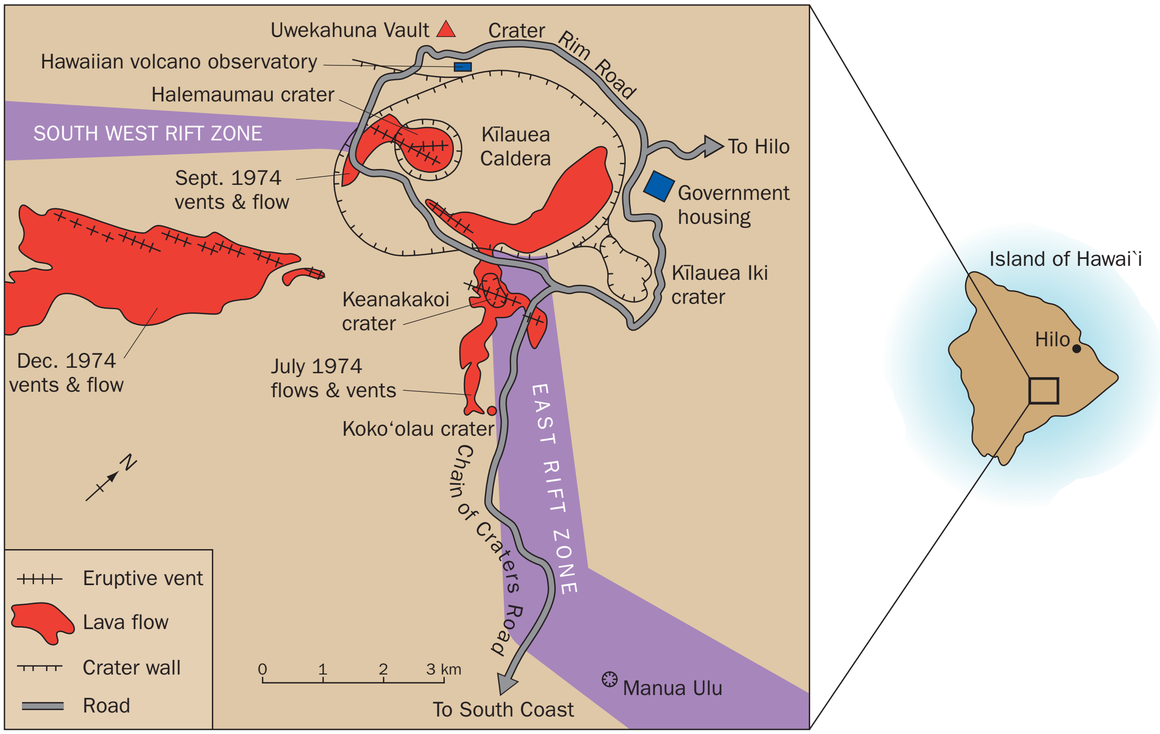

Fig. 1.10 Principal features of Kīlauea volcano summit area. Modified from Lockwood et al. (1999).

MAUNA ULU ACTIVITY

In late 1969, molten rock from Kīlauea's magma reservoir system worked its way to the surface about 10 km from the summit of the mountain in a zone of weakness called the East Rift Zone. What had been a gently sloping forested highland suddenly became the stage for an eruption of gushing lava that ultimately constructed a satellitic volcanic edifice nearly 1 km across at the base and some one hundred meters high. Local Hawaiians named it Mauna Ulu "Growing Mountain" (Fig. 1.10).

Mauna Ulu's vent-filling lava lake demonstrated episodic lava fountaining activity that alternated with periods of lava drainage in late January of 1974. The high fountaining episodes involved gas-charged geysers of lava up to 100 m in height that would sometimes play for hours on end. This activity was followed by copious lava overflows, noisy de-gassing, and then rapid lava lake drainage and lake surface lowering. The periods of fountaining were especially awesome because of their noise. Frequently, while asleep in our government housing on the summit of Kīlauea, we would be awakened by a rhythmic rattling of window panes caused by the intense roaring from the Mauna Ulu lava fountains 10 km away. Outside, the night sky in the direction of Mauna Ulu would turn bright orange-red, reflecting off overhead clouds when they were present. Such events made it necessary to drive to HVO to check instruments and make certain that no dangerous change in eruptive style was occurring (one of the most important missions of the Observatory is to advise the Hawai`i Volcanoes National Park of any eruptions that could endanger park visitors and campers).

Don Peterson, the HVO scientist-in-charge, and I (JPL) had driven to the Observatory late one night in the winter of 1974 to check a new surge of activity indicated by a glow on the skyline from Mauna Ulu. After noting an increase in seismic activity in that area on HVO seismographs, we decided to hike out to the eruptive area to inspect the action at closer range. Together with our wives, the four of us drove as close as possible and began to hike over fresh lava flows to inspect the erupting vent. The surfaces of pāhoehoe (smooth surfaced lava) solidified quickly, and within a half hour or so the solid crusts were thick enough to support one's weight (a 5 cm thick crust is strong enough so long as the crust is underlain by molten lava and not by a gas bubble!). We had to keep moving across the hot flows so that the soles of our boots didn't get too hot, as this can cause painful steam burns. We learned quickly what sorts of boot soles hold up under these conditions; the soft rubbery kinds catch fire too quickly and melt easily. The first warning you may have of this is when your footing becomes slippery!

As the four of us reached the rim of Mauna Ulu's crater, we found that the lava surface had lowered about 15 m below the vertical rim of the 40 m wide lava lake. The radiant heat from the pooled lava below was reminiscent of that from a giant blast furnace, but the hot air rose vertically rather then spreading out horizontally to drive us away. When the winds did shift and the sulphur fumes were stronger, I thought of Mark Twain's words, written after his exposure to volcanic fumes from Halema`uma`u in 1873: "The stench of sulphur is not entirely unpleasant to the sinner!" If I may, I would like to amend Twain's wording to add "nor to the volcanologist!"

Mauna Ulu's lava lake was directly connected by subterranean conduits to the principal magma chamber underlying Kīlauea's summit, 10 km away, and as I watched the pulsating surface of the lake surface below me, I realized that I was looking at an exposed top of this sprawling magma system. Up until then the term "magma chamber" seemed to be little more than a mysteriously abstract way of explaining instrumental measurements at the Observatory. Now here it was – *for real*! The roiling lava lake I was privileged to be watching was directly connected via subterranean dikes to the principal magma chamber beneath Kīlauea caldera. That chamber was itself connected by a nexus of passageways downwards to the area some 60–80 km below the surface where fresh basalt magma was being "sweated" out of the earth's upper mantle far below the Earth's crust. This sweating process, called "partial melting," (Chapter 3) had created the magma that was now reaching the Earth's surface for the first time after its formation – perhaps only months or maybe years before. As this magma reached the Earth's surface in the crater below me, it could at last be called lava.

Fig. 1.11 Mauna Ulu lava lake. Thin lake crust is descending into "drain-back" at the margin of the lake, accompanied by 5 m-high fountains. USGS photo by J. P. Lockwood.

There was little sound from the lake, other than "blurping" noises as large gas bubbles frequently broke the lava surface. The lava surface was gently convecting, and plates of descending crusts would trigger fountaining at the crater's edge (Fig. 1.11). Don, Betty, and Marti were on the south rim, and I had walked about 75 m to the west for a better look into the roiling lava below.

As I was enjoying the view of the lava lake that night, I heard a persistent "popping" sound behind me and noted that a crack was slowly opening about 5 m back from the rim. I stood over the slowly widening fissure and saw that the crack was spreading eastward toward my companions. It began to open faster, exposing glowing rock below and opening up like a zipper towards Don and our wives, who were mesmerized by the lava lake circulating below. I shouted an alarm. They saw the advancing crack and began running south – away from the lake. I ran fast behind them, but they were about 25 m ahead of me when I heard a loud splashing sound and the clouds above me turned bright red as a large fragment of crater rim plunged into the lake below.

Don slowed down to look back as I ran toward him, and I saw him gaze upwards at the column of lava spatter that rose above us. "Keep running!" he screamed. I needed no encouragement, and almost *flew* down slope over the rough lava to rejoin the others in a safe area. No worse for the experience, we went back to the Observatory to inspect the seismic records and found that the collapse of this large crater rim had indeed been recorded on a nearby seismometer. It was comforting to see that our technology worked on such a fine scale!

A few days later, as I probed with my geologist hammer into small toes of fluid lava that emerged from flows descending down the flanks of Mauna Ulu, I realized that my hand was directly connected to a non-broken conduit of primordial fire, fire that led down to the birthing place of magma itself within the so-called "hotspot" beneath Hawai`i. I humbly thanked Pele for this incredible privilege; I would never again be able to view volcanoes without thinking of their magmatic roots and about the crucibles of fire that lead to their creation.

Survival Tips for Field Volcanologists:

Pay attention to sounds when on eruptively active volcanoes – especially along the margins of craters. Rocks commonly begin to fracture slowly at first as they begin to fail – making audible cracking sounds before sudden failure. Major phreatic explosions have been preceded by audible sound changes. Pay attention to the "normal" sounds a volcano makes, and be concerned if those sounds begin to change!

THE SUMMIT ERUPTION OF JULY 19–21, 1974

My last view of molten lava at Mauna Ulu was on July 10th. Nine days later, Don Peterson and I were at sea off the west coast of Hawai`i exploring undersea volcanic features from a US Navy deep sea submersible. Rick Hazlett was lucky enough to be on duty at HVO on July 19, as a new chapter in Kīlauea's eruptive pattern was about to open. Here is his narrative of what happened:

> *Around 03:30 on the morning of July 19 the tremor alarms sounded in park housing, and a few bleary-eyed HVO staffers drove quickly over to the Observatory to see what was going on.* ***Tremor****, a continuous shuddering of the Earth related to the shallow movement of magma, commonly precedes eruptions. Perhaps Mauna Ulu was about to experience another major overflow! Preliminary indications showed that the source of this shallow earthquake activity lay much closer to the Observatory, however, and was only 2 to 5 km distant along the southern rim of Kīlauea's caldera. For this reason the HVO response team quickly called upon park rangers to evacuate the southern part of Crater Rim Drive and all of Chain of Craters Road (Fig. 1.10), areas that would ordinarily be swarming with visitors and tour buses soon after sunrise.*
>
> *I arrived at HVO at 08:00 to find Bob Tilling in charge of the crisis response. No eruption had yet started, but he sent two crews of observers into the now-closed area to report on any visible changes in the ground surface possibly related to the strong earth tremor, which by now had shifted close to a small pit crater called Keanakako`i, where ancient Hawaiians once mined fine-grained basalt for stone tools. I rode with one crew down the Chain of*

Craters Road, while the other field team parked along Crater Rim Drive right at the northern rim of Keanakako`i, within sight of the Observatory. After driving only a few miles our vehicle came to a sudden stop, as up ahead we saw fist-sized holes opening in the asphalt. It took only a few minutes for each new hole, deep and black, to open, and every few tens of seconds we felt sharp earthquakes. Making a hasty radio report to the Keanakako`i team, our crew drove further upslope along the evacuated highway, closer to seismic "ground zero" where Kīlauea was likeliest to begin erupting. We parked in woods next to Koko`olau Crater, another prehistoric vent, Stepping out to an overlook, the strengthening volcanic tremor was now physically apparent. The ground seemed to sway gently, but erratically, as if standing on a giant bowl of vibrating gelatin. Every few tens of seconds a sharp jolt interrupted the continuous rocking. Some of the surrounding trees nearby creaked and moaned though little wind blew.

No more than a couple of minutes of this unusual experience elapsed when a park ranger's patrol car arrived and our radio burst to life with Tilling's words: "The eruption has started by Keanakako`i! The vent is opening in your direction – get out fast! *" We were now in a race with time to avoid being trapped. As we raced back up the road, we soon saw roiling light blue, brown, and white eruption clouds rising above the tree line to the west, getting closer by the second. The instruments had indeed been accurate in forecasting an outburst in this area, and our closely-timed ground observations had been useful for corroborating this pre-eruption seismic monitoring. The opening fissure intersected the road no more than a minute or two after we drove past.*

Reunited at the edge of Keanakako`i, the two field crews watched as a sheet of fountaining lava ripped the ground open across the southern end of the 35 m deep crater about 400 m away, safely propagating at a right angle to our lines of sight. I was impressed that the escaping magma seemed to ignore *the presence of the crater; the opening vent followed its linear path irrespective of any surface landform. Cascades of blood-red lava soon poured over Keanakako`i's rim and erupted through the tear in its southern wall and base – volcanic chaos taking place simultaneously over just a few square kilometers of landscape. From 1 km away the eruption sounded like surf crashing on a distant shore. Up close, however, it sounded like thousands of fire hoses blasting away all at once.*

The unsteady rolling of the ground continued off and on where we stood, when suddenly one of our team, exploring about 30 meters away cried out, "Hey, look at this. Another crack is opening!" We made haste to join him, and sure enough watched a fresh linear trench widen and deepen where flat earth had existed moments before. Knowing what was coming next, we stepped back, upslope and upwind, and within a few minutes a billowing mass of dense white steam poured out, quickly fading to the telltale blue of nose-pinching volcanic fumes and soon followed by the ejection of plate-sized globules of lava. The ends of this new fissure lengthened at the rate of a slow, steady walk, and within a half hour mounds of quenched lava ejecta, called spatter ramparts, had grown several meters high all along its upslope rim. As we were studying these developments, a colleague obtained a memorable photo from his vantage point at HVO 3 km away (Fig. 1.12).

The eruption climaxed only about 45 minutes after the outbreak began and the development of new vents ended. For the next three days, activity gradually simmered down. This is typical of many eruptions at red volcanoes; they wax rapidly and wane slowly. Little did we appreciate at the time, however, that this small but spectacular eruption heralded the end

Fig. 1.12 July, 1974 eruption of Kīlauea volcano as viewed from the Hawaiian Volcano Observatory a few minutes after outbreak of typical "curtains of fire" from multiple en echelon vents near Keanakako`i crater. A USGS monitoring crew is observing the middle vents. USGS photo by John Forbes.

of the long-lived activity at Mauna Ulu – which has not been active since. Kīlauea had once again changed her eruptive style – the next two eruptions, in September and December, would also be in the summit area (Lockwood et al. 1999).

CONCLUSIONS

Some useful generalities emerge from these eruption narratives:

1 Volcanic eruptions evoke feelings of awe, excitement, and to a greater or lesser extent, concern and fear for those nearby.
2 Effusive red volcanoes such as Kīlauea tend to have frequent, gentle eruptions that can be studied close up, whereas eruptions of the explosive grey volcanoes are less frequent but have far-reaching impacts.
3 Eruptions of grey volcanoes are more dangerous than those of red ones, and much more caution is needed during close observation.
4 People's lives can best be protected in areas where eruptive activity is frequent (e.g. Java, Hawai`i). This is because in areas of relatively frequent eruptive activity, residents are better informed and are more likely to recognize early warning signs of impending activity, and volcanologists will be able to prepare more accurate predictions of future activity. Most

important, local residents are more likely to accept the advice of public officials and comply with mitigation efforts such as evacuation.

5 The magma reservoirs beneath effusive volcanoes are typically complex and dynamic, and can send dikes great distances at shallow depths underground, even tens of kilometers from the volcano's top. Flank eruptions are common, and can be the norm. In contrast, the magma systems beneath typical explosive volcanoes are usually more localized beneath volcano summits.

6 Erupting lava and gases are the major concerns of effusive eruptions on red volcanoes, but simple field precautions can usually prevent disaster. In contrast, explosive eruptions of grey volcanoes typically involve serious hazards such as falling ash and pyroclastic ash flows (Chapter 7), and mudflows (Chapter 11). Eruptions may threaten extensive areas, and evacuations of large numbers of people are often necessary. This makes a major volcanic eruption as much a sociological and economic event as a geological one.

These eruption accounts illustrate some of the reasons that volcanoes are being studied and illustrate the sort of practical use volcanologists are trying to make of their knowledge. The modern science of volcanology combines well-documented field observations and instrumental surveillance of active volcanoes, as well as careful field mapping of older volcanoes to learn their histories. Laboratory studies that reveal how magma is formed, stored, and evolves beneath active volcanoes are also vitally important. The long-term goal of all volcanologists is to have a better understanding of "how volcanoes work". Only such understanding of volcanoes can lead to the knowledge and development of tools needed to fulfill our ultimate goal – the protection of human lives and property. Volcanologists seek to recognize hazardous areas and evaluate risk, warn of danger, and thus save lives. In addition to these benefits, volcano studies have revealed many other equally important connections between volcanic activity and the human experience. The final section of this book, entitled "Humanistic Volcanology," explains the relationship of volcanoes to our history, our climate, and to the metals and energy that we use and to the soils whose productivity provide our food. It is no exaggeration to state that without volcanic activity life might never have developed on Earth. Without the ore-concentrating roles of magmatic systems and volcanoes technical civilization would be impossible. Volcanoes are infamous for their destructiveness, but they are also beautiful, have created much of the land we live on, and help sustain the world in ways which few of us fully grasp.

Generalizations being what they are, there are exceptions and elaborations needed for each of the statements made above, and we shall touch on them again throughout this book. For the time being, however, we've shared some of our personal experiences, and hopefully hinted at reasons why this science is an exciting humanistic as well as a scientific journey.

Some Basic Terminology

As humans develop specialized knowledge, whether it be about the baking of bread, ballroom dancing, brain surgery or whatever, new words are coined to describe common features or processes. These words become "shorthand" to express thoughts in a few words rather

Fig. 1.13 Kronotsky volcano, on the eastern shore of Lake Kronotsky, Kamchatka. The 3500 m high summit of this perfectly symmetrical composite volcano was the site of minor phreatic explosions in 1923. When the lake surface is smooth, the reflection of this volcano on the water is one of the most beautiful sites in the world. USGS photo by J. P. Lockwood.

than many. Volcanologists have their own shorthand jargon, though we strive to avoid complex terminology as this can be a barrier to effective communication with the general public. We here define some of terms we will be using in this book – in narrative form rather than presented in a glossary. The Index (p. 526) will also direct you to further definitions when needed.

First, just what is a **volcano**? Most people first think of volcanoes as those beautiful, steep-sided, symmetrical, pointed cones like Mount Fuji [113] in Japan, Mount Shasta [26] in California, or Mount St Helens in Washington State (at least as it was before the catastrophic eruption of 1980!). But in fact most volcanoes have shapes and forms that differ greatly from the postcard views and cartoon sketches we all learn to draw in school. Volcanoes come in many shapes and sizes, from small hills to the largest mountains on earth, and to even larger mountains on other planets. Their shapes vary from majestic cones (Fig. 1.13) to inconspicuous hills, huge, lake-filled craters with volcanic rims, and vast lava-covered plains.

In this book we accept the common understanding of what a volcano is – a mountain or hill (an edifice) that develops when molten rock reaches (or closely approaches) Earth's surface and erupts**.** But while this serves as a practical definition, it has limitations. For example, the floors of the world's oceans are dominantly underlain by lava flows, but those volcanic rocks are mostly derived from elongated fissure vents within deep sea rift valleys in ways that commonly did not allow for construction of conspicuous near-vent edifices. Vast areas of the

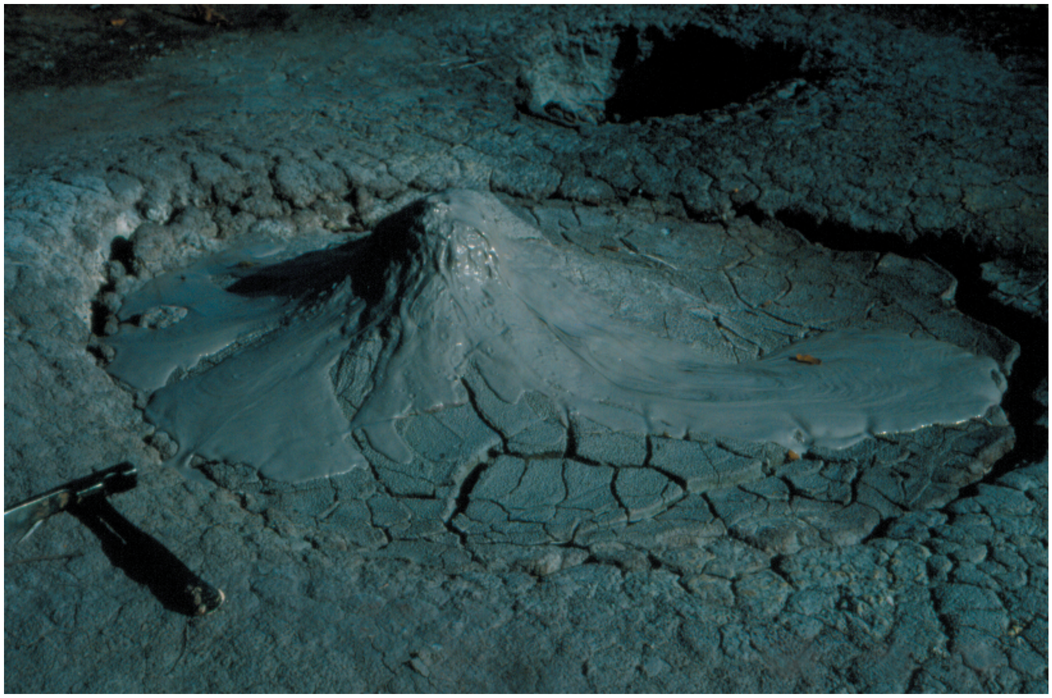

Fig. 1.14 A small "mud volcano" in the Uzon geothermal basin, Kamchatka. This one was formed by rising steam above a "mudpot"; other mud volcanoes, rising from sedimentary basins because of density contrasts, can spread out to cover vast areas. USGS photo by J. P. Lockwood.

continents are also blanketed by incredibly voluminous outpourings of lava or hardened volcanic ash that buried pre-existing topography, but resulted in no conspicuous "volcanoes" that grew above the land. In an instance like this, the "edifice" built is not a mountain or hill with a crater on top, but rather are sprawling gently sloping volcanic plains that can be related to a common source vent or cluster of vents. It might seem a stretch to call features like this volcanoes, but they are.

Some non-volcanic landforms such as the "mud volcanoes" of sedimentary basins and geothermal areas (Fig. 1.14) and the "asphalt volcanoes" found on the seafloor above salt domes are also sometimes referred to as volcanoes, and can form very large submarine edifices (e.g. Fryer et al. 2000). Although they can also impact large subaerial areas (e.g. the devastating Indonesian mud volcano "Lusi;" Davies et al. 2008), they are not true volcanoes in our sense, because they do not serve as vents for molten rock, and will not be considered here. Terrestrial volcanic eruptions mostly involve the escape of siliceous magma and gas, but other sorts of very different volcanic activity can also occur on the outer planets of the solar system, where the make-up of "rock" is quite unlike what we find on Earth (Chapter 12).

Igneous rocks result from the cooling of molten material originating inside the Earth. They are divided into two related clans: **volcanic** (or **extrusive**) and **plutonic** (or **intrusive**) rocks. Volcanic rocks are products of erupted magma, whereas the plutonic rocks are formed from magma that crystallizes underground. In general, volcanic rocks have sparse visible mineral crystals (**phenocrysts**) owing to rapid cooling of magma after eruption; whereas plutonic rocks are usually coarsely crystalline owing to slow cooling. Compositionally, most igneous rocks range from those like **basalt** typically containing low relative proportions of silica molecules (SiO_2), to those like **rhyolite** and **granite** that are silica rich. Rocks like **andesite** and **dacite** that have moderate amounts of silica are said to be **intermediate** in composition. As you will learn, silica content plays an important role in eruptive processes (Chapter 3).

Large bodies of magma underlie most volcanoes, and the terms **magma reservoirs** and **magma chambers** have been used interchangeably by many writers to describe them. Bachman and Bergantz (2008) would distinguish between the two terms on the basis of magma eruptibility. We prefer to define magma "chambers" as single bodies of fluid melt and magma "reservoirs" as the overall magmatic system underlying a volcano or volcanic center – a system that may well consist of several separate magma chambers and feeder conduits. Magma chambers may cool to form masses of coarsely crystalline intrusive rocks called **plutons**, and especially large plutons or closely spaced plutons may form extensive **batholiths** beneath volcanic belts. When exposed by later erosion, such batholiths may form majestic mountain ranges like the Sierra Nevada of California, their volcanic covers completely eroded away. Coarse-grained igneous rocks can also form at shallow depths directly beneath volcanoes. If directly related to overlying volcanoes, such rocks, whether coarse or fine-grained, are referred to as **subvolcanic** or **hypabyssal** rocks.

The passageways that supply magma from subterranean chambers to the volcanoes above are called volcanic **conduits**, and come in many shapes. When magma freezes in elongate fractures, the thin, sub-vertical tabular structures called **dikes** are formed (Chapter 4). Magma may also intrude laterally from magma chambers (or from dikes) to form the sub-horizontal structures called **sills**.

Eruptions may take place from single pipe like vents or from long fissures. The eruptions may be **explosive**, blowing out large amounts of fragmented (**pyroclastic**) debris (or "ejecta") consisting mostly of quenched magmatic lava fragments, commonly mixed with older rock material; or they may be **effusive**, erupting mainly fluid lava. Pyroclastic material is classified according to the sizes and shapes of fragments with the finest material, dust to fine sand-sized particles termed volcanic **ash**. Solidified ash beds are called **tuffs**, and **welded tuff** results where settling ash particles are so hot that they melt together. Coarser pyroclastic fragments include **lapilli**, **bombs**, and **blocks** (Chapter 7). Volcanic **breccias** are accumulations of large, blocky fragments embedded in finer, generally pyroclastic material. If the blocks are separated from one another so that they are not in mutual contact, then they are said to be "matrix supported." Otherwise they are "clast supported."

In contrast to pyroclastic debris and breccias, lava flows are classified according to their surface features. Smooth flows, as mentioned above, are called **pāhoehoe**, and rubbly ones **`a`ā**. There are also **blocky lava flows** (Chapter 6).

Eruptions resulting from the direct action of magma or magmatic gas are **magmatic** eruptions. There are various kinds of magmatic eruptions, classified according to their relative explosiveness and volcanic products, including Hawaiian, Strombolian, Vulcanian and Plinian-type activity. Eruptions generated by the heating of water external to the magma (**hydrovolcanic eruptions**) may take place either in shallow water (Surtseyan-type eruptions), or on land, where magma interacts with shallow groundwater (Chapter 7). **Phreatic** eruptions, from the Greek word for "well," are dry-land steam-blast explosions which throw out only the solid fragments of surrounding older rocks. Similar eruptions in which the material ejected is partly or wholly magmatic are termed **phreatomagmatic** eruptions. Phreatomagmatic eruptions produce **maars** – wide, low-rimmed craters commonly occupied by lakes.

Eruptions are invariably driven by the expansion of dissolved gases (**volatiles**) within the magma as it nears the surface. Some eruptions show mixed explosive and effusive characteristics, in some instances taking place simultaneously on different parts of the same volcano. The pyroclastic material accumulating from explosive eruptions may be deposited by powerful, extremely dangerous ground-hugging ash clouds called **pyroclastic density currents** (PDCs), or by material falling from above – **airfall**, or simply **fall** deposits.

Geologists recognize several distinctive types of volcanic edifices (Chapters 9–12). Those long-lived, large ones that grow from repeated eruptions through the same conduit system are referred to as **polygenetic**, while those that result from a single eruption are called **monogenetic**. Polygenetic volcanoes include **shield** volcanoes and **composite** (or "**strato**") volcanoes. Monogenetic volcanic edifices can be separate, individual volcanoes or distributed as structures at satellitic vents on the flanks of larger polygenetic volcanoes, and include **pyroclastic cones** (spatter, cinder, pumice, or ash), volcanic **domes**, and **lava shields**.

Shield volcanoes, such as those characteristic of Hawai`i and most other mid-oceanic islands, include the largest volcanoes on Earth, have very long lives, and are mostly made up of long, thin lava flows that form broad, gently sloping (generally 5–10°) shield-shaped mountains (Fig. 1.15). Many eruptions occur on the flanks of these volcanoes tens of kilometers from their summits, in some instances localized along radial fracture zones termed **rift zones**.

Composite volcanoes (Chapter 9) are the massive, steep sided (30–35°), "pointy" mountains of classical shape like Mt Fuji or Kronotsky [127] (Fig. 1.13). These volcanoes are built up over long periods of time from hundreds or thousands of eruptions. They are composed of layers of pyroclastic material, primarily volcanic ash, interbedded with lava flows.

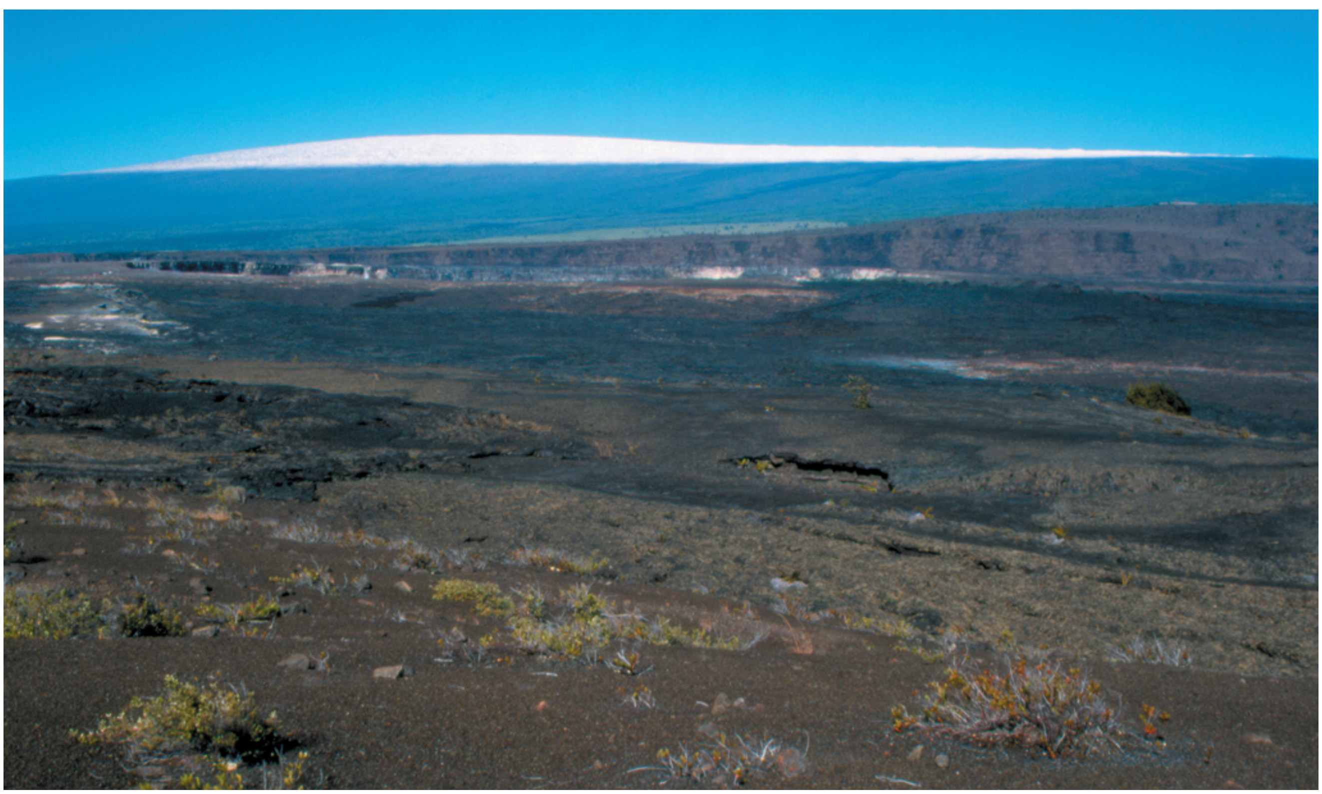

Fig. 1.15 The shield form of Mauna Loa volcano, Hawai`i – as viewed across Kīlauea caldera. Mauna Loa (4170 m) is the Earth's most voluminous volcano (> 50,000 km^3), with a base more than 5 km below sea level. The shield profile of Kīlauea volcano's summit is also evident, beyond the fuming Halema'uma'u crater. USGS photo by J. P. Lockwood.

Of the monogenetic volcano types, **cinder cones** (sometimes also called **scoria** cones) are the most common subaerial volcanoes on Earth. They are made up of a bubbly type of lapilli called cinder, and have cup-shaped craters at or near their summits. Some are horseshoe shaped and may be associated with lava flows. Cinder cones have short lives and may build up in a few days or a few decades at most. A volcanic **dome** is a jagged mound of lava that was very stiff and partly or even completely solidified as it escaped the vent. Domes may form gradually over a period of years, swelling from within and occasionally exploding or oozing out sluggish lava tongues.

In some areas, clusters of volcanoes and minor volcanic landforms exist around a central volcano called a **volcanic center**. The central volcano and surrounding edifices may share the same magma reservoir or may maintain separate conduits to their sources of melt, which in turn derive from a common source of heat. Especially large clusters of volcanoes, with or without volcanic centers, comprise **volcanic fields**.

Many volcanic centers are centered around **calderas**, large collapse craters generally many kilometers in diameter formed from the sudden withdrawal of magma and gases from a shallow underlying magma chamber (Chapter 10). The largest and structurally most complex calderas occur in continental settings. Much simpler and generally smaller ones occur on mid-oceanic islands.

There you have it – a starter potpourri of terms. Now let's learn about the history of volcanology.

History of Volcanology

THE AGES OF SUPERSTITION

火 山

[Japanese kanji: "Fire Mountain"]

Among all creatures subject to volcanic eruptions, human beings are unique in that they feel compelled to understand the reason why "fire" should come from the Earth. The earliest explanations of these fearsome "fire mountains" were given in religious terms based on superstition, and usually invoked the actions of subsurface gods who were either displeased with the terrestrial world or were fighting among themselves. Many of these legends are well described in books by Sigurdsson (1999) and Vitaliano (1973), but conversations with long-time residents of any volcanic area will reveal other unrecorded legends that are still being passed down by story-telling.

The knowledge of traditional peoples living near volcanoes should not be underestimated. Their stories are worth listening to, for no matter how embellished they may be by "poetic license" of generations of story-tellers, "grains of truth" from which the legends have sprung are found in most of these stories. Although traditional peoples did not have modern tools or knowledge, their stories of past eruptions are mostly based on actual observations, and attempts to reconcile these human accounts with modern volcanic knowledge can be a most fruitful source of information for volcanologists interested in understanding "prehistoric eruptions." As examples, I (JPL) was fascinated to find that native peoples in the Virunga volcanic belt (eastern Congo and Rwanda) knew very well which volcanoes had been active in pre-written history because they distinguished between "female" and "male" volcanoes. The lady volcanoes were those that had "emitted blood" (i.e. lava) in times past, whereas the male volcanoes were the ancient ones that had not erupted for a very long time. Their accounts matched scientific observations very well.

A Navajo woman in Grants, New Mexico once told me a story to explain a long, narrow pāhoehoe flow (the McCartys flow) that extends more than 50 km between Gallup and Albuquerque. The woman apologized before sharing the legend saying, "Of course you won't believe this – this is just old superstition," and then recited a detailed tale about a battle between an evil giant and young brave: "When the giant (Ye'litsoh) was felled by a stone from the young man's sling, he fell to the earth and made the ground shake all over. The giant's blood poured forth as a red torrent that flowed like a river across the land. When the red blood dried it turned black – you can see this dried-blood river today." This eruption (the youngest in New Mexico) took place over 3,000 years ago – yet the events (earthquakes and eruption) that people witnessed are still vividly documented through story-telling – a testimony to the power of oral tradition.

Seismic activity almost always precedes volcanic eruptions, and is commonly described in legendary accounts. Another example comes from Hawai`i, where "prehistoric" time conventionally refers to the period before European written accounts. Although there are many credible legends about pre-European eruptions of Kīlauea volcano, none had been known about prehistoric Mauna Loa [13] eruptions, until I came across a previously overlooked story dealing with the origin of some littoral cones ("Na Pu'u O Pele") along the southwest coast of Hawai`i Island. Westervelt (1963) recounted a tale he had been told by an old Hawaiian man about the origin of these cones, a story of Pele's ire after she had been jilted by two chiefs who had spurned her romantic advances. In the story, Pele was so mad at the chiefs that she had "caused the earth to shake by stomping her feet on the ground in anger" before sending two lava flows to the sea, trapping the chiefs between them and turning them into the cones. Later mapping showed that two separate flows had indeed been erupted at this time and that the "legend" was an accurate description of the sequence of events that formed the two cones. This eruption was radiocarbon dated at 300 BP, showing that Mauna Loa's humanly recorded history began long before Hawai`i was "discovered" by Captain Cook! Hawaiians understood basic volcano processes very well – long before Westerners came for formal study. They knew that their chain of island-volcanoes is younger to the southeast, and interpreted this as evidence for the migration of Pele from west to east over time. They also knew that magma was stored beneath the summit of Kīlauea Volcano, and that this magma (i.e. Pele in their oral traditions) could travel along subterranean pathways to erupt on Kīlauea's lower flanks.

The Bible is also a source of possible volcano legends. The Old Testament (Genesis 19: 24–26) speaks of a possible volcanic eruption in the Israel–Jordon region (Chapter 13), and a "pillar of fire" is mentioned in Exodus 13:21–22 – could this also be an eruption reference? Geologic studies indicate that the volcanoes of these areas near the Dead Sea erupted long before the time of biblical stories, but perhaps the writers of these words had known about volcanic activity that did occur nearby in Old Testament times – on the Arabian Peninsula and in the Red Sea? Another volcano figures in the account of Genesis 8.5: "On the seventeenth day of the seventh month after The Flood, Noah's arc landed on Mount Ararat . . . [a dormant

Fig. 1.16 Mount Ararat, a dormant volcano in northeastern Turkey, viewed from the north in Armenia. This is the volcano where Noah's arc is reported to have landed after The Flood (photographer unknown).

5165 m volcano (Fig. 1.16)]." On the first day of the tenth month after The Flood the top of a nearby, younger volcano appeared above the receding waters (see Fig. 1.16), but probably Noah did not appreciate the volcanological significance of his historic expedition! Some eruptions may be the source of legends that have lost their volcanic affinities, such as the possible volcanic destruction of the "Lost Continent of Atlantis" (Chapter 13).

As classical Greek civilization spread across the Mediterranean 2500 years ago, a panopoly of gods were devised to explain the natural world. **Hephaestus** (εφέατσος) was the son of the all-powerful god Zeus, but had been thrown down from heaven by his father after an argument and was condemned to spend his days on (and within) the Earth. He was badly injured on landing, and although lame and ugly (Fig. 1.17), he was a gentle god and became responsible for all artisans, including weavers, sculptors, and blacksmiths. To forge metal, he sought fire in the Earth and was henceforth associated with active volcanoes of the Mediterranean. When the Roman Empire vanquished Greek civilization 2200 years ago, they accepted many of the Greek gods as their own, but gave them different assignments to suit their imperial needs. They renamed

Fig. 1.17 Hephaestus, Greek god of blacksmiths and other artisans, later named Vulcan by the Romans. Sculpture by R. Spada. Photo J. P. Lockwood.

Fig. 1.18 Vulcan, the Roman god of volcanoes and blacksmiths, as depicted by a 17 m-high statue in Montgomery, Alabama, where it looms above Vulcan Park, in honor of Birmingham's steel industry. This is the world's largest cast iron statue, and is much larger than any Vulcan statues found in Italy. Photo by M. L. Kennedy, courtesy of Vulcan Park Foundation.

Hephaestus *Vulcan* (Fig. 1.18) and his duties were focused only on the forging of metal; he became responsible for manufacturing swords and armor. His principal forge was beneath the active island-volcano north of Sicily named Vulcano which has lent its name as a descriptive term to all other volcanoes of the Earth and to the science of volcanology. Roman philosophers made many important speculations about the origins of volcanoes (Macdonald 1972), but the decay and fall of the Roman Empire marked the end of an interest in natural explanations for natural phenomena. The Western world then plunged into a dark millennium where only religious dogmas were allowed to flourish. Active volcanoes were considered to be gateways to Hell and were thus to be avoided!

THE AGE OF ENLIGHTENMENT

Around 600 years ago, as the Renaissance dawned, men began to seek more logical natural phenomena to explain volcanic activity, but encountered stiff opposition from conservative authorities who preferred religious interpretations. Non-believers in prevailing dogma could be condemned to death for heresy. Early alchemists (who spent most of their efforts attempting to transform materials into gold) attributed volcanoes to pent-up gases ignited by burning coal, sulfur, or oil, to electricity, or to frictional heating of air blowing through confined passages. Because of their inability to travel or to explore, they never made field observations. While their ideas might seem strange to us today, these experimenters were courageous to look beyond the supernatural in seeking explanations for natural phenomena, and they paved the way for the Age of Science that was about to unfold. By the mid eighteenth century, academic discussion began to focus on an explanation that volcanoes are the products of erupted molten material formed deep inside the Earth. At that time, French geologists, notably Jean-Etienne Guettard (1715–86) and Barthelemy Faujas de Saint-Fond (1741–1819) recognized the volcanic origin of various cones and craters in the Clermont-Ferrand region of south-central France. They recognized the existence of former volcanoes in a landscape, and came to epitomize the *School of Volcanists* – those who believed that volcanic activity had been more common in the world than people imagined.

Abraham Gottlob Werner (1749–1817), a German professor of mineralogy from the School of Mines in Freiburg, developed a competing **geognosic theory** of geology, based on biblical interpretation that was widely embraced by the religiously conservative "establishment" of the day. He posited that the earth had cooled solid long ago (forming granites and metamorphic rocks), but had later been covered by a primitive, global, ocean from which all stratified rocks and minerals making up the crust (including lava flows) precipitated. Fossils in some strata, though absent in lava flows, were good evidence of marine origin. Volcanoes were merely anomalies, associated with burning coal deposits. There were, Werner pointed out, extinct volcanoes in the Bohemian coal fields – evidence that burning coal had produced them. A powerful public speaker who held his post for 40 years, Professor Werner did not travel more than a few tens of kilometers from his home town and so, like most of his predecessors, was hampered by lacking solid physical evidence for his hypotheses. But his logic, though misplaced, was internally consistent, and he was very persuasive. His theory fit in well with religious belief in a Great Flood, and Werner's perspectives became known as the **Neptunist** School. Meanwhile, resulting from these observations, an epic controversy arose between Werner's Neptunists and many of the leading scientists of the day. Even the great German poet Goethe (an accomplished naturalist in his own right, who had climbed Vesuvius [79] and observed erupting lava during a spectacular eruption in 1787) questioned the popular conclusions of Werner (see the epigraph for Chapter 3).

The leading opponent of Werner's theories was James Hutton (1726–97), an influential Scottish geologist with great field experience, who had seen undeniable proof that many igneous rocks had been intruded into sedimentary rocks from below – an impossibility if the layered rocks were younger. Hutton and his fellow disbelievers were called **Plutonists**, and were much disparaged by their opponents. Hutton was honest about the limits of his knowledge, and respected the limits of what is knowable, unlike some of his scientific predecessors. In 1788 he wrote: "Our knowledge is extremely limited with regard to the effects of heat in bodies, while acting under different conditions, and in various degrees." He knew that molten rock is active in earth's crust but did not pretend to know why. It would take nearly two centuries and much additional scientific controversy before answers emerged, thanks to the development of new geophysical techniques for examining the earth's interior and to the discovery of plate tectonics in the 1960s (Chapter 2).

One of Werner's influential students was Leopold von Buch (1774–1853). Although originally a staunch Neptunist, he traveled extensively and made observations of volcanoes and lava flows in Italy and France that seemed to have no relation to the presence of coal beds required by Werner as a causative agent for volcanism. His further observations of lava flows in the Canary Islands in 1815 showed that they were too obviously related to volcanoes and not to sedimentary processes, and he finally broke with his professor and became an avid supporter of the Plutonist school. Unfortunately, he went too far and began to posit that the intrusion of molten material from below caused the *uplift* of many volcanoes and even mountain ranges like the Alps! He developed a widely accepted "Craters of Elevation" theory which sought to explain the inclined lava flows around volcanoes as evidence that volcanic landforms were caused by internal magmatic intrusions that uplifted and deformed originally flat-lying lava flows.

THE EMERGENCE OF MODERN VOLCANOLOGY

> *Volcanic action exhibits itself chiefly in the eruption or exhalation of heated matter in a solid, semi-liquid, or gaseous state, from openings in the superficial rocks that compose the crust of the globe. (Scrope 1862)*

Fig. 1.19 George Poulett Scrope. Photo © Natural History Museum, London.

The modern science of volcanology began to develop in the early nineteenth century, after the fundamentals of geology had been established by geologists of the preceding century. The first scientist to devote most of his life to the study of volcanic activity was George Poulett Scrope (1797–1876) (Fig. 1.19). Scrope was a cosmopolitan, well-educated gentleman who made contributions to many fields in addition to volcanology; he is also known for his writings in economics and for his pioneering social work. He studied at both Oxford and Cambridge, there under the pioneer geologist Adam Sedgwick. He was a friend of Charles Lyell, and like Lyell realized the critical importance of fieldwork. He was fascinated by active volcanism and spent his early years observing the active volcanoes of Italy, carefully observing eruptive activity at Stromboli [83] and Etna [82] and studying the eruptive products of Vesuvius and the Phlegraen fields. In later years he went on to study older volcanoes near Rome and the extinct volcanic fields of France and Germany. Although born George Julius Thomson, he married the wealthy heiress Emma Phipps Scrope in 1821, changed his last name, and was elected to Parliament where he worked tirelessly to improve the welfare of England's poor. While still a young man in 1826 he published the first-ever modern textbook in volcanology, entitled *VOLCANOES – The Character of their Phenomena, their Share in the Structure and Composition of the Surface of the Globe, and their Relation to its Internal Forces: with a Descriptive Catalogue of all known Volcanoes and Volcanic Formations* (Scrope 1862). Scrope made many important observations, including a recognition of the role of water (steam) as the driving force of explosive eruptions. He also became a partisan in the raging debate over von Buch's "craters of elevation" theory, using his wealth of field studies to refute von Buch's ideas. Scrope and his contemporary Charles Lyell together proved the essential role of careful field studies, and paved the way for the major advances in volcanology that were about to occur as a new generation of geologists began systematic exploration of active volcanoes around the world.

Fig. 1.20 James D. Dana, "America's first volcanologist." Dana devoted his life to the study of volcanoes and mineralogy, and was editor of the *American Journal of Science*. Lithograph by Rudolph Hoffmann – after photo by Matthew Brady, Courtsey of Yale University Library.

James D. Dana (1813–95) (Fig. 1.20) studied under Benjamin Silliman at Yale, traveled to the Mediterranean after graduation, witnessed an eruption of Vesuvius, and had already authored his classic *System of Mineralogy* when he was selected (at age 25) to join the US Exploring Expedition, the "Wilkes Expedition," for a four-year scientific exploration of the Pacific Ocean. This four-year voyage gave Dana a global perspective of volcanology, and enabled him to recognize the evolution of young volcanic islands through old age and eventual submergence beneath atolls. During Dana's month-long stay in the Hawaiian Islands in 1840–1, he saw Kīlauea in eruption and met the "missionary volcanologist" Titus Coan (Chapter 5). This friendship was to prove seminal in fostering his life-long interest in volcanology. Returning to Yale University to teach, he married Benjamin Silliman's daughter Henrietta, later became Chairman of the Department of Geology and Editor of the influential *American Journal of Science*, where he ensured that many classic volcano studies were published. After publication of his classic *Characteristics of Volcanoes* in 1890, Dana became generally regarded as America's first volcanologist.

Fig. 1.21 Ruins of St Pierre, Martinique, after the devastating eruption of Mount Pelée in 1902. Photo by C. D. Arnold, courtesy of US Library of Congress.

An important development was about to revolutionize volcanology – the development of a worldwide telegraph system in the last half of the nineteenth century. The telegraph made it possible for news of volcanic eruptions in far-away places to reach scientists in near real time and for expeditions to be mounted to investigate major eruptions. The cataclysmic 1883 eruption of Krakatau volcano was reported around the world almost before the tsunami waves had receded, and major international expeditions were soon mounted to begin investigations of the tragedy. The report of the Dutch expedition to their colony (Verbeek 1895) was the most comprehensive documentation of a major volcanic eruption that had ever been prepared. The contrast between the reporting of the Krakatau eruption with the lack of documentation of previous major devastating eruptions (e.g. Asama – 1783 or Tambora – 1815) is revealing. Before the Age of Communications began less than 200 years ago, news of major eruptions never reached the scientific community.

Mt Pelée [63] rose with apparent innocence above the island of Martinique in the southeastern Caribbean in 1902. Although the mountain had been "smoking" for a long time, and earthquakes had been shaking the island for months, residents of the important city of St Pierre did not realize that Mt Pelée was a dangerous volcano about to erupt. When the volcano did erupt violently on May 8, 1902, almost 30,000 people lost their lives (Fig. 1.21). The entire world was shocked by the tragic loss of life, and scientific commissions flocked to Martinique to investigate the tragedy. The Mt Pelée eruption was one of three large eruptions around the margins of the Caribbean in 1902 (devastating eruptions also occurred that year at La Soufrière-St Vincent[1] [62] and Santa Maria [46] volcanoes), and was soon followed by another devastating eruption of Vesuvius volcano in 1906. These eruptions at the dawn of the twentieth century focused the world's attention on volcanic activity, had a major impact on the development of volcanology, and would change the careers of three people who were not volcanologists at the time. These three men, Lacroix, Jaggar, and Perret, had never considered the study of volcanoes particularly important before 1902, but would go on to make major contributions to volcanology as they bridged the gap between two centuries.

François Alfred Lacroix, (1863–1948) (Fig. 1.22) was a well-known French mineralogist who had never studied volcanoes before he was sent to Martinique after the 1902 disaster.

[1] There are two volcanoes named "La Soufrière" in the Lesser Antilles – this one, more specifically referred to as "La Soufrière-St Vincent," and another 300 km to the north on the island of Guadeloupe.

Fig. 1.22 Alfred Lacroix (second from left) inspecting pyroclastic flow deposits above St Pierre, Martinique after the 1902 Mt Pelée disaster. It was here that Lacroix coined the term "nues ardentes" to describe the PDCs that form such deposits. Photo from the Krafft Archives.

He spent a year on the island, conducted critical interviews of eye-witnesses, and published the most detailed reconstruction of the events that preceded and accompanied the eruption. He was the first to recognize the nature of the deadly flowing clouds of hot gas and rock that he named "*nues ardentes*," an internationally used term equivalent to "pyroclastic flows". He founded the Observatoire Volcanologique de la Montagne Pelée and went on to study the major eruption of Vesuvius in 1906. Although mainly known for his contributions to mineralogy, he continued to advise the French Government about volcanic crises for the rest of his life. His meeting with Thomas Jaggar in the ruins of St Pierre was doubtless a factor in the evolution of Jaggar's career.

Thomas A. Jaggar (1871–1953) (Fig. 1.23) was a young Harvard geology professor in 1902 and had made important studies of many geologic processes – but had never seen a volcano. Following the tragic eruption of Mt Pelée in 1902 he was dispatched on an emergency mission to Martinique by the US Government. Although he only spent a few weeks there, the experience of walking among the ruins of St Pierre and viewing the corpses of thousands of victims still lying in the ruins completely changed his life. As he wrote in his biography (1956):

> *As I look back on the Martinique expedition, I know what a crucial point in my life it was and that it was the human contacts, not field adventures, which inspired me. Gradually I realized that the killing of thousands of persons by subterranean machinery totally unknown to geologists and then unexplainable was worthy of a life work.*

His career did indeed change and the rest of his life was devoted to the study of volcanoes. He made several volcano expeditions in the next few years: to Vesuvius (1906), to the

Aleutian volcanoes (1907), to Hawai`i and Japan (1909), and to Costa Rica (1910) in order to gain understanding of volcanic activity and hazards. His 1906 trip to Italy was especially important as he there met Frank Perret (see below) and Tempest Anderson (who had described the 1902 La Soufrière eruption), and again worked with Lacroix. He also learned about the important work of the historic Osservatorio Vesuviano, founded in 1841 (see Chapter 16). These expeditions convinced Jaggar that *expeditionary* volcanology (mostly after disasters) could never be successful for understanding the *processes* of volcanism. Without an understanding of volcanic processes, there was no possibility of ever *predicting* eruptions, and prediction had to be the primary goal of what he termed "*Humanistic Geology*." He made fervent public appeals for the establishment of permanent observatories to continuously monitor volcanoes and seismic regions.

Fig. 1.23 Thomas A. Jaggar, founder of the Hawaiian Volcano Observatory, in 1928 alongside a prototype of the amphibious landing craft he invented. USGS photo from Hawaiian Volcano Observatory Archives.

After the 1906 San Francisco earthquake disaster he succeeded in urging the Geological Society of America to pass a resolution calling on "Governments and private enterprise to establish volcano and earthquake observatories"; and, in a widely-read article in *The Nation* (1909), he decried the preoccupation of geologists with studies only of the past ("the bones of Jurassic reptiles, and in finding out all about iron and coal") and urged young men to devote their lives to "humane rather than historical" science. After his visit to Kīlauea volcano in 1909, he resolved to found a permanent volcano observatory there, and spent the next three years raising funds to accomplish his goal. He took "leave of absence" from MIT in 1912, left his family behind, and moved to Kīlauea to found the Hawaiian Volcano Observatory (HVO). He never returned to MIT (nor to his first family), and the rest of his life was devoted to assuring that the HVO record of volcano observation would be unbroken. He was a prolific writer on many subjects besides volcanology, an avid inventor of new devices for volcano monitoring, and an eloquent spokesman for his "humanistic" beliefs. He was *not* a very good observer, however, and his descriptions of Hawaiian volcanic eruptions are so entwined with his interpretations that they are of limited value today. As Gordon Macdonald told me (JPL) in frustration one day, "Jaggar always thought like a promoter, not like a geologist – he never made a map to let us know what happened!"

Frank A. Perret (1867–1940) also was touched (more indirectly) by the Mt Pelée disaster and subsequently became one of the most fascinating of the early twentieth-century volcanologists. Perret never finished college, nor had formal training in geology, yet his contributions to volcanology in the form of his lucid descriptions of explosive volcanic activity are timeless. Perret was self-educated as an electrical engineer, worked directly with Thomas Edison, and later founded his own company in New York to manufacture electric motors and batteries. When word of the 1902 Mt Pelée disaster arrived in New York, his only previous awareness of volcanism was associated with his viewing the "amazing sunsets" associated with the 1883 eruption of Krakatau as a young man. His health began to fail in 1902, however, and while on a recuperation visit to the Caribbean, he stopped by Martinique to visit the ruins of St Pierre. Like Jaggar and Lacroix before him, Perret's life was forever changed by the destruction wrought by Mont Pelée, and he devoted to rest of his life to the study of volcanoes.

To learn about active volcanism, he abandoned his business, traveled to Italy in 1904, and apprenticed himself to R. V. Matteucci, Director of the Vesuvius Volcano Observatory. He lived in Naples for 20 years, witnessed the devastating 1906 eruption of Vesuvius, and wrote a classic description of the eruption and its effects (Perret 1924). He later became affiliated with the Carnegie Institution in Washington, DC, where all of his volcano studies were published. Although plagued by ill health, he traveled widely to active volcanoes of the world, and his frail, dapper figure, well-dressed with Van Dyke beard and straw hat (Fig. 1.24) became a well-known sight during volcanic eruptions. He traveled to Hawai`i with R. A. Daly and Thomas Jaggar in 1909, made some of the first ever quantitative measurements of molten lava temperatures, and was one of the first people to recognize the importance of explosive activity in Kīlauea's past. When Mt Pelée returned to activity in 1929, Perret returned to Martinique the following year to observe the activity and advise local residents about future activity. He lived in a shack high on the flanks of the volcano to better observe the activity, and was nearly killed by a nuee ardente in 1930. His nonchalant eye-witness accounts of this activity (see Chapter 7) make for some of the most exciting reading in the annals of volcanology.

Fig. 1.24 F. A. Perret with an improvised "seismometer," listening to subterranean noises at the Campi Flegrei, Italy. Photo from the US Library of Congress.

Active volcanoes are found throughout the world, and it is no surprise that the major volcanologists of the twentieth century have come from countries facing the greatest eruptive perils.

Alfred Rittman (1893–1980) (Fig. 1.25) was born in Basel, Switzerland, and there met the wealthy Swiss banker Immanuel Friedlander, a widely traveled amateur volcanologist who published the influential journal *Zeitschrift für Vulkanologie* (1914–36), and privately founded the Institute of Volcanology based in Naples. Rittman was named the Director of Friedlander's institute, and there pioneered the use of petrographic, geochemical, and geophysical methods to better understand volcanic processes; his studies of the magmatic evolution of Vesuvius and Etna were major contributions to the foundations of volcanology. When Friedlander's institute closed on the eve of World War II, Rittman was offered a university position in Germany, but refused the appointment as he did not wish to associate with the Nazi Party. He taught for a while in Egypt, and later became Director of the Institute of Volcanology in Catania. His influential textbook *Volcanoes and their Activity* (1962) remains in use today. The English language reference cited here is a translation of the original *Vulkane und ihre Tätigkeit* (1936), which was also translated into French and Italian. His system for "Eruption diagrams" (see Chapter 5) is an excellent, but largely overlooked, graphical means to portray the nature of individual eruptions. He was one of the longest serving Presidents of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) from 1954 to 1963.

Fig. 1.25 Alfred Rittmann (1893–1980), pioneering Swiss volcano-petrologist who spent most of his life studying the magmatic evolution of Vesuvius and Etna. Photo by G. A.Macdonald.

There are more than 30 active volcanoes in Russia, all part of the Pacific "Rim of Fire" extending from Kamchatka down the Kuril Islands. The Soviet Union produced many great volcanologists in the twentieth century to study these volcanoes, but because most of their publications are in Russian, and because Cold War complexities made travel for Soviet scientists and international exchanges difficult, not much has been known about their work. Georgii S. Gorshkov (1921–75) (Fig. 1.26) was able to travel widely and became well known in the west. He began his volcanological studies with extensive field work along the length of the Kuril Islands, and then began to study the numerous active volcanoes of Kamchatka. Gorshkov was primarily a volcano seismologist, and pioneered the study of *teleseisms* (earthquake waves generated by distant earthquakes) to define the geometries of magma chambers underlying closer volcanoes. He documented the 1956 eruption of Bezymyannii volcano [128] (Gorshkov 1959), a volcano whose pre-eruptive behavior closely mimicked the pre-eruptive behavior of Mount St Helens as that volcano approached its 1980 eruption. Unfortunately, volcanologists in Washington did not appreciate the similarity in eruptive style, and did not realize that the catastrophic eruption that was about to occur on May 18 was almost an exact duplicate of the catastrophic eruption precursors that Gorshkov described at Bezymyannii.

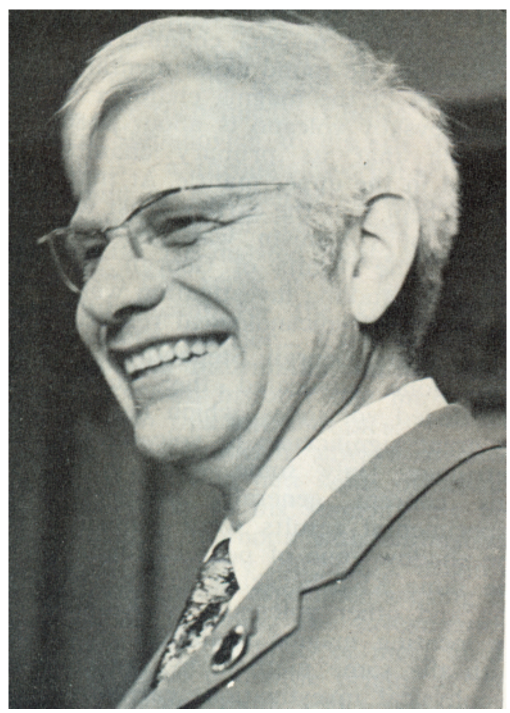

Fig. 1.26 Georgii S. Gorshkov, pioneering Soviet volcanologist. Photographer unknown.

Fig. 1.27 Professor Takeshi Minakami, the founder of modern Japanese volcanology and leading volcano seismologist. Photo courtesy of Shigeo Aramaki.

Japan is one of the most volcanically active areas on Earth, and has more than 40 on-land volcanoes that have erupted in historical time – almost 70 if one counts minor islands and submarine volcanoes in its territory. From a public safety standpoint, however, earthquakes have been a more serious threat to human life and property, and Japanese earth science was traditionally focused on the field of seismology. When Thomas Jaggar founded the HVO, he turned to Japan for expertise, and HVO's original seismometers were designed by Fusakichi Omori (1868–1923), the pioneering Japanese seismologist whom Jaggar had met in 1909. Omori gave Jaggar one of his seismographs and plans for a seismic vault, and HVO's Whitney Seismological Laboratory was constructed in accordance with these plans. Volcanology itself was not an important focus of Japanese science, however, until Takeshi Minakami (1910–83) (Fig. 1.27) was assigned to the Asayama Physics Research Laboratory on the slopes of Asama volcano [112] northwest of Tokyo in 1934. Minakami had trained as a seismologist at Omori's Imperial University, but at Asama his interests in volcanology blossomed, and he can rightfully be called the "Father of Japanese Volcanology." Asama was extremely active while Minakami was there, and with great effort (he needed to carry heavy batteries upslope to his laboratory for several years as there was no electrical service) he pioneered the field of volcano seismology. He recognized two different classes of volcanic earthquakes, and analyzing them allowed him to successfully forecast several eruptions. His "Minakami Classification" of type "A" (deep, sharp) and type "B" (shallow, long-period) volcanic earthquakes is now used worldwide to recognize the ascent of magma within volcanoes. Minakami's visit to Indonesia before World War II was critical to enabling Indonesian volcano observatories to function during the war years under military occupation. His many students and junior associates have gone on to make Japan one of the world's leading centers for volcano research. A historic visit of Minakami and his associates to HVO in 1963 for cooperative research studies set the stage for the close cooperation between Japanese and American volcanologists that continues today.

There are many recently deceased "pioneers" in volcanology whose contributions we should perhaps honor, but that list is long, and we must be getting on with the rest of this book. Suffice it to say that most of today's volcanologists owe their careers to the influence of great teachers who have passed away in recent years. These teachers include giants like Robert Decker, Peter Francis, Dick Stoiber, and George Walker – dear friends and incredibly productive volcanologists whose contributions to our science and to hundreds of their students are immense and long-lasting.

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Chapter 1

Questions for Thought, Study, and Discussion

1 Outline the major differences between the eruptions of "red" and "grey" volcanoes. Why are these volcanoes designated with these colors?

2 Contrast the hazards of doing volcanological field work at Kīlauea and Galunggung volcanoes. Do you think it would be any easier to have a serious accident studying one volcano or the other? Explain your answer.

3 Why is the definition of a volcano simply as a "mountain or large hill that erupts" inadequate?

4 Would you define "volcano" any differently than we have? Why, or why not?

5 What are the two largest kinds of volcanoes, and how would you recognize each? What are three smaller kinds of volcanoes, and how are they distinguished?

6 A steep-sided volcano consisting of many layers of hardened lava alternating with beds of cinder suddenly rips open with a sluggish flow of molten rock pouring out of a crack extending down its flank. No ejecta are disgorged and volatile release is minor. (a) What kind of volcano is this? (b) What kind of vent opened up? (c) What kind of eruption is this?

7 Eruptions of highly fluid lava with very little associated pyroclastic material create what kinds of volcanic features?

8 Contrast the Neptunist and Plutonist schools of thought. What evidence finally allowed the Plutonists to overcome the Neptunists?

9 There are admirable goals and benefits to both "pure" volcanological research focused on the expansion of human knowledge, and to "applied" volcanology focused on the immediate social and economic needs of society. What is the proper balance between these two end uses of volcanology? What balance would *you* hope to strike if you pursue a career in volcanology?