

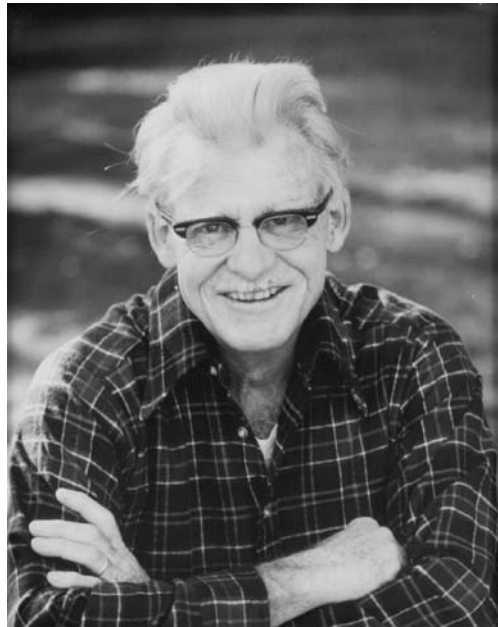
# VOLCANOES



# VOLCANOES

## DEDICATION

*We dedicate this book to Gordon A. Macdonald (1911–78), a great volcanologist, teacher, and dear friend, who wrote an excellent textbook (Volcanoes – 1972) that served as the progenitor of this work, and also to the memory of all volcanologists who, motivated by concerns for their fellow human beings and by their desires to understand volcanoes better, came “too close to the flames,” and paid the ultimate price.*



*Rob Cook, Elias Ravian*

*David Johnston*

*Salvador Soto Piñeda*

*Alevtina Bylinkina, Andrei Ivanov, Yurii Skuridin, Igor Loginov*

*Alexander Umnov*

*Maurice & Katia Krafft, Harry Glicken*

*Victor Perez, Alvaro Sanchez*

*Geoff Brown, Fernando Cuenca, Nestor Garcia, Igor Menyailov, Jose Zapata*

*Asep Wildan, Mukti*

Karkar, 1979

Mount St. Helens, 1980

El Chichón, 1982

Kluhevskoi, 1951–1986

Karymsky, 1986

Unzen, 1991

Guagua Pichincha, 1993

Galeras, 1993

Semeru, 2000

# VOLCANOES

*Global Perspectives*

**John P. Lockwood** and **Richard W. Hazlett**

**WILEY** Blackwell

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111 River Street, Hoboken, NJ 07030-5774, USA

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# Preface

This book has a long history. It was originally conceived as a revision of Gordon Macdonald's classic book *Volcanoes* (Prentice-Hall, 1972), following his too-early passing in 1978. We had both worked with Macdonald, who friends called "Mac," and wanted to see his plans for a second edition of *Volcanoes* fulfilled. Originally John "Jack" Lockwood (JPL) planned a simple updating of Mac's text, and Richard "Rick" Hazlett (RWH) planned to contribute artwork to make a more attractive new edition. We quickly found that a simple updating of the original *Volcanoes* would not be sufficient, however, as much of Macdonald's writing reflected the uncertainties of his time, which meant a major revision would be needed. Over the years, under the guidance of several Prentice-Hall editors, the focus of our book changed; less and less of Mac's original writing remained, and a decision was eventually made by Prentice-Hall to abandon preparation of a second edition. Arrangements were then made for publication of this book by Wiley-Blackwell Publishing. Although Gordon Macdonald no longer is formally listed as a co-author of this book, his legacy of volcanic knowledge was heavily relied upon, and some of his original words remain in this text (with the permission of Prentice-Hall and Mac's family).

Rick joined the project as co-author in 1993. His long experience in teaching volcanology to students at universities in Hawai'i and California adds invaluable academic perspectives to this book.

When Gordon Macdonald wrote *Volcanoes* in 1970, the science of volcanology was poised at the threshold of a new era of discovery and understanding, but that threshold had not yet been crossed. In his influential 1972 book, Mac wrote that "Comparatively little progress has been made in understanding the fundamental processes of volcanic activity." How true those words were in 1970, but how untrue now! In the decades since the 1972 edition of *Volcanoes*, people have undoubtedly learned more about the causes and nature of volcanism than in all previous time: Inclusion of this new knowledge and placing it in a global framework has been the foremost challenge before us.

Revolutionary new tools and techniques have also been developed since Macdonald wrote the original *Volcanoes*. Our knowledge of volcanism at that time was almost entirely based on observations of subaerial volcanoes, since those were the only ones readily available for study. Manned deep submersible vehicles, originally used mostly for biological observations, have subsequently become available as "field tools," and have increasingly been deployed for direct observations of submarine volcanoes and volcanic terrain on the floors of the world's oceans. These observations, along with new side-scan sonar imaging techniques, Remotely Operated Vehicles (ROVs) and extensive research drilling of the oceanic crust, have at least quadrupled the numbers of known volcanoes around the world. Exploration of the Solar System over these years has now revealed that volcanoes are actually commonplace extraterrestrial features. Volcanic eruptions have taken place on the Moon, Mars and Venus, and active volcanoes (of a sort very different than those of Earth) have been observed on the moons of Saturn, Jupiter and Uranus.

The eruption of Mount St Helens in 1980 had a major impact on volcanology. Not only was this complex eruption one of the best documented in history, but it also served to change the perceptions of millions of North Americans, who learned that they too had active volcanoes in their backyard – just like the volcanologists had been saying all along! This eruption provided examples of numerous volcanic

processes that had been poorly understood and never observed in detail before; illustrations from Mount St Helens are used liberally throughout this new edition. Four other major volcanic eruptions followed (or began) over the next 15 years, and were also well studied by volcanologists before, during, and after their principal activity – the long-lived East Rift zone eruption of Kīlauea that began in 1983, the Mauna Loa eruption of 1984, the Mt Pinatubo eruption of 1991, and the ongoing eruption of Soufrière Hills volcano, Montserrat – which began in 1995. Each of these five eruptions was very different from one another, and each provided important new information about “how volcanoes work” – information that we have relied on extensively.

While writing this book, we have carried on Macdonald’s emphasis on descriptive rather than “interpretive” aspects of volcanology, although the processes that form volcanic features are also described where understood. In some sections we touch upon more theoretical aspects of contemporary volcanology, but only to provide an idea of some approaches that can be taken rather than to provide comprehensive treatments. Our bibliography points the way forward for those who are more deeply interested in theory. We have also unashamedly tried to emphasize “applied” aspects of volcanology where appropriate. The applied interfaces between volcanic activity, global ecology, and human society are summarized in Part V: “Humanistic Volcanology.” That term was coined by Thomas Jaggar, founder of the Hawaiian Volcano Observatory, and was used by Gordon Macdonald in his writings. We have strived to continue this “humanistic” focus in our book, and are carrying on the chain of human contacts that lead from Jaggar to Macdonald, and now to us and to this book.

We are grateful to many colleagues who shared important insights and knowledge of subjects they know far more about than we do. Many of our colleagues have reviewed parts of the manuscript at various times and shared their ideas and constructive criticisms over the years, including Steve Anderson, Oliver Bachmann, Charley Bacon, Steve Bergman, Greg Beroza, Kathy Cashman, Ashley Davies, Pierre Delmelle, Dan Dzurisin, John Eichelberger, Bill Evans, Tim Flood, Patricia Fryer, Darren Gravley, Michael Hamburger, Ken Hon, Tony Irving, Caryl Johnson, Steve Kuehn, Ian Macmillan, Mike Manga, Doug McKeever, Calvin Miller, John Mahoney, Chris Newhall, Harry Pinkerton, Karl Roa, Mike Ryan, Hazel Rymer, Tim Scheffler, Steve Self, Phil Shane, Ian Smith, Jeff Sutton, Carl Thorner, Bob Tilling, Frank Trusdell, and Colin Wilson. Having had so many well-qualified geologists comment on parts of this book has caused a minor problem: we’ve found that there is no universal agreement as to what should be included, and it is clear that no single book will “make everyone happy.” We have learned from each of these reviewers, and have humbly tried to accommodate their oft-conflicting suggestions as best we could. Many other colleagues have contributed photographs for this book, or provided insights from their own expertise. These include Mike Abrahms, Shigeo Aramaki, Tom Casadevall, Bill Chadwick, Yurii Demyanchuk, Bill Evans, Dan Fornari, Brent Garry, Magnus Gudmundsson, Cathy Hickson, Rick Hobblit, Caryl Johnson, Stefan Kempe, Hugh Kieffer, Minoru Kasakabe, Takehiko Kobayashi, Yurii Kuzman, Paul-Edouard de Lajarte, John Latter, Brad Lewis, Andy Lonero, Jose Rodríguez Losada, Sue Loughlin, Yasuo Miyabuchi, Setsuya Nakada, Tina Neal, Vince Neall, Hiromu Okada, Paul Okubo, Tim Orr, Aleksei Ozerov, Tom Pierson, Jeff Plescia, Mike Poland, Ken Rubin, Mike Ryan, Etushi Sawada, Lee Siebert, Tom Sisson, Don Thomas, Dorian Weisel, Chuck Wood, and Ryoichi Yamada. The late Tom Simkin of the Smithsonian Institution and five USGS colleagues (Pete Lipman, Jim Moore, Chris Newhall, Bob Tilling, and the late Bob Decker) deserve special acknowledgement for their wisdom shared with us over the years, and for the ideas we have purloined from their many seminal publications. We are indebted to support personnel at the University of Hawai‘i, Pomona College, and the US Geological Survey, for encouragement and expert advice over the years, including Jim Griggs of the USGS and Dianne Henderson of the University of Hawai‘i, who gave extensive help with preparation of photographs and line illustrations. Paul Kimberly of the Smithsonian Institution and Wil Stetner of the USGS provided the Dynamic Map files we used in the *Volcanoes of the World* map. (In the text numbers within square brackets following a volcanic site’s name refer to that site’s position on this map.) Ari Berland and Todd Greeley, both Pomona College undergraduates, and Jacob Smith of the University of Hawai‘i at Hilo compiled extensive data bases, reviewed writing from a student standpoint, and prepared maps. Andrika Kuhle spent long hours

compiling and organizing book figures. Julie Gabell's careful editing greatly improved parts of the manuscript. Our friends Maurice and Katia Krafft, who were tragically killed at Unzen Volcano in 1991, provided invaluable background information from their wealth of volcano knowledge, and loaned historical photographs, several of which are used in this book. Bob McConnin and Patrick Lynch of Prentice-Hall, and Ian Francis, Rosie Hayden, and Janey Fisher of Wiley-Blackwell provided critical editorial guidance, as did many other staff at Wiley-Blackwell. A sabbatical semester Lockwood spent at the University of Hawai'i at Manoa in 1988 gave important logistical support and stimulation, as did a research period at Pomona College in 2003. The US Geological Survey's Volcanic Hazards Program supported Lockwood for many years – enabling him to investigate volcanic eruptions and disasters in many lands, and to learn “under fire” from colleagues and foreign volcanologists. A 2002 sabbatical stay at the Alaska Geophysical Institute, and a 2006 sabbatical semester at the University of Auckland provided Hazlett with wonderful facilities and colleagues to aid in final writing.

I (JPL) wish to express gratitude to my wife Martha, who has been my able but unpaid field companion and assistant in the falling ash, mud, and sulphurous fumes of active volcanoes around the Pacific, and who has always kept on, even when paid assistants have faltered because of fatigue, boredom, or fear. She has also been a constant source of editorial and technical counsel as this edition has come to completion over the past several years, and has endured extensive “loss of companionship” over the final months as “The Book” took priority over normal marital responsibilities.

Part of the royalties from this edition will be used to establish a *G. A. Macdonald Student Volcanological Field Research Fund* at the University of Hawai'i, so that young men and women at the University will be better able to seek volcanological knowledge from the ultimate source – the volcanoes themselves.

### John P. (“Jack”) Lockwood, Ph.D.

Jack Lockwood worked for the US Geological Survey for over 30 years, including 20 years in Hawai'i, based at the Hawaiian Volcano Observatory. In Hawai'i he monitored dozens of eruptions of Kilauea volcano, and the last two of Mauna Loa. During non-eruptive times he deciphered the prehistoric eruptive history of Mauna Loa by geologic mapping, and became a leader of USGS international responses to volcanic crises and disasters worldwide. He has monitored eruptive activity of volcanoes as diverse as Gamalama, Nevado del Ruiz, Nyiragongo, and Pinatubo. Increasingly he has become focused on “humanitarian volcanology” – the application of volcanology to the needs of society. He left the USGS in 1995 to form a consulting business, Geohazards Consultants International, to continue international service. He is a commercial pilot, and with his wife Martha operates a ranch near the summit of Kilauea.



Photo by G. Brad Lewis.

### Richard W. (“Rick”) Hazlett, Ph.D.

Richard Hazlett is Coordinator of the Environmental Analysis Program and a member of the Geology Department at Pomona College in Claremont, California, where he teaches an upper-level course in physical volcanology. He has undertaken and supervised geologic mapping, geochemical studies, and stratigraphic analyses on many volcanoes worldwide, including a hazards assessment at San Cristobal volcano in Nicaragua, seismogenic landslide analysis at Vesuvius in Italy, study of blue-glassy pāhoehoe and phreatomagmatic ejecta at Kilauea, Hawai'i, and most recently, research on the late prehistoric history of Makushin, one of the most active volcanoes in the Aleutian Islands. His work has involved detailed examination of ancient volcanic terrains as well, focusing upon the Mojave Desert region in the US Southwest. Further interests include environmental science and *agroecology* – the development of sustainable agriculture by applying the principles of ecology to food production.







# PART I

# INTRODUCTION

*Volcanology* is a specialized field of geology – the science of volcano study. *Volcanologists* are not only the scientists who study volcanoes (mostly geologists, geophysicists, geochemists, and geodesists), but also the devoted technicians who spend their lives monitoring volcanoes at observatories. To become a volcanologist, one must certainly study a great deal of geology and other physical science, but the title cannot be meaningfully earned by reading books or bestowed by any university. Volcanoes themselves are the best teachers of volcanology, and the most respected volcanologists are those who have studied volcanoes in the field for many years. Volcanologists strive for a better understanding of volcanoes, and are concerned about how their work will contribute to human social needs. Protecting life and property, utilizing the tremendous stores of volcanic energy for society, and perhaps learning to lessen the dangers of certain volcanic phenomena – these are noble goals to strive for!

This Part contains only one chapter, an important one that begins with introductory narratives for a clearer understanding of what volcanic eruptions are like to experience first-hand, discusses some basic terminology, and includes a section on the history of our young science.



## 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)

**V**olcanic 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

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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 Kilauea 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) Cikasah 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



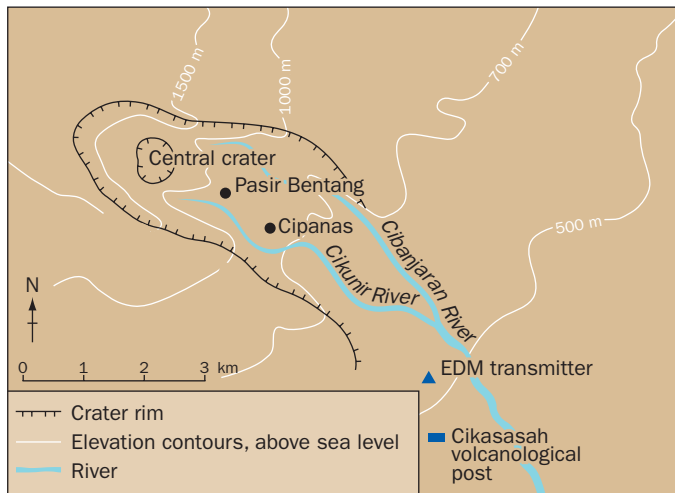


**Fig. 1.1** Refugees from falling ash at midday, outside the Galunggung Volcano Observatory, Cikasasah, Indonesia, August, 1982. USGS photo by J. P. Lockwood.



**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 Cibanjuran 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<sup>2</sup> 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 aisle 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



**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 electrostatically charged ash. USGS photo by J. P. Lockwood.

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.

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 Cikasah 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 (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 Cikasah 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 Cikasah, 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, August 1982. A small pyroclastic flow is beginning to cascade down the crater wall, and the thin deposits left by similar small flows 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 Cikasah 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 Cikasah 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 Cikasah – 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 Cikasah 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 demonstrate quantitatively 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.

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.

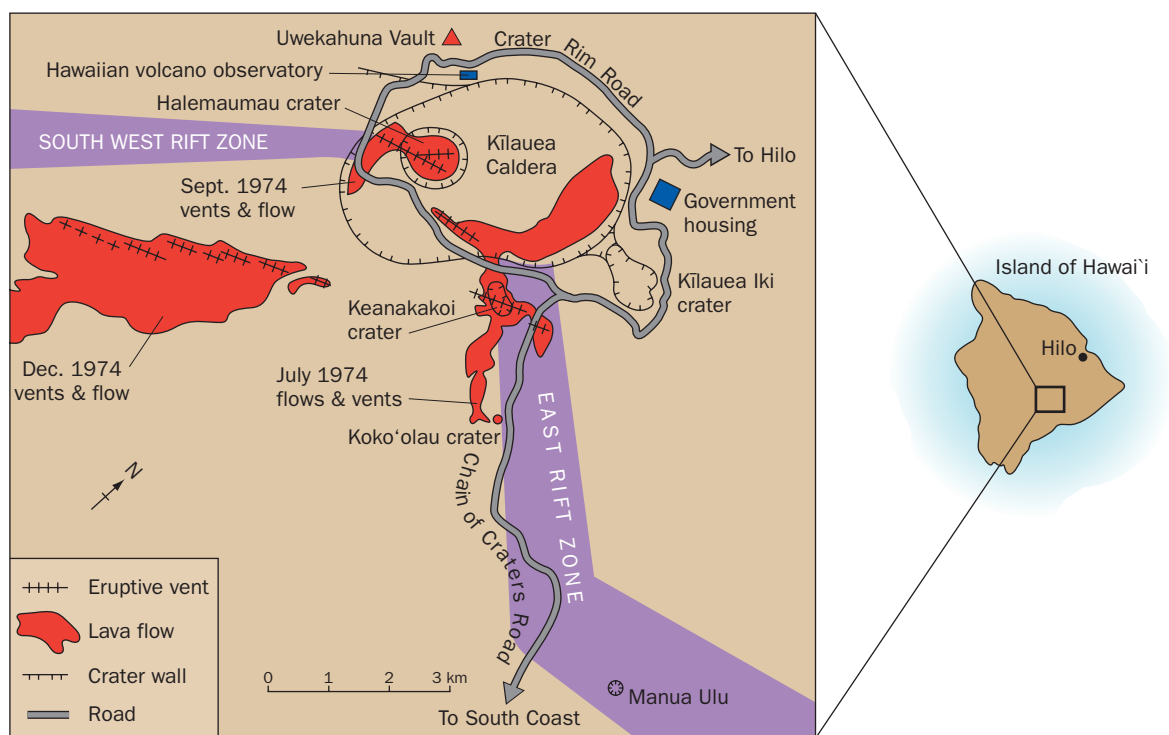
Richard “Rick” Hazlett (RWH), then an undergraduate researcher from Occidental College, also arrived on the HVO staff during that time, and was learning how to track the underground migrations of molten rock and how to forecast volcanic eruptions. His arrival led to an academic career in volcanology 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.

“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



## MAUNA ULU ACTIVITY

In late 1969, molten rock from Kilauea'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 Kilauea, 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

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

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 than 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 smell of sulphur is strong, but not 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.

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"

**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.



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.

## 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*

### 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!

*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*