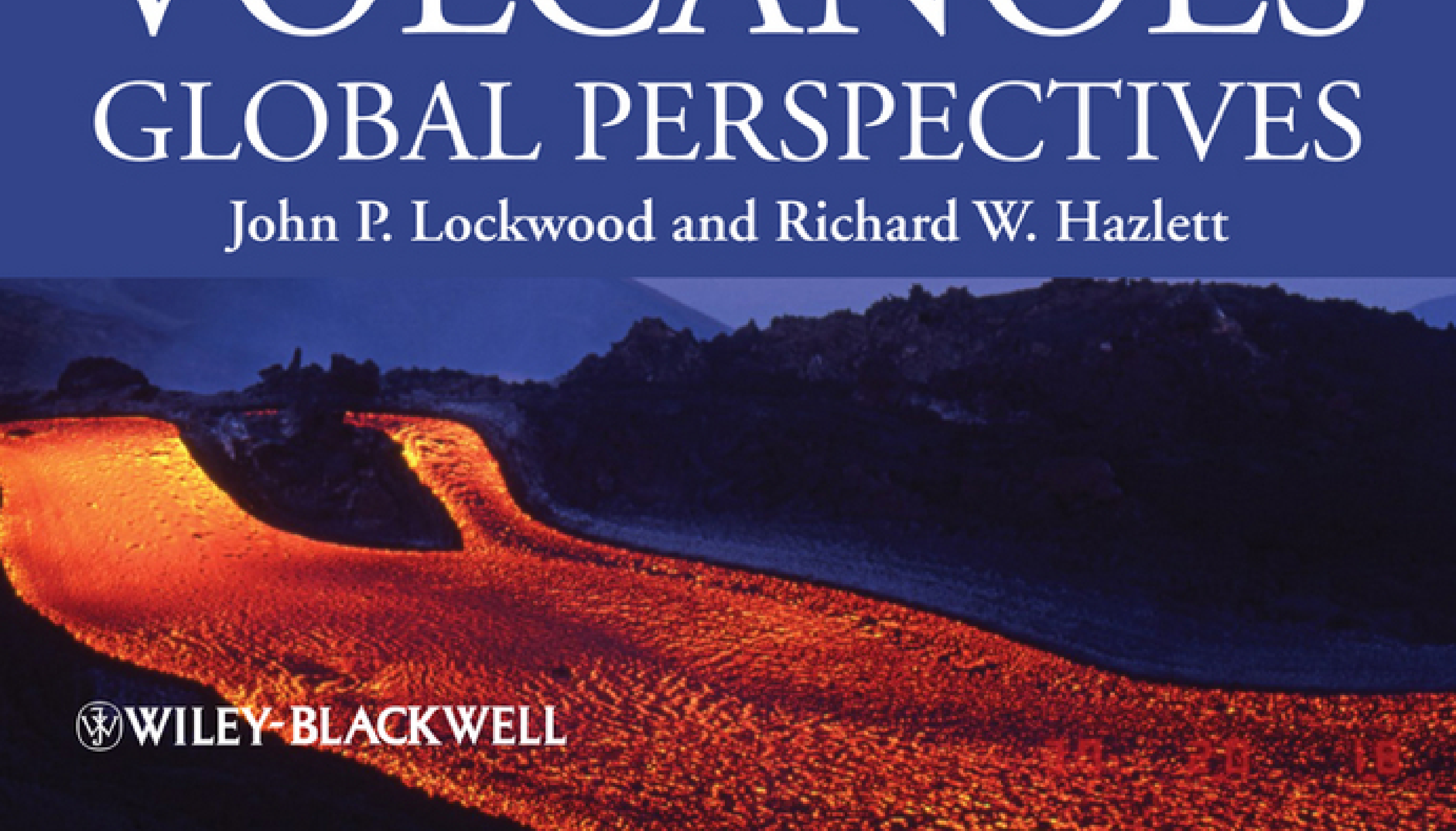
VOLCANOES

GLOBAL PERSPECTIVES

John P. Lockwood and Richard W. Hazlett



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Contents

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

WILEY-BLACKWELL
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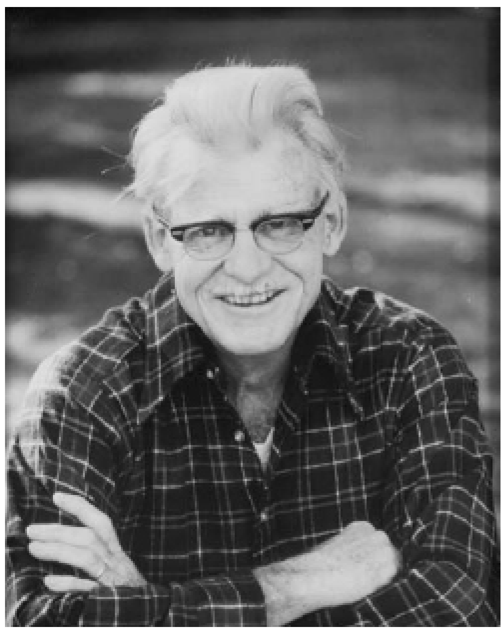
DEDICATION

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	Karkar, 1979
David Johnston	Mount St. Helens, 1980
Salvador Soto Piñeda	El Chichón, 1982
Alevtina Bylinkina, Andrei Ivanov, Yurii Skuridin, Igor Loginov	Kluchevskoi, 1951–1986
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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 Thornber, 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.

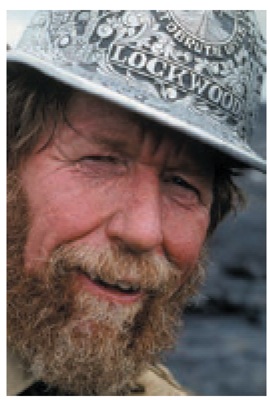
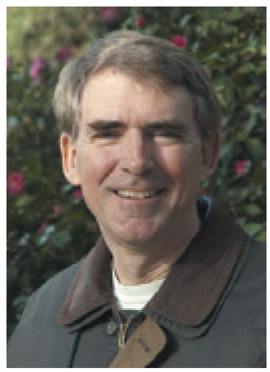


Photo by G. Brad Lewis.

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 Kīlauea 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 Kīlauea.

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 Kīlauea, 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)

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 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.

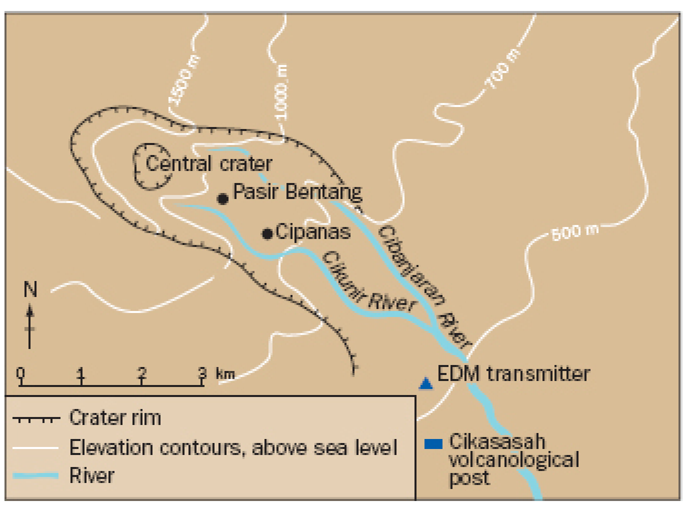
Inside the post, a beehive atmosphere prevailed as technicians busily checked seismographs and shouted out readings to communications specialists in an adjoining room. Their reports were being radioed to Civil Defense Headquarters in the city of Tasikmalaya, 17 km away (Fig. 1.2) and to the VSI Headquarters 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 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. 1.1 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.

Galunggung is at the center of the most fertile, heavily populated agricultural land in central Java. It is a horseshoeshaped 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. Hardworking 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.

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



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