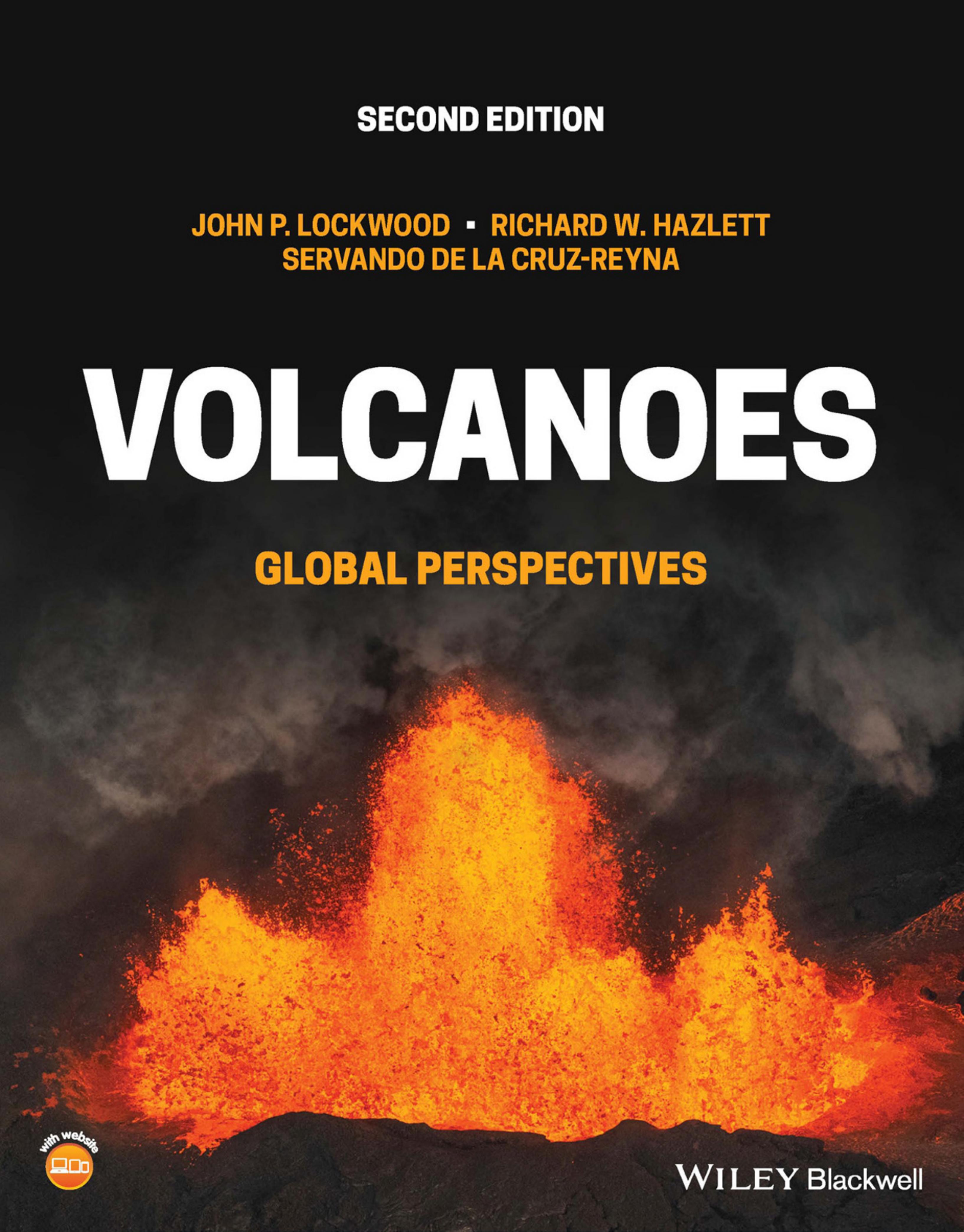


SECOND EDITION

JOHN P. LOCKWOOD ▪ RICHARD W. HAZLETT
SERVANDO DE LA CRUZ-REYNA

VOLCANOES

GLOBAL PERSPECTIVES

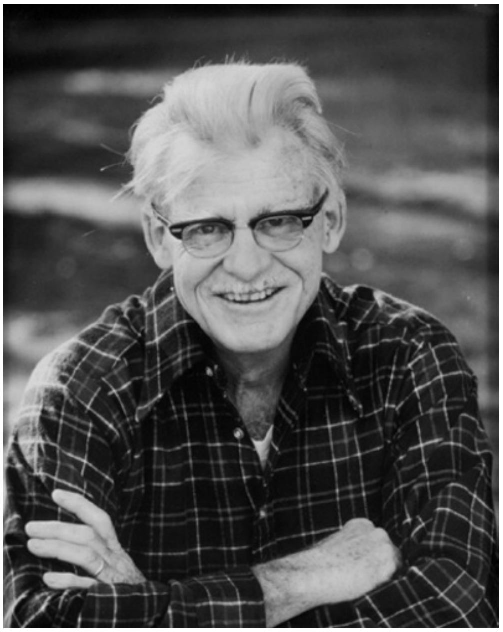
with website

WILEY Blackwell

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	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
Alexander Umnov	Karymsky, 1986
Maurice & Katia Krafft, Harry Glicken	Unzen, 1991
Victor Perez, Alvaro Sanchez	Guagua Pichincha, 1993
Geoff Brown, Fernando Cuenca, Nestor Garcia, Igor Menyailov, Jose Zapata	Galeras, 1993
Asep Wildan, Mukti	Semeru, 2000

Volcanoes: Global Perspectives

Second Edition

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Contents

Volcanoes – Global Perspectives: Preface To The Second Edition

More than ten years have passed by since the First Edition of *Volcanoes* was published in 2010. Our world of volcanology has changed in exciting ways over this decade, and we have much important new material to discuss in this Second Edition. Volcanoes have continued to erupt (some 61 eruptions exceeding VEI 3 have taken place since 2010), and we are describing the largest of these and the ones that have had the most impact on society since the First Edition. This new edition contains more than 80 new photographs and figures to better illustrate volcanic features and processes more clearly, discusses or refers to more than 180 important volcanoes whose properties are summarized in an Appendix, and includes an updated Bibliography (with more than 1000 entries) that includes important papers describing recent eruptions and new findings.

Professor Servando de la Cruz-Reyna of the National University of Mexico has joined us as a co-author, and this edition benefits greatly from his long experience in applying statistical tools to analyze volcanic hazards and risk, as well as his invaluable Latin American perspectives on volcanic activity. In the first introductory chapter, Servando, Rick and I describe our personal experiences with specific eruptions that we have learned from, eruptions that have taught particularly important lessons for volcanology. A visit to St. Pierre, Martinique in 2019 stimulated a renewed appreciation for the impact of the 1902 Mount Pelée eruption on the development of volcanology, and led to the realization that we had failed to pay enough attention to the Peléean class of volcanic eruptions in our First Edition – that failing is now addressed. We have also greatly improved our discussion of pyroducts, the subsurface conduits of molten lava responsible for the areal distribution of pahoehoe lava flows, and of the genesis of the caves remaining when pyroducts drain after cessation of eruptive activity. Volcanologic research is improving the foundations of knowledge upon which all our science rests, and we briefly summarize the most important of these advances and new research tools developed over the past twelve years. The most productive of these new tools are remotely operated, and are constantly monitoring volcanoes and their impacts on the Earth's atmosphere from space and exploring new volcanic worlds beyond the bounds of Earth. We discuss the remotely operated vehicles (ROVs) that are now widely used to reveal the secrets of the most active volcanoes on Earth, those beneath the sea.

Although basic research is essential, the most important volcanological advances of concern to Society at large are those aspects that directly benefit Society – advances that enable humans to co-exist more harmoniously with the Earth's volcanoes. These are the broad fields of "Applied Volcanology," where volcanologists focus on better understandings of the hazards associated with volcanic activity, the means to evaluate and mitigate volcanic risk, and the best ways to share their knowledge with others – enabling people to live and work more safely with their volcano neighbors. Great strides have been made in these fields, and the past decade has seen major advances in our ability to better monitor active volcanoes and to provide advance warnings so that vulnerable populations can evacuate from dangerous areas. One measure of our success in these efforts is to compare the numbers of people killed by volcanic activity in the recorded period before and after 2010. From the advent of modern communication and better reporting of volcanic activity in 1850 (widespread use of telegraphy) to 2010, there were about 100,000 volcano-related fatalities, or about 6,250 fatalities per decade. In the 11 years since 2010, only about 1200 people lost their lives. This is of course related to good fortune (there have been no eruptions with VEI's in excess of 5 in this period!), but also reflect the fact that our capabilities to forecast eruptions and to evacuate the vulnerable have improved greatly. Of interest is the fact we identified 19 volcanologist colleagues who were killed by volcanic activity prior to the 2010 publication of our First Edition. Fortunately, we have no more martyrs to add to this list – which attests to the value of remote sensing tools volcanologists are using to monitor hazardous eruptions, but also perhaps to good luck!

"Applied Volcanology" is not limited to academic research. Earth Science teachers at all levels are applying their understanding of volcanology to better inform their students about volcanic activity and the nature of volcanic hazards. This will enable students who may never see an erupting volcano to better evaluate news stories about far-away eruptions, and to distinguish between overly sensational stories and factual reporting that puts facts in context. An entire new journal, the *Journal of Applied Volcanology* is now devoted to publishing important research focused on volcanic hazards and risk mitigation. Emergency managers, land use planners, and civic officials also have need to understand volcanic processes when their communities are threatened. We have endeavored again in this new edition to avoid overly technical discussions and unnecessary use of "jargon," with the important needs of civil authorities, teachers and students particularly in mind. We also hope that laymen and travelers will find our book useful for understanding the volcanoes they meet along the way, and to hear the exciting stories of fire and fury that all volcanoes have to share with passers-by who pay attention! Volcanologists mostly write papers and books focusing only on the scientific aspects of volcanoes they know, but some write Memoirs about their lives, and some write fiction based on stories volcanoes have told them. We include an appendix called "*Fun Reading*" to show what volcanologists write about in their "spare time"!

Our debt to colleagues who have shared their knowledge of volcanology with us remains deep. We cited over 100 of them in our Preface to the First Edition, and will not repeat their names here. We do however again wish to again acknowledge Pete Lipman, Jim Moore, and Chris Newhall, who reviewed sections of this book. Dave Clague and Ken Rubin kept us abreast of their exciting new discoveries of active submarine volcanism. Stephan Kempe provided us with important insights into the dynamics of fluid lava flow emplacement processes, and we really mean <u>IN</u>sights! Kempe's studies from <u>inside</u> pahoehoe lava flows around the world have revealed important details about the critical roles played by pyroduct conduits in subsurface lava transport. Shawn Willsey of Twin Falls Idaho shared valuable perspectives on Snake River volcanism. Anne-Marie LeJeune, then Director of the Volcanological and Seismological Observatory of Martinique was a wonderful host during a visit to St. Pierre and has provided new perspectives about the impact of the 1902 eruption on volcanology. Hugo Moreno-Roa (OVDAS) answered many questions about southern Chilean volcanism. Luis Gonzalez de Vallejo and Pedro Hernandez Perez provided important updates and photographs of the large, destructive 2021 eruption of Cumbre Vieja volcano on the island of La Palma. Scott Bachmeier (University ofWisconsin-Madison) and Walt Dudley (University of Hawai'i-Hilo) contributed importantinformation about 2022 Tonga eruption dynamics and its tsunami impacts. The 2018 eruption of Kilauea volcano changed many of our concepts about this volcano, and we appreciate the professional photography of Brad Lewis and Bruce Omori, who contributed many photographs. Matt Patrick of the USGS Hawaiian Volcano Observatory also contributed important photos of Kilauea features. Jake Smith again did magnificent work to compile the data necessary to update our list of volcanoes mentioned in text and the endpiece map, as well as kept track of the many new photographs used in this edition. He is also largely responsible for digital contributions to the e-book version of VOLCANOES. Andrew Harrison, Rosie Hayden, Rathi Aravind, Shyamala Venkateswaran and other Wiley editors in Oxford and India turned our rough manuscript submittals into the fine book you are holding today!

As always, despite our best efforts, we know that some factual errors or mechanical shortcomings may have crept past editors, and we will very much appreciate readers letting us know about any of these or about shortcomings you would like to see corrected in future Editions!

JOHN ("JACK") LOCKWOOD, VOLCANO, HAWAI'I
RICHARD ("RICK") HAZLETT, HILO, HAWAI'I
SERVANDO DE LA CRUZ-REYNA, MEXICO CITY
JUNE, 2022

JOHN P. ("JACK") LOCKWOOD

Jack Lockwood nearly died on the first active lava flow he ever saw (Hawaii – 1971), but the experience of working with molten rock was an epiphany that changed his life's focus to volcanology. He spent the next two decades working with the U.S. Geological Survey's Hawaiian Volcano Observatory and later as a USGS team leader responding to volcanic crises and disasters worldwide. His primary professional interest has been on what Thomas Jagger called *Humanitarian Volcanology* — the application of volcanology to the needs of Society. He left the USGS in 1995 to form an international consulting business focusing on volcanic hazards and risk assessments. He is now semi-retired, living with his long-term field partner and wife Martha on the lower slopes of Mauna Loa volcano.

RICHARD ("RICK") HAZLETT

Richard Hazlett has spent most of his career in geology teaching at Pomona and Occidental colleges and the University of Hawaiʻi at Hilo. His research in volcanology includes Neogene volcanism in California's Mojave Desert and eruptive activity at San Cristóbal (Nicaragua), Vesuvius (Italy), Krafla (Iceland), Kīlauea (Hawaiʻi) and Makushin (Alaska) volcanoes. While at Pomona he also devoted significant time to environmental education, including establishment of the Pomona College Organic Farm and senior editorship of the Oxford University Press Encyclopedia of Agriculture and the Environment. He presently is retired in Hilo, Hawaiʻi, where he maintains a research connection with the Hawaiian Volcano Observatory while continuing to learn folk guitar and develop familiarity with local reef fishes as an avid snorkeler and diver.

SERVANDO DE LA CRUZ-REYNA

Servando de la Cruz-Reyna has dedicated his life to research at the Institute of Geophysics of the National Autonomous University of Mexico (UNAM). For years he has advised the Mexican National Civil Protection System on different aspects of volcanic risk management and is one of the founder members of the Scientific Advisory Committee for Popocatépetl Volcano, and of other active Mexican volcanoes, receiving the National Award for Civil Protection in Prevention 2006. He has worked on modeling physical processes in active volcanoes, on the recognition of eruption precursors, on the statistical assessment of long-term volcanic hazards, and on the applications of those methods to volcanic risk management and social response, particularly on Popocatépetl, Colima, El Chichón, and Tacaná volcanoes. He has taught the graduate course on volcanic risks at UNAM for decades. Currently, he is editor-in-chief of Geofísica Internacional.

Preface To The First Edition

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 Hawaiʻi 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 Thornbur, 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, Yurii 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 Hawaiʻi, 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 Hawaiʻi, 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 Hawaiʻi 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 Hawaiʻi 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 Hawaiʻi, 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

Jack Lockwood worked for the US Geological Survey for over 30 years, including 20 years in Hawaiʻi, based at the Hawaiian Volcano Observatory. In Hawaiʻi 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

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 p*a*hoehoe and phreatomagmatic ejecta at Kīlauea, Hawaiʻi, 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.

About the Companion Website

This book is accompanied by a companion website.

www.wiley.com/go/lockwood/volcanoes2

This website includes:

- Interactive volcanoes map
- List of prominent world volcanoes
- Figures from the book, in Powerpoint slides

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 include 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 sciences, but the title cannot be meaningfully earned only 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 spend their careers seeking better understandings of volcanoes but must also be concerned about how their work will contribute to human social needs. Enabling people to coexist better with their volcano neighbors, sharing their knowledge with students and the public, devising means to utilize the tremendous stores of renewable energy stored within volcanoes, and perhaps saving lives along the way – these are all noble goals to strive for!

This part contains only one chapter, an important one that begins with introductory personal narratives written by authors to give a clearer understanding of what volcanic eruptions are like to experience first-hand. We then discuss some basic terminology and include a section on the history of this young science.

Volcanoes: Global Perspectives, Second Edition. John P. Lockwood, Richard W. Hazlett, and Servando De La Cruz-Reyna.

Companion website: www.wiley.com/go/lockwood/volcanoes2

CHAPTER 1

Eruptions, Jargon, and History

Source: Credit J. Lockwood.

Volcanoes: Global Perspectives, Second Edition. John P. Lockwood, Richard W. Hazlett, and Servando De La Cruz-Reyna.

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> *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.*
>
> *(Decker and Decker 1991)*

Volcanic eruptions are the most exciting, awe-inspiring phenomena of all of 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 be 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*** (gray volcanoes). "Red volcanoes" are those volcanoes that are mostly found on mid-oceanic islands and are characterized by **effusive** activity (flowing red lava). The "gray 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 gray ash. This is a 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 three authors will describe our personal experiences during three major eruptions – one "red" and two "gray." This is our chance to describe the reality of dealing with major, destructive eruptions in personal terms, with the freedom to discuss our feelings as we deal with the human, political, and volcanic uncertainties that characterize all major eruptions.

"Rick" Hazlett will start off by describing his experiences during the 2018 eruption of Kīlauea, Hawai'i [17] – the most voluminous and destructive eruption in that volcano's history. Servando De la Cruz-Reyna will then discuss his human emotions and exciting experiences during the explosive eruption of El Chichón, Mexico [57] in 1982 – an eruption that caused the deaths of about 2000 people. "Jack" Lockwood will follow with his experiences during the 1991 Pinatubo, Philippines [135], eruption. Pinatubo was the second largest eruption of the entire twentieth century, and it had a major social impact in the Philippines, political repercussions, and global climate impact. In these and a few other places where we use the first person "I" with reference to personal experiences, we will identify ourselves by our initials, RWH (Hazlett), SCR (Servando De la Cruz-Reyna), or JPL (Lockwood).

A "Red Volcano" in Eruption – Kīlauea – 2018

In early April 2018, I (RWH) was working as a volunteer researcher at the United States Geological Survey (USGS) Hawaiian Volcano Observatory (HVO) on the island of Hawai'i, perched on the rim of the huge crater (caldera) atop Kīlauea volcano. This was a major place of worship for early Hawaiians, some of whom continue their ancient cultural practices here even today, honoring the Fire Goddess, Pele. In more recent times, Kīlauea has also become a major hub of world volcano science. The eruptions of Kīlauea are frequent, and most are gentle enough to study up close, though "gentle" is a relative term as you will see when you soon read the accounts of my co-authors! In the first five months of 2018, Kīlauea volcano was behaving in its typically dynamic but non-threatening way. Until early spring, there was no reason to believe that anything was about to change. . .

Unlike ordinary gray volcanoes with their centralized vents, Kīlauea has developed a far-flung internal magma transport system over a few hundred thousand years, allowing it to erupt fluid lava in multiple places, sometimes tens of kilometers from the summit. A complex magma reservoir system, extending several kilometers beneath the summit, frequently feeds lava to the floor of a broad central caldera, or collapse basin, in the form of persistent, sluggishly active lava lakes. Underground outlets can also divert the magma underlying the summit into one or two narrow rift zones – or zones of weak, fractured crust, stretching down the flanks of the volcano to the east and southwest. The East Rift Zone, by far the more active of the two, extends 130 km from Kīlauea's summit (elevation 1250 m) to the ocean floor 4–5 km below sea level (Figure 1.1)

For ten years prior to April 2018, Kīlauea had been erupting highly fluid lava simultaneously in two locations: A lava lake confined to a cylindrical pit about 200 m wide on the floor of Halemaʻumaʻu Crater, which played to the delight of visitors viewing the scene from the Jaggar Museum overlook next to the observatory, 1.5 km away (Figure 1.2). Twenty kilometers to the east, lava also issued from a large spatter and lava shield, PuʻuʻŌʻō, a structure that had begun forming in 1983, and remained almost continuously active ever since. PuʻuʻŌʻō rose above remote forest in the uninhabited central part of the rift zone, but its vent frequently sent streams of lava to the south coast of the island, cascading down a 300–400 m tall slope. These flows destroyed dozens of homes and inundated roads on the East Rift Zone flanks where they spread out and gradually added hundreds of hectares of new land to Hawai'i Island. Despite the destruction, local residents and visitors alike took delight in observing the frequent displays of volcanic creation.

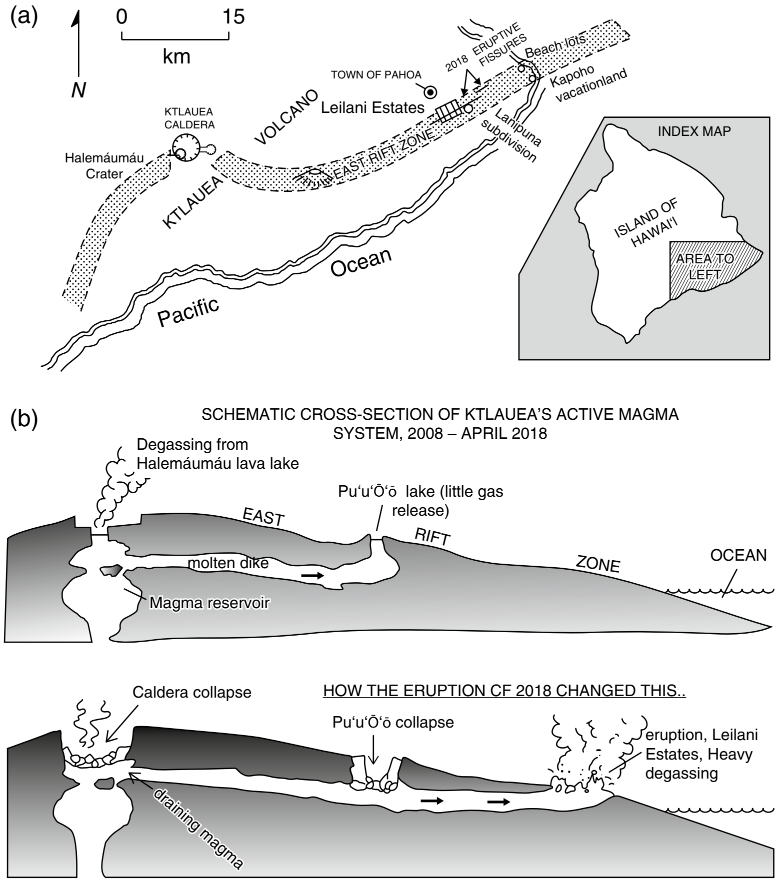

FIGURE 1.1 (a) Map of Kīlauea volcano [17], island of Hawaiʻi, showing major features related to the great eruption of May–August 2018; (b) cross-sections of the volcano before and during the eruption, drawn along the trace of the East Rift Zone

FIGURE 1.2 Halemaʻumaʻu lava lake, as seen within the summit caldera of Kīlauea volcano [17] on 1 February, 2014, was continuously active between 2008 and 2018. It drained away rapidly at the start of the 2018 Lower East Rift Zone eruption. Source: USGS photo by Matt Patrick.

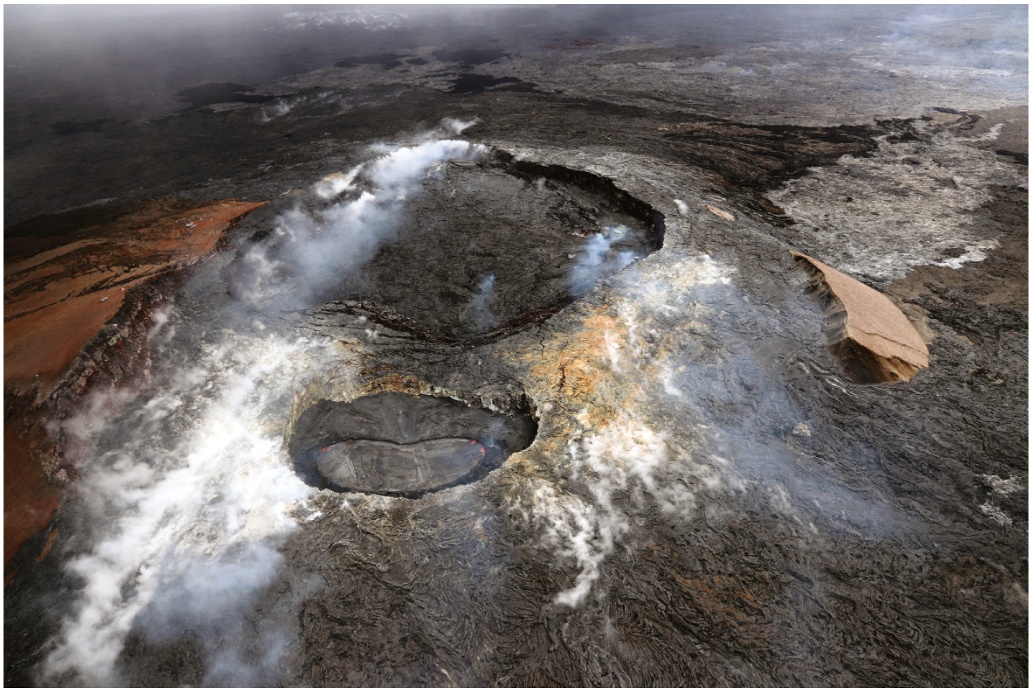

FIGURE 1.3 Puʻu ʻŌʻō vent area looking east, on 18 April, 2018. The vent consisted of a jagged, gently sloping lava mound surmounted by a cluster of craters with active lava circulating in the pit closest to the viewer. Source: USGS photo by Carolyn Parcheta.

The connection between summit lava lake and rift zone activity at Puʻu ʻŌʻō had been stable for many years: The Halemaʻumaʻu lava lake served as a chimney for gases escaping the underlying magma reservoir, behaving like a natural standpipe, with the fluctuating lake level reflecting magma pressure within the molten reservoir below. The Puʻu ʻŌʻō vent, 20 km to the east, behaved more like a drain for this system, tapping off magma from the summit reservoir that otherwise would accumulate there. Much less gas escaped from Puʻu ʻŌʻō as a result. From a distance on many days this flank vent appeared inactive, although molten lava was churning beneath the crust (Figure 1.3).

In mid-March, devices that measure the slope of the mountainside, called tiltmeters, indicated that pressure was pushing up the land all around Puʻu ʻŌʻō. Observatory scientists knew that a shallow pocket of magma must be accumulating there, and on 17 April, they warned the public that a fresh outbreak of lava was likely "somewhere" in the vicinity. As pressure rose beneath Puʻu ʻŌʻō, the lava lake in Halemaʻumaʻu, as though responding to a blockage, also began rising. On 21 April, it overflowed the rim of its vent pit, spilling out onto the surrounding crater floor. The observatory issued another eruption hazard bulletin three days later.

Then, on 30 April, the situation abruptly changed. The molten lava at Puʻu ʻŌʻō suddenly drained and the floor of the pit there began falling in. Swarms of earthquakes indicated that the pent-up magma was shifting underground along the East Rift Zone, like water rushing from a breaking dam, into the Puna lowlands ("Lower East Rift Zone" or LERZ) not far from the town of Pāhoa, an area where tens of thousands of people lived. The earthquakes were accompanied by a distinctive type of shaking called harmonic tremor which is produced by liquid (magma) intruding through cracks in fractured rock. HVO issued a public alert. It was time for residents to consider evacuating!

I knew that if a major eruption broke out in this heavily populated region of Hawai'i, I would be deeply involved in any emergency response. I was not afraid of what might happen, though I was certainly concerned – I had seen plenty of eruptive activity during a summit eruption of Kīlauea back in 1974 (see my account in the First Edition of this book) – but that had taken place in an uninhabited part of the Hawaiʻi Volcanoes National Park, where no lives nor homes were ever threatened. This was definitely different, and I realized that if lava broke out here, it would cause serious problems for many, perhaps thousands of people.

Leilani Estates (Figures 1.1a and 1.4) is a residential subdivision in the LERZ, close to the town of Pāhoa. Even though State and County officials and developers were well aware of volcanic hazards and the volcanic risk of authorizing development in this area – smack atop the East Rift Zone – this subdivision was approved and by the mid-1960s, housing began to spring up throughout Leilani Estates. Other nearby subdivisions also were approved and grew, including Lanipuna, Beach Lot Estates, and Kapoho Vacationland near the eastern cape, where the LERZ continues into the sea. Thousands of people now live in what was clearly seen by geologists and civil defense authorities as a hazardous area.

Mid-afternoon on 3 May, the first eruptive vent, later called "Fissure 1" opened in the midst of homes in Leilani Estates. Fortunately, most residents had safely fled by then, but no one could tell exactly where or when – even if – the eruption would break out next. Many evacuees worried about lost pets, friends, and their properties which might or might not be looted if not destroyed. No one knew when they could safely return home. Many were retirees, with scant social safety nets and life savings threatened. For

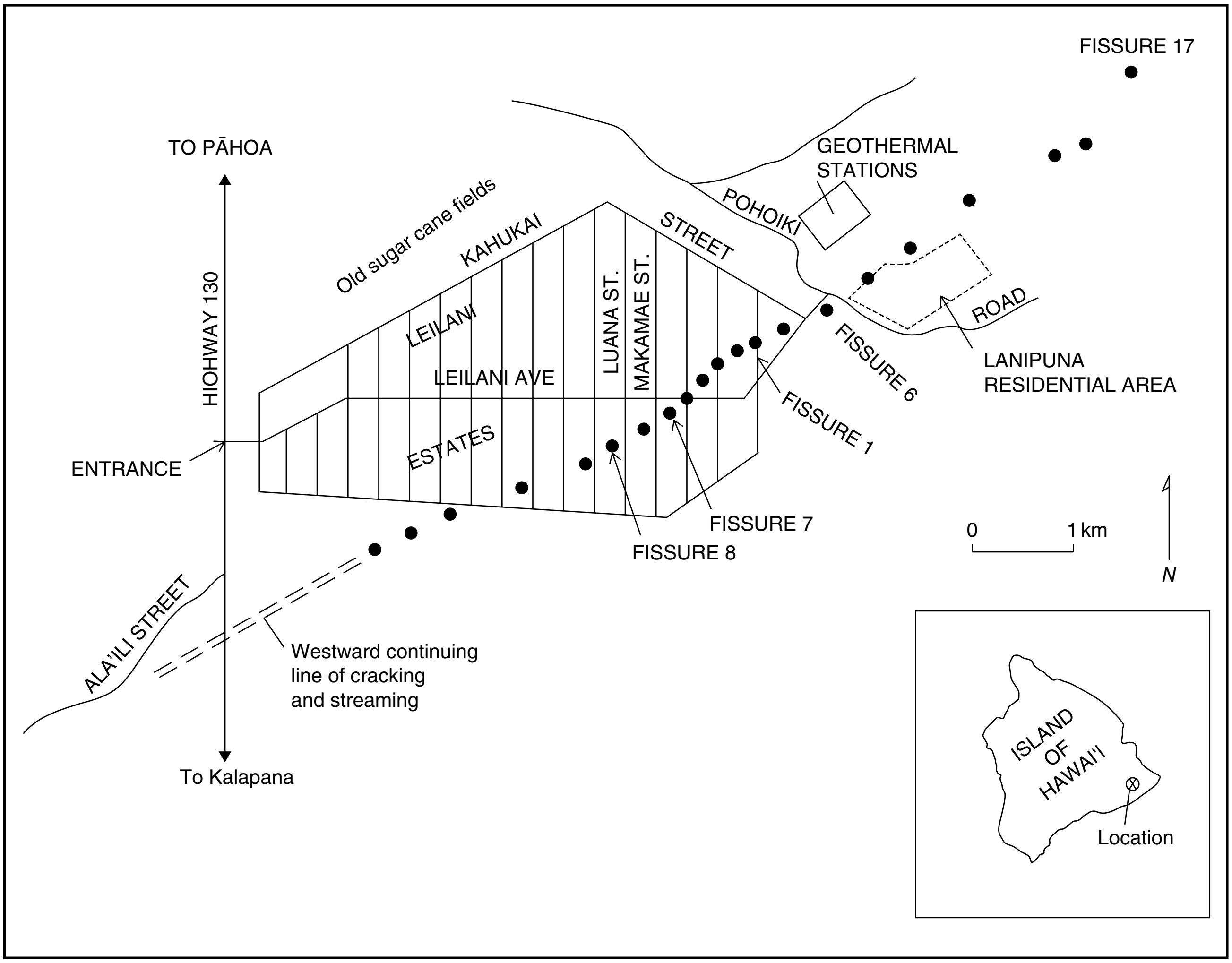

FIGURE 1.4 Map of Leilani Estates and 2018 eruptive fissures (black dots).

most disasters, the intense psychological stress of a hurricane or earthquake, typically comes and goes in short order – these are brief physical events. Imagine how a developing disaster with no end in sight would impact individual psyches, and no end was in sight for this eruption!

Adding to this stress, a magnitude (M) 6.9 earthquake jolted the island on 4 May. The south flank of Kīlauea shifted seaward as much as five meters when this happened, causing light to serious damage across several hundred square kilometers. Perhaps the earthquake occurred in response to the buildup of magma pressure in the East Rift Zone. Almost certainly, it opened fractures allowing magma to reach the eruption site more easily, fed from the bloated summit magma reservoir. By this time, the level of the lava in the Halemaʿumaʿu lake was dropping rapidly.

"Fissure 1" was to be followed during the next three weeks by the opening of 23 additional eruptive fissures, each no more than a few hundred meters long, stretching in a 6-km-long set of closely spaced vents, both up- and downrift of the original outbreak. No order in the developmental sequence could be seen; fresh outbreaks of lava jumped up- or downrift relative to earlier-opened fissures, though the general trend was one of migration *down* the East Rift Zone, closer to the subdivisions at the coast (Figures 1.1a and 1.5). Hawai‘i County Civil Defense, Police, and Fire Departments, all worked in close collaboration with the National Guard, HVO, and USGS geologists to assure that no lives would be lost and that residents could remove as much property as they safely could before homes were inundated by lava. They were remarkably successful doing so.

Like typical Kīlauea rift zone eruptions, this one began along numerous fissures, but eventually settled down to concentrated outpouring from a single vent ("Fissure 8") along the initial 24-fissure system in the middle of ill-fated Leilani Estates. A measure of my excitement during the first three weeks of this eruption can be reconstructed from journal notes I took during this early stage:

4–5 May: The Observatory asked me to partner with Carolyn Parcheta, a new staff geologist, to monitor eruptive activity in the field. We got going around 7 p.m. on Friday night, and did not knock off until 6 a.m. the next day. Our first objective was 'Fissure 6' in the thick woods at the east end of Leilani Estates, just south of a major geothermal plant. Entering the Civil Defense closed zone we met the team we were assigned to relieve at a street intersection in the dark forest. Silhouetted through the trees, repeated blasts of lava kept occurring, pitching bright yellow-orange globs of molten spatter up to a couple of hundred feet. Wild, gaseous bursts

FIGURE 1.5 Fissure 20 springs to life, 14–16 May, 2018, with lava gushing as much as 50–100 m above the mouth of the fissure that guides it to the surface. Hawaiian geologists sometimes call the line of lava fountains a "curtain of fire," a characteristic feature of red volcano eruptions. Source: USGS photo by Richard Hazlett.

reverberated every few seconds with a background noise of loud hissing. Our cameras could not do the stark scene justice. Our senses alternated between awe at the beauty of the eruptive activity, and shock about what was happening.

"The vent was no longer growing, and we proceeded to spend the next six hours simply watching activity die out here while making sure that the steaming, sulfurous cracks in the adjacent streets were not opening further. (I used my ruler a lot!) Everything seemed pretty quiet during the early morning hours of Saturday. We went patrolling for ground cracks in the abandoned Leilani subdivision, locating them where they broke street pavements and measuring their widths. By about 5 a.m., we were tired but remained alert because we knew that things could change quickly; Kīlauea's eruptions take breaks like this, sometimes lasting for a few days, then pick right back up again. Around 5:30 a.m., while measuring one crack, I heard a familiar, unwelcome noise coming out of the woods very close to us, behind some houses nearby (a sound resembling waves sloshing up on a beach or water coming out of a blowhole). I told Carolyn to turn off the car engine to hear this warning-sound better, and to see if we could ascertain the direction of its source. She agreed a new outbreak must have begun, though neither of us had a good idea where it was. Sulfur gas began filling the air all around us, so we donned our masks and drove further into the subdivision to find the new vent. We ran into a concerned local resident still in the process of evacuation, delayed in part because he feared looters. He said that he thought there were actually two new outbreaks nearby – 'somewhere'. With this tip, we moved along Kahukai Street – the north road, and sure enough up we soon came upon a dense cloud of wood smoke and fume rising from the trees ahead. No lava was erupting from this new crack yet, but we reported the location to the mobile command post in Pāhoa for a helicopter pilot to investigate. We then backtracked along the north road; there was no other way to exit. I kept looking down each of the south-trending streets that we intersected as we drove along, all the while feeling a pit in my stomach. And suddenly, looking down Makamae Street, *I saw it*; an explosive outburst of blood-red lava fountaining above the forest only about a half mile away. Carolyn turned onto the street and drove us toward this new vent. Taking care as we parked to turn the vehicle around for a quick getaway, we walked to within a few hundred feet of the roaring fissure (Figure 1.5) where she took a GPS measurement and photos. She was a bit braver than I about approaching the outpouring flow, but we both worried with good reason about the burning roadside power line. During our brief time there, we saw that the vent was becoming increasingly active – certainly more active than all previous openings we had seen in this eruption so far. HVO formally designated 'our' new openings Fissure 7 and Fissure 8."

Carolyn and I witnessed the ongoing activity of Fissure 8 directly across Luana Street in Leilani Estates late in the day on 5 May. We had to move our field vehicle back up the street from this site, not so much because of advancing lava but because the power poles around us were beginning to burn down, and live electrical wires were threatening. I saw a lot of methane flame emerging from openings in the edge of the active flow and heard a continuous series of muffled explosions in the surrounding woods;

grenade-like methane bursts. We avoided entering the surrounding forest – for multiple reasons. A photograph taken later in the eruption by Brad Lewis, shows a flow advancing on a Leilani street road as the adjacent vegetation was being consumed by fire and blue methane flames were emerging from road cracks (Figure 1.6).

The rest of May flew by in kaleidoscopic fashion. I witnessed new vents opening and homes burning, measured lava fountain heights (Figure 1.7), and met with stunned residents who were forced to evacuate and leave most belongings behind, just before their homes were destroyed. Multiple streams of lava poured southeast from the evolving set of fissures, covering scattered homes and some of Puna’s most productive agricultural land (Figure 1.8).

As the various fissures, 1–24 opened in May, magma intruding the LERZ from uprift drove out pockets of older, still liquid magma stranded underground from previous eruptions and intrusive episodes. Aging magma cannot erupt on its own, having cooled, become more viscous, and lost the gas concentrations needed to help erupt. If driven out by fresh melt from below, however, older magmas tend to erupt explosively; sudden pressure reduction causes gases that remain trapped within them to gather into enormous bubbles that ultimately burst with great force through the viscous liquid. Fissure 17 opened in this way on 12 May, releasing a torrent of andesite lava, a rare composition in Hawai‘i that can only form through the fractional crystallization of aging, stored magma. The andesite likely evolved from molten rock originally emplaced in 1955. In contrast, all the other fissures erupted only more fluid basaltic lava.

The explosive eruption of Fissure 17 led to one of the few injuries of the eruption. A large block, tossed ballistically hundreds of meters from a vent, tore through the roof of a house and injured a resident who had refused to

FIGURE 1.6 A Leilani Estates road is buried by an advancing pāhoehoe lava flow as methane gas being distilled from heated vegetation burns in road cracks. Source: Photo © Brad Lewis.

FIGURE 1.7 Trigonometry works! Measuring the height of a lava fountain within with a GPS and inclinometer. Fountains rise about 60 m above the base of a freshly forming cone (Fissure 8) in Leilani Estates. This cone has since been named Ahu’ailāʻau by Hawaiian elders, meaning “Altar of Ailāʻau” (a vindictive Hawaiian volcano god before Pele). Downed power lines and electric cables litter the landscape. Source: USGS photo by Samantha Gassett.

FIGURE 1.8 Lava flows course through the Malama Ki area of the LERZ on 21 May, 2018, on their way to building new land along the southeast coast of the island of Hawai‘i. Source: USGS photo by R.W. Hazlett.

evacuate the area. Fortunately, the injury was not grave, though it well might have been. The concussive bursts from Fissure 17 blasts were strong enough to rattle and even shatter glass in neighboring homes, requiring geologists and other observers to wear ear protection within a kilometer or so distance of the vent.

On 25 May, volcanic activity in the LERZ entered its prolonged final stage, as Fissure 8 reactivated to become the dominant remaining vent of the eruption. The escaping magma had a composition more closely matching that of the Puʻu ʻŌʻō lavas, and the discharge rate (amount of lava released per unit time) accelerated. Hundreds of millions of cubic meters issued through a set of closely spaced lava fountains, around which a 55-m-high cone of spatter and pumice fragments grew (Figure 1.7). An outlet on the northeast side of the cone released a molten river that traveled as fast as 30 kph into a channel as much as 250 m wide that carried the lava all the way to the ocean 10 km to the east, reaching Beach Lots and Kapoho Vacationland subdivisions. Frequent small overflows from the channel built levees that both confined and deepened the lava river (Figure 1.9). Ironically, even though the eruption rate had increased, the threat to the remaining homes in Leilani subdivision had diminished owing to the way the flow path of the lava had stabilized.

6 June: "I took the 2–10 p.m. shift today with Brian Shiro, the HVO seismic system manager. (Brian had recently transferred to the Observatory from the Pacific Tsunami Warning Center in Honolulu.) As usual, I started out with a set checklist of places to investigate in the field, and then the unexpected happened to make life more interesting. The first 'unexpected' came with a drive to the southwestern end of the new rift [fissure] system, in a forested area of rural residences and farms along Alaʻili Road. Some observatory geologists are concerned that the eruption will soon spread from its current vent at Fissure 8 to the west, cutting the last open highway into south coastal Puna. I believed that there was little evidence to support this forecast, but Brian and I were surprised to discover quite a few new ground cracks crossing Alaʻili Road in a zone about a kilometer wide. We measured, oriented, and photographed the biggest ones. None had opened to more than about 1.5 cm wide, but their presence was certainly significant. We cannot tell when they opened. Possibly these were older and not related to a fresh, new dynamic development. Anyhow, this fracturing has now directed our eyes westward to be sure that we are not 'flanked' as this eruption progresses.

"The mid-afternoon overflight on this day brought deep, powerful shock: We witnessed the Kapoho Beach Lots/Vacationland subdivisions being consumed by lava Figure 1.10). A massive ‘aʻā [rough, crumbly lava] flow poured rapidly through the subdivision, reaching beautiful Kapoho Bay on the night of 3 June. Now, it was rapidly filling this shallow bay (Figure 1.11). Residents had been evacuated just before their homes were consumed, but most of their belongings had been left behind in the rush. We watched helplessly as many beautiful homes including one belonging to a friend of mine, and another owned by the County Mayor – burst into flames and instantly disappeared underneath monstrous fiery masses of advancing ʻaʻā, in places 15 m thick. Kapoho Bay and its wide fishpond were island treasures, but quickly became a peninsula of jagged hot rock extending over a kilometer into the ocean. We could only track with our GPS

FIGURE 1.9 A vast river of lava in this area up to 150 m wide escapes Fissure 8 and pours through Leilani Estates behind self-constructed levees. A small tongue of lava overflows a levee in the lower center view toward one home. (It never got that far.) Overflows like this helped construct levees as high as 20 m above the pre-existing landscape. Source: USGS photo by R.W. Hazlett.

FIGURE 1.10 Lava consumes homes in the Kapoho Beach Lots subdivision, 4 June, 2018. The helicopter pilot and I were both choked up to see this, each having friends who owned homes here. Source: USGS photo by R.W. Hazlett.

FIGURE 1.11 4 June, 2018. View westward across Kapoho Bay just after dawn. A rapidly moving ‘a’a lava flow more than 10 m thick has already destroyed about 100 homes, and is now entering the bay. A total of nearly 500 homes would be destroyed by this flow, including all of these visible here. Source: USGS photo by Matt Patrick.

the northern perimeter of the flow because heat, gas, and laze [acidic vapor produced by lava entry into the sea] made flying conditions to the other side perilous. Through the billowing mist we could tell that the lava had made it all the way to the edge of the spectacular coral tidepools at Waiʻopae that everyone feared would be lost. A day and a half later, they are all gone (Figure 1.12). Lava is Nature’s ultimate ‘clean-slater’. A hurricane, earthquake, and even an atomic explosion will leave traces behind of what once was. But a lava flow buries and incinerates human-built structures slowly and utterly, though the social shocks of obliteration and personal losses echo in the aftermath. How strange from the air to see the patterns of streets, orchards, homes, and powerlines now disconnected in small patches across the district like random pieces of a jigsaw puzzle scattered across black asphalt (Figure 1.8). The lava is adding to the island in a beautifully powerful way and providing a future platform for new life, but that is not much comfort here and now.”

As these exciting events were taking place 35–45 km east of Kīlauea’s summit, the floor of Kīlauea’s caldera collapsed in a stepwise fashion. The reservoir beneath Halemaʻumaʻu was pouring out its magma supply through far-away Fissure 8. My notes from 6 July describe this phenomenon:

“The southern part of Kīlauea caldera’s floor continues to drop dramatically, in two ways – (1) by gradual subsidence day-by-day, broken by (2) sudden downward ‘bolts’ we are calling ‘Type-A events’, which can lower an area now covering several square kilometers as much as two meters *all at once*. This rapid, scraping drop generates big, shallow, long-duration earthquakes, generally in the magnitude 5-6 range. Each Type-A event is followed within minutes by a sudden jump back up in the area immediately overlying the magma chamber, and none of us really knows why. Geophysicists think that it must have something to do with alternate release and re-dissolving of gases in response to suddenly changing reservoir pressure. Or, perhaps it is elastic rebound in the crust. There is little empirical background to explain anything at this scale. No one ever expected a Hawaiian-type caldera to develop this way.”

“Mysterious Type-A events are taking place like clockwork. Each event is about the same size, and each is spaced by about a day, 24–26 hours. Like a giant Old Faithful Geyser, you can plan your visit to the summit around them, which HVO does while it continues to evacuate equipment and gear from its creaking headquarters building on Uwekahuna Bluff (now spalling plaster from twisting I-beams). Movers in Hilo wait until a Type-A event takes place, then scurry on up, since for a period of 3–4 hours following each collapse, everything is eerily quiet and stable atop the volcano. After that, the forecastable earthquake swarm leading up to the next event, mostly in the magnitude 2–3 range, starts up once again, putting people on edge once more who live within a few kilometers of the mountaintop.”

FIGURE 1.12 Lava enters the ocean across a broad front, nearly a kilometer wide in this view, where Kapoho Vacationland subdivision and its famous coralline tidepools (Wai'opae) existed a few days earlier. Over a 6-week period, this flow added over 3 km^2 of new land to the island of Hawai'i. Source: USGS photo by R.W. Hazlett.

FIGURE 1.13 Kīlauea [17] caldera floor collapse (foreground) during a Type-A, M-5 seismic event, observed on the afternoon of 6 July, 2018. The crumbling, dust-shrouded outer caldera and crater walls in the background are a couple of hundred meters high, 3 km from the camera. Source: USGS photo by R.W. Hazlett.

I took an afternoon shift viewing Kīlauea caldera from the overlook at the abandoned Volcano House Hotel, perched on the stable north rim. I wanted to experience a Type-A event close at hand and was certainly not disappointed. When it happened an hour and a half after arrival, it startled the hell out of me – the power of it was so overwhelming. It began with a noise like a sonic boom, followed by violent shaking that forced me to grab a rail next to the lounge overlook to avoid being thrown down. My colleague was “dancing” around with me. Inside the hotel, I could hear shifting furniture and a lot of clinking glasses, stored behind the bar. Almost at once, another noise rumbled in, resembling the rushing shush of an approaching wave. This was the sound of countless rockfalls cascading down the high caldera wall to the west (Figure 1.13). The big, widening maw of Halemaʻumaʻu suddenly filled with an evolving plume of dust. This persisted for what seemed like the better part of a minute. Then all this activity stopped as suddenly as if someone had thrown a switch! For the next several hours, the summit was absolutely calm and peaceful – just another beautiful Big Island afternoon. A GPS station indicated that the south caldera floor had dropped 1.7 m during this one intense event.”

Over 60 Type-A events with magnitudes >5 eventually took place, finally ending on 4 August with the new caldera floor over 600 m deeper than it was at the start of the eruption. The rims of a yawning pit, 6 km^2 in area, marked the perimeter of the drained, underlying reservoir. Throughout most of this collapse, from mid-May on, essentially no fresh magmatic ash erupted; this was primarily a *passive* collapse occurrence; just lots of noise and rock dust billowing into the air whenever the crust suddenly dropped.

Within 1–2 hours of each Type-A event, a surge or pulse of lava emerged from Fissure 8. The timing was not coincidental, geophysicists thought, though other surges and pulses, timed from a few minutes to 10–15 minutes apart, also could be seen in the

TABLE 1.1 **Chronology of Events, 2018 Lower East Rift Zone Eruption of Kīlauea Volcano.**

17 April – Hawaiian Volcano Observatory (HVO) issues warning of a possible new vent opening either at PuʻuʻŌʻō or along adjacent areas of the East Rift Zone

21 April – Building magmatic pressure causes the lava lake at Halemaʻumaʻu Crater to overflow

24 April – HVO issues another volcanic hazard warning based on continuing swelling and earthquake activity around PuʻuʻŌʻō.

30 April – PuʻuʻŌʻō Crater floor begins collapsing as earthquakes propagate east into populated lower Puna area.

1 May – Lava lake begins draining at Halemaʻumaʻu. HVO warns residents in lower Puna that an eruption is possible there in a matter of a few days.

3 May – At 5 p.m., Fissure 1 opens up in Leilani Estates subdivision.

4 May – A magnitude 6.9 earthquake, the biggest to strike Hawai‘i in 43 years, takes place as the south flank of Kīlauea slips seaward as much as 5 m.

3–10 May – Short fissures continue opening in Leilani Estates with bursting eruptions of lava from old, stored magma trying to escape. Small flows fed.

10 May – Halemaʻumaʻu lava lake now drained down 300 m, no longer visible from crater rim. HVO issues warning that new fissure outbreaks are likely downrift of Leilani Estates.

12 May – New fissure opens up downrift of initial set, as forecast.

15 May – HVO issues warnings of explosions imminent in draining Halemaʻumaʻu conduit.

16 May – First Halemaʻumaʻu explosions take place.

18 May – Series of Halemaʻumaʻu explosions continues, while hotter, less viscous lava begins pouring from Lower East Rift Zone fissure vents. Larger than previous ones, the flows begin heading toward the sea.

23 May – Series of Halemaʻumaʻu explosions continue, while first lava flows reach the sea southeast of Leilani Estates

27 May – Lava eruption focuses on reactivated Fissure 8 in Leilani Estates, which formed in early May. A large flow moves northeast, soon turning east toward Kapoho.

30–31 May – The main caldera floor begins subsiding around Halemaʻumaʻu. The first of 62 collapse events (“Type-A”) takes place with as many as 700 magnitude 4+ earthquakes per day, for the next two months. Summit gas emissions decline and explosions cease.

3–5 June – Lava reaches the ocean at Kapoho Bay, destroying adjacent residential neighborhoods and farmland. Activity continues unabated at Fissure 8. Type-A events continue at summit.

Mid-July – Lava eruption from Fissure 8 begins to pulsate as height of lava fountaining slowly declines.

2 August – The last of the Type-A events occurs at the summit.

4 August – Eruption has ceased at Fissure 8, except for sporadic bursts of spatter immediately around the crater vent, last visible the first week in September.

stream of emerging lava in the LERZ, possibly related to the way gases escaped the erupting conduit. In general, the greater the time interval between surges, the greater their intensity. We still do not understand their origin.

By the first week in August, Kīlauea had essentially exhausted itself. Lava continued to spurt weakly from the vent inside the Fissure 8 cone until for another month, but otherwise, the show was over. The eruption had not only provided a new, instructive view of what the red volcano Kīlauea could do, but it was also a remarkable opportunity to test new ways of studying volcanoes, from applied drone technologies to infrasound, RSAM analyses, communication-apps, flow-path software, and many other imaginative and useful approaches (Chapter 14). The great eruption of 2018 was certainly an historic event for Hawai‘i, not only the most destructive to property, but one of the best managed in terms of public safety. Not a life was lost. During the 150 days of this activity, about 0.77 km^3 of lava poured out – mostly through Fissure 8 – covering 35 km^2 of land and adding 3.5 km^2 of new land to Hawai‘i Island. The lava buried 50 km of roads and destroyed 716 homes. Total loss of property has been estimated at nearly $800 million dollars. Table 1.1 summarizes the 2018 events.

2021 UPDATE: Kīlauea’s return to activity on 20 December, 2020

Kīlauea’s dramatic summit collapse in 2018 (Figure 1.13) accompanied by rift zone eruptions was not unprecedented; major collapses or drainages of lava from the caldera almost as significant also occurred in (or shortly before) 1823, 1832, 1840, 1868, and 1924. In each case, the caldera eventually healed its “wounds” with outpourings of fresh lava that gradually filled collapse pits and built up new caldera floors, though long quiet periods sometimes passed before eruptions resumed. The collapse in 2018 was no exception. The new subsidence basin remained tranquil, degassing peacefully for 27 months, long enough for a small water lake to appear at the bottom supplied from the surrounding, higher-standing water table. But then on 20 December, 2020, a fresh fissure opened in the northern wall, disgorging molten lava that quickly evaporated the water lake and steadily created a pool of lava ultimately over 200 m deep (Figure 1.14). The eruption was very sluggish compared to all the excitement in 2018, and lasted

FIGURE 1.14 16 April, 2021 view of Halema’uma’u, the ever-changing collapse pit on the floor of Kīlauea Caldera. The down-dropped fault block in the middle ground, 80 m below the overlook, preserves part of the severed National Park Crater Rim Road – still intact though clearly inaccessible. The active lava lake lies 280 m farther down, and has filled Halema’uma’u to a depth of 215 m. The eruptive source vent on the northwest margin of the lake is marked by a plume of blue SO_2 gas. Source: USGS photo by R.W. Hazlett.

a little over five months before the volcano once again became peaceful ...But, not for long! On 29 September, 2021, the volcano sprang back to life in almost the same location, and continues to erupt up to the present (June, 2022). The lake of lava has deepened a further 65 m in the interim.

A Gray Volcano, El Chichón, Erupts in 1982

El Chichón Volcano [57] is located in the State of Chiapas (17.36°N, 93.23°W), a region of southeastern Mexico predominantly populated by the Zoque indigenous people. After six centuries of quiescence, El Chichón erupted explosively on 28 March, 1982, producing heavy ashfalls over southeastern Mexico, forcing the closure of numerous airports and roads. Moderate eruptions continued for a week, and then two major Plinian ("violently explosive"; Chapter 5) eruptions took place on 3 and 4 April. The explosive episode lasted about a week, and it is estimated that it caused nearly 2000 fatalities and the evacuation of about 20,000 people, as well as heavy losses of livestock, and major damage to coffee, cocoa, banana, and other crops. This was the worst volcanic disaster in the history of Mexico, and I (SCR) was there. Before the 1982 eruption, there was scarce information about previous volcanic activity in the region. Around 1928, felt earthquakes and the appearance of small fumaroles in a hill locally called "El Chichón" for a common, locally growing plant, motivated the visit of the German–Mexican geologist Federico Müllerried from the Institute of Geology of the National Autonomous University of Mexico (UNAM) who wrote three papers recognizing El Chichón as an active volcano (Müllerried 1932a, 1932b, 1933). However, no eruption followed the 1928 seismic swarm. Afterwards, El Chichón remained quiet and little-studied for about 40 years. Research revealed that the volcano had not erupted for six centuries, which gave people the general impression that it was dormant and therefore not very threatening. However, its proximity to an oil-producing region and potential for geothermal energy production prompted further geological study. Two geologists from the Mexican Electrical Power Company (Comisión Federal de Electricidad, CFE) felt earthquakes during their fieldwork on the volcano between December 1980 and February 1981 and described them in an unpublished internal CFE report (Canul and Rocha 1981) that was released only after the eruption ended.

But of course, at the time I was not aware of any of that. Until then, my background had been mostly in physics of the Earth's interior. I began switching to physical volcanology after observing the 1975–1976 and 1982 effusive activity of Volcán de Colima [51]. The first news about something happening in Chiapas arrived at our Institute of Geophysics (IGEF) at UNAM in Mexico City, 667 km to the northwest of El Chichón, on Monday 22 March, 1982. Local Zoque residents living in a remote jungle area with poor communications had been reporting earthquakes to authorities for weeks. They seemed to be increasing in magnitude. Around Tuesday 23 March, the Chiapas state government contacted UNAM with a request to investigate the phenomenon. At this stage, it was not quite clear at the IGEF if the felt seismicity was a tectonic swarm – not uncommon in the intensively fractured water-rich karstic crust of Chiapas (Figueroa 1973; Mota et al. 1984) – or volcano-related seismicity. The volcano sits in the middle of a massive tertiary siltstone and sandstone mountain range, underlain by Cretaceous dolomitic limestone and a sequence of Jurassic or Cretaceous evaporitic anhydrite and halite beds. It is isolated; its closest other volcano of geologically young age is 200 km away (Duffield et al. 1984). Apart from the Müllerried study, the only published information about El Chichón at the time was a brief geographical description in the International Association of Volcanology and Chemistry of Earth's Interior (IAVCEI) Catalog of Active Volcanoes of the World and Solfatara Fields (Mooser et al. 1958) and a single mineralogy-oriented paper (Damon and Montesinos 1978).

At the time, the IGEF did not have a department of volcanology and we belonged to the Department of Seismology. At UNAM, the staff involved with seismic studies was split into two separate institutes: (1) Geophysics, which focused on tectonic seismology and (2) Engineering, concerned with construction in earthquake-prone environments (IGEF and IINGEN, respectively). Mexico is a country with high tectonic seismicity and recording the aftershock activity that followed major earthquakes was a common task. That was done mostly using 15 kg MEQ-800 "portable" seismic stations each consisting of a battery-operated smoked paper helicorder, a vertical-motion seismometer, and two car batteries with a charger to power electronics for a reasonable time, plus various accessory equipment.

Survival Tips for Field Volcanologists

In emergency situations, always have an escape plan; know the lay of the land and available routes for making any exit needed. Look over your shoulders from time to time to be sure that you are not blindsided by something happening nearby; e.g. a hidden lava flow moving through the forest, a slope that is shedding small, frequent rockfalls, strange sounds. Near threatened structures watch out for "secondary" hazards, such as downed electric lines, potentially explosive fuel tanks or septic systems. Be personally prepared. . .have personal protection equipment handy, plenty of water, flashlight and batteries, gloves, strong boots, basic first aid kit, and survival snacks. Radio or cellphone communication capability is essential.