Characteristics of Hawaiian Volcanoes
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Chapter 1

The Hawaiian Volcano Observatory—A Natural Laboratory for Studying Basaltic Volcanism

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> A volcano observatory must see or measure the whole volcano inside and out with all of science to help.
>
> —*Thomas A. Jaggar, Jr.* (1941)

Abstract

In the beginning of the 20th century, geologist Thomas A. Jaggar, Jr., argued that, to fully understand volcanic and associated hazards, the expeditionary mode of studying eruptions only after they occurred was inadequate. Instead, he fervently advocated the use of permanent observatories to record and measure volcanic phenomena—at and below the surface—before, during, and after eruptions to obtain the basic scientific information needed to protect people and property from volcanic hazards. With the crucial early help of American volcanologist Frank Alvord Perret and the Hawaiian business community, the Hawaiian Volcano Observatory (HVO) was established in 1912, and Jaggar's vision became reality. From its inception, HVO's mission has centered on several goals: (1) measuring and documenting the seismic, eruptive, and geodetic processes of active Hawaiian volcanoes (principally Kīlauea and Mauna Loa); (2) geological mapping and dating of deposits to reconstruct volcanic histories, understand island evolution, and determine eruptive frequencies and volcanic hazards; (3) systematically collecting eruptive products, including gases, for laboratory analysis; and (4) widely disseminating observatory-acquired data and analysis, reports, and hazard warnings to the global scientific community, emergency-management authorities, news media, and the public. The long-term focus on these goals by HVO scientists, in collaboration with investigators from many other organizations, continues to fulfill Jaggar's career-long vision of reducing risks from volcanic and earthquake hazards across the globe.

This chapter summarizes HVO's history and some of the scientific achievements made possible by this permanent observatory over the past century as it grew from a small wooden structure with only a small staff and few instruments to a modern, well-staffed, world-class facility with state-of-the-art monitoring networks that constantly track volcanic and earthquake activity. The many successes of HVO, from improving basic knowledge about basaltic volcanism to providing hands-on experience and training for hundreds of scientists and students and serving as the testing ground for new instruments and technologies, stem directly from the acquisition, integration, and analysis of multiple datasets that span many decades of observations of frequent eruptive activity. HVO's history of the compilation, interpretation, and communication of long-term volcano monitoring and eruption data (for instance, seismic, geodetic, and petrologic-geochemical data and detailed eruption chronologies) is perhaps unparalleled in the world community of volcano observatories. The discussion and conclusions drawn in this chapter, which emphasize developments since the 75th anniversary of HVO in 1987, are general and retrospective and are intended to provide context for the more detailed, topically focused chapters of this volume.

Introduction

The eruption of Vesuvius in 79 C.E. prompted the first scientific expedition (by Pliny the Elder) to study volcanic phenomena, as well as the first written eyewitness account (by Pliny the Younger) of eruptive activity (Sigurdsson, 2000). The new science of geology emerged in the 19th century, focusing on the deduction of past events from current Earth exposures—"the present is the key to the past." This approach was also used for studying active geologic processes like volcanic eruptions: scientific studies of volcanoes were conducted during short-lived expeditions, generally undertaken in response to major eruptions (for

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instance, the 1815 Tambora and 1883 Krakatau eruptions in Indonesia) and done substantially after the event was over. Three large explosive eruptions in the Caribbean-Central American region in 1902—La Soufrière (Saint Vincent, West Indies), Montagne Pelée (Martinique, West Indies), and Santa María (Guatemala)—claimed more than 36,000 lives and showed the inadequacy of the deductive approach for protecting people and property from natural disasters. These catastrophic eruptions in the early 20th century set the stage for the emergence of the science of volcanology as we know it today.

Dr. Thomas Augustus Jaggar, Jr., a 31-year-old geology instructor at Harvard University (and also a part-time employee of the U.S. Geological Survey [USGS]), was a member of the scientific expedition sent by the U.S. Government to investigate the volcanic disasters at La Soufrière and Montagne Pelée in 1902. High-speed, incandescent pyroclastic flows (nuées ardentes) from Montagne Pelée obliterated the city of St. Pierre and killed 29,000 people in minutes, making it the deadliest eruption of the 20th century (Tanguy and others, 1998, table 1). The Pelée eruption's power and deadly impacts left a profound impression on the young professor, and he decided to devote his career to studying active volcanoes (Apple, 1987). A half-century later, Jaggar reflected in his autobiography: "As I look back on the Martinique expedition, I know what a crucial point in my life it was. . . . I realized that the killing of thousands of persons by subterranean machinery totally unknown to geologists and then unexplainable was worthy of a life work" (Jaggar, 1956, p. 62). In reaching his life-changing decision, Jaggar was swayed by his strong conviction that the expeditionary approach in studying volcanoes was inadequate. Instead, he firmly believed that, to understand volcanoes fully and to mitigate effectively the impacts of their hazards, it is necessary to study and observe them continuously—before, during, and after eruptions. After meeting the renowned American volcanologist Frank Alvord Perret, who was already using this approach at Vesuvius in 1906, Jaggar became even more convinced about advocating for the establishment of permanent Earth observatories. While at Harvard, and later as a professor at the Massachusetts Institute of Technology (MIT), Jaggar pursued his life's goal to establish a permanent observatory at some place in the world to study volcanoes and earthquakes (see "Founding of the Hawaiian Volcano Observatory" section, below).

Scope and Purpose of This Chapter

In 1987, to commemorate the 75th anniversary of the founding of HVO, the U.S. Geological Survey published Professional Paper 1350 (Decker and others, 1987). This two-volume work still stands as the most comprehensive compilation of the many studies on Hawaiian volcanism by USGS and other scientists through the mid-1980s. The 62 papers contained in Professional Paper 1350 (and the references cited therein) provide an invaluable database for understanding Hawaiian volcanism. It is beyond the scope of this volume to synthesize fully the abundance of scientific data, new interpretations, and insights that have accrued in the quarter century since that publication. Instead, the papers in this current volume are retrospective and focus on volcano monitoring and selected topical studies that refine and extend our ideas about how Hawaiian volcanoes work. Efforts summarized here have been led primarily by HVO researchers and other USGS scientists but were often completed in close collaboration with non-USGS colleagues from government, academic, and international institutions. Much of HVO's contribution to science since 1987 has been the direct result of monitoring the continuing eruption of Kīlauea Volcano.

Specifically, this introductory chapter provides historical context for the subsequent chapters, which encompass these themes: the key role of permanent seismic and other geophysical networks in volcano monitoring (Okubo and others, chap. 2); evolution of oceanic shield volcanoes (Clague and Sherrod, chap. 3); flank stability of Hawaiian volcanoes (Denlinger and Morgan, chap. 4); magma supply, storage, and transport processes (Poland and others, chap. 5); petrologic insights into basaltic volcanism (Helz and others, chap. 6); chemistry of volatiles and gas emissions (Sutton and Elias, chap. 7); dynamics of Hawaiian eruptions (Mangan and others, chap. 8); effusive basaltic eruptions (Cashman and Mangan, chap. 9); and natural hazards associated with island volcanoes (Kauahikaua and Tilling, chap. 10). Interpretations provided by these topical studies are derived from, and constrained by, long-term data—visual, geophysical, and petrologic-geochemical—on the eruptive processes and products of Kīlauea and Mauna Loa obtained by HVO over many decades. The papers in this volume, we believe, reflect current HVO science and reinforce Jaggar's vision that reduction of volcano risk requires the integration of systematic monitoring data and related research, comprehensive hazards assessments based on past and current eruptive activity, and effective communication of hazards information to authorities and the potentially affected populace. Thanks to the progress in the past 100 years, we now have many more scientific tools than were available in the early 20th century to improve our understanding of volcanic phenomena. Clearly, the legacy of Thomas Jaggar is alive and well.

The history of HVO is, in many ways, the history of basaltic volcanology. It is almost impossible to separate contributions by HVO and USGS scientists and student volunteers from those of our partners in academia and other institutions, but we chose to focus on the big ideas that came from work on Kīlauea that predominantly involved scientists and students from HVO and other USGS groups. The future of systematic scientific studies of Hawaiian volcanoes relies now, as during the past century, on continued government-academic and scientist-student partnerships.

Founding of the Hawaiian Volcano Observatory

After his work at Montagne Pelée in the Caribbean and Vesuvius in Italy, Thomas Jaggar led a scientific expedition, funded by Boston businessmen, to various volcanoes in the Aleutian Islands of Alaska in 1907. There, he witnessed the reactivation of Bogoslof volcano rising out of the sea but bemoaned the loss of data on the continuing eruption after the expedition had returned to the United States:

> The remarkable processes of volcanism and earth movement in the Aleutian Islands deserve continuous, close study from an observatory erected for the purpose on Unalaska. The winter of 1907–8 has been wasted—lost to science, because no observers were stationed there. (Jaggar, 1908, p. 400).

The Messina earthquake, later in 1908, added to the human toll from natural disasters that Jaggar summarized as "100 persons a day since January 1, 1901" (Jaggar, 1909). In his 1909 publication about the earthquake, Jaggar put forth his master plan for 10 small observatories in "New York, Porto Rico [sic], Canal Zone, San Francisco, Alaska, Aleutian Islands, Philippines, Hawaii, Scotland, and Sicily." The overall cost would be a $4.2 million endowment that would continue support for each observatory with $10,000 per year (Jaggar, 1909). The goals of these observatories were simple: (1) prediction of earthquakes, (2) prediction of volcanic eruptions, and (3) earthquake-proof engineering and construction in volcanic and seismic lands (Jaggar, 1909).

He also expressed deep admiration for the efforts of the Japanese in establishing geophysical monitoring (". . . their island empire is girdled with observatories") and spent 5 weeks in Japan in 1909 with layovers in Honolulu both ways (Jaggar, 1910). During his return layover, Jaggar spoke to the Honolulu Chamber of Commerce about the unique possibilities for science afforded by the establishment of an observatory at the edge of Kīlauea Volcano. Lorrin Thurston, a well-connected businessman and political figure, also spoke to the Chamber about the "purely commercial advantages of securing for Kilauea such an observatory. . . . From a purely business point of view it would pay Hawaii to subscribe the funds necessary for the maintenance of the observatory, irrespective of the great scientific benefit to accrue." Jaggar asked for a commitment of $5,000 per year to locate an observatory at Kīlauea but received a promise of only half that amount before he left for Boston (Hawaiian Gazette, 1909). With this partial encouragement, Jaggar redoubled his efforts back in Boston to seek financial supporters—in New England as well as in Hawai‘i—to build the observatory, including the facilities to house instruments and records, a laboratory, and offices.

Jaggar and his associates were able to raise funds during 1909–11 in Boston to purchase seismometers and temperature-measuring instruments, to support initial field studies at Kīlauea, and to construct a temporary small frame building (the "Technology Station") on the rim of Halema‘uma‘u Crater (fig. 1*A*) for observations of the continuous lava-lake activity. Neither Jaggar nor any other MIT scientists were able to travel to Hawai‘i during 1910–11, however, and so the earliest observations and studies at Kīlauea fell to E.S. Shepherd (Geophysical Laboratory of the Carnegie Institution of Washington, D.C.) and Frank A. Perret (Apple, 1987). Doubtless, Jaggar worried that his delay would be during a critical time in the nascent observatory; thus, he wisely enlisted Perret—a prominent, volcano-savvy scientist already well known for his work at Vesuvius, Etna, and Stromboli volcanoes—to be his proxy. Jaggar considered Perret to be "the world's greatest volcanologist" (Jaggar, 1956, p. xi).

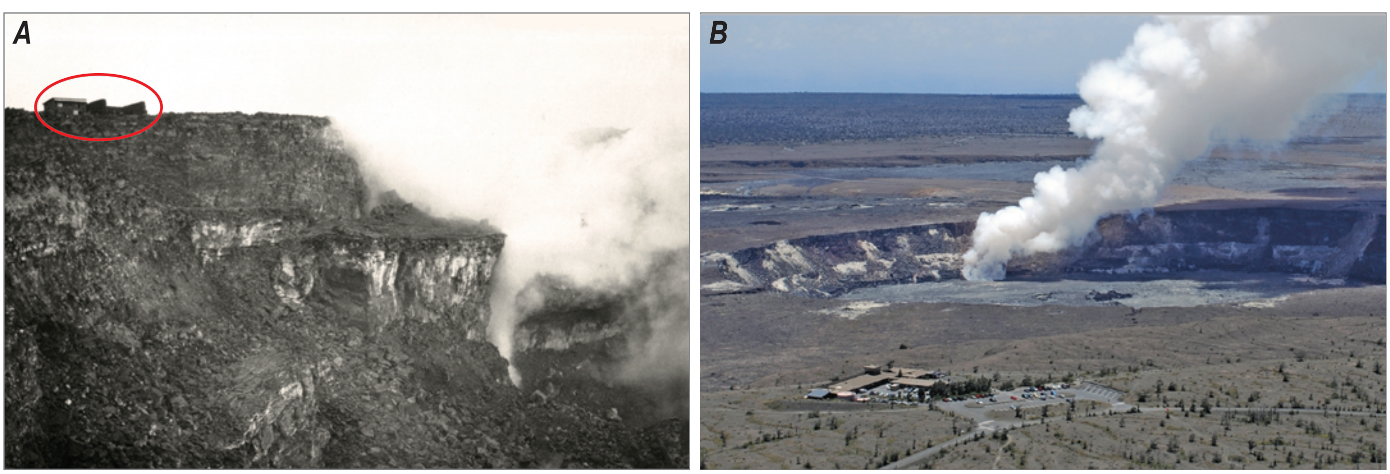

Figure 1. Photographs showing facilities of the Hawaiian Volcano Observatory (HVO) through the years. *A*, The "Technology Station" (circled) on the eastern rim of Halema‘uma‘u Crater, built by Frank A. Perret in 1911, was the first, though temporary, of a number of buildings that HVO has occupied since its founding (USGS photograph by Frank A. Perret). *B*, Aerial view of present-day HVO and Jaggar Museum (lower left corner) on the northwestern rim of the summit caldera of Kīlauea Volcano, with plume rising from vent in Halema‘uma‘u Crater. This vent opened in mid-March 2008 and has remained active through mid-2014 (USGS photograph taken in September 2008 by Michael P. Poland).

Under Jaggar's direction, Perret built the Technology Station and conducted an experiment to measure the temperature of Kīlauea's active lava lake (see "Field Measurements of Lava Temperature" section, below). He also started nearly continuous observations and measurements of the lava lake then within Halema'uma'u Crater. At Thurston's urging, he wrote weekly updates in *The Pacific Commercial Advertiser* (later *The Honolulu Advertiser*), which happened to be owned by Thurston. In those updates, which began HVO's long tradition of regular scientific communications and public outreach (see "Communication of Scientific Information and Public Outreach" section, below), Perret listed himself as "Director pro tem" of the Technology Station, the first building of the not yet formally established observatory. In the summer of 1911, Perret's work, as summarized weekly in Thurston's newspaper, greatly impressed and excited Thurston's group of Honolulu financial backers, prompting the group—formally organized on October 5, 1911, as the "Hawaiian Volcano Research Association" (HVRA)—to renew their pledge of financial support for the permanent observatory at Kīlauea. Perret's achievements thus provided a solid financial, as well as scientific, base upon which Jaggar soon built the formal observatory. HVRA's funds, however, did not directly support HVO's effort until mid-1912, when the 5-year contract between HVRA and MIT became official (Dvorak, 2011).

In January 1912, Jaggar (fig. 2) arrived to resume the continuous observations begun by Perret and to start erecting an observatory building with financial and material donations from Hilo businesses. The year 1912 has long been recognized as when HVO was founded. Though there was no formal ceremony or event to mark its "official" establishment, 1912 has long been recognized as the year when HVO was founded. In any case, the founding date must be some time between July 2, 1911, when Perret arrived to begin continuous observations, and July 1, 1912, when Jaggar received his first paycheck as HVO Director from the HVRA (Dvorak, 2011; Hawaiian Volcano Observatory Staff, 2011). By mid-February 1912, construction was begun on what was to become the first of several permanent facilities of HVO, located near the present-day Volcano House Hotel on the northeastern rim of Kīlauea Caldera (Apple, 1987).

Why in Hawai'i?

To fully appreciate Jaggar's accomplishment in establishing HVO, we first must look back in time to the early 20th century. Before 1912, only three volcano observatories existed in the world: (1) the Vesuvius Observatory (Reale Osservatorio Vesuviano [now a museum] on the flank of Vesuvius volcano in Italy), whose construction was completed in 1848; (2) the fledgling observatory established in mid-1903 on the island of Martinique by the French in response to continuing eruptive activity at Montagne Pelée; and (3) the Asama Volcano Observatory, Japan, established in 1911 (Suwa, 1980) by the renowned seismologist Fusakichi Omori, who later became a close colleague and friend of Jaggar.

Given Hawai'i's geographic isolation in the middle of the Pacific Ocean, what prompted Jaggar to build a volcano observatory at Kīlauea rather than pursuing his scientific studies at one of the three existing observatories? Jaggar (1912, p. 2) had a number of compelling scientific, as well as practical, reasons, including these: (1) Kīlauea's location is in "American" territory rather than in a foreign land, "and these volcanoes are famous . . . for their remarkably liquid lavas and nearly continuous activity"; (2) at other volcanoes the eruptions are more explosive and an observatory located close

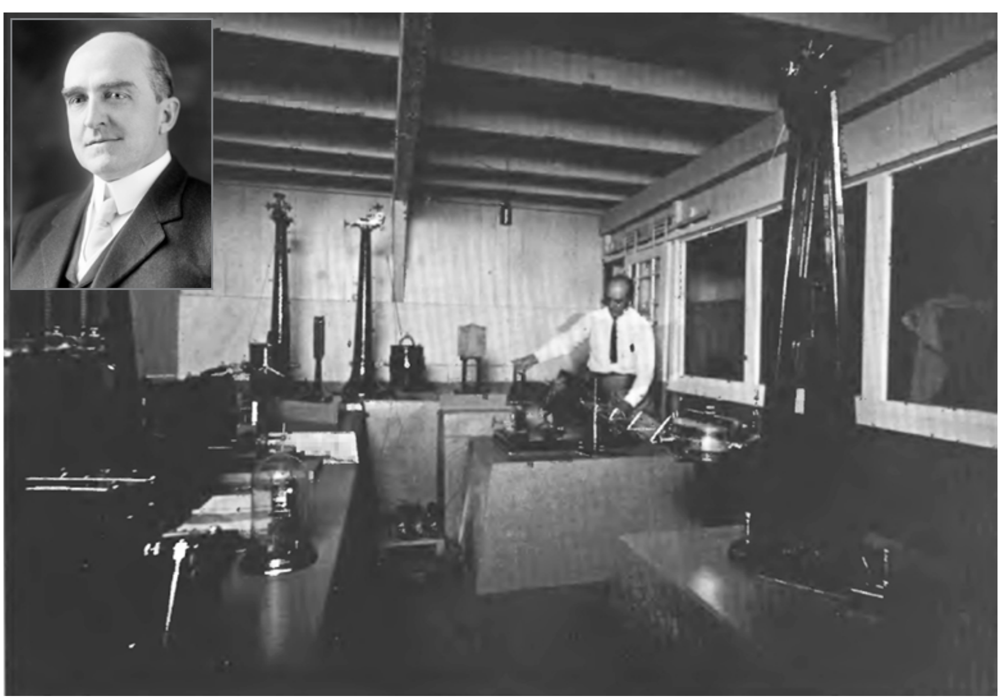

Figure 2. Photograph showing Thomas A. Jaggar, Jr., founder of the Hawaiian Volcano Observatory (HVO), tending to seismometers in 1913 in the Whitney Laboratory of Seismology (photograph courtesy of the Bishop Museum, Honolulu). Inset (upper left corner) shows portrait photograph of Jaggar in 1916 (USGS/HVO photograph).

enough to the center of activity is in some danger. Kīlauea, while displaying great and varied activity, is relatively safe; (3) earthquakes are frequent and easily studied; and (4) "Kilauea is very accessible," only 50 km by road from Hilo harbor, which, in turn, is only a one-day sail from Honolulu (the most developed city in the Territory of Hawaii). Jaggar obviously believed that these reasons more than compensated for the disadvantages of Hawai‘i's geographic remoteness.

For Jaggar, another important motivation for locating an observatory in Hawai‘i was the powerful support from Thurston, who was well connected financially and was keen to promote Kīlauea as a tourist attraction. At the time, the volcano was already an emerging tourist destination, and Thurston was the major stockholder of the Volcano House Hotel on the rim of Kīlauea Caldera and the owner of the train from Hilo to the volcano. Thurston's role as a tourism promoter is aptly described by Dvorak (2011, p. 35):

> His grand plan was to make Kilauea one of the scheduled stops for the increasingly numerous passenger ships crossing the Pacific. If someone wanted to see the lava lake, that person had to ride his train; if anyone wanted to stay overnight, his hotel would provide the only available accommodations.

Indeed, according to Allen (2004, p. 196), "Lorrin A. Thurston created the foundation for Hawaii tourism." Conceivably, funds raised by the HVRA to support HVO were given more for the promise of tourism enhancement, rather than for stated reasons of scientific advancement or reduction of risk. This notion, while not explicitly documented, may explain the final phrase of one of Jaggar's major goals for HVO (Jaggar, 1913, p. 4): "*Keep and publish careful records, invite the whole world of science to co-operate, and interest the business man*" [italics in original]. A skillful promoter himself, Jaggar thus successfully merged his scientific interests with the more commercial interests of the Honolulu businessmen.

Reflecting on the founding of HVO decades later, Jaggar comments in his book *Volcanoes Declare War* (1945, p. 148):

> It is appropriate that Honolulu should have been the American community to establish first a volcano observatory. We are in the midst of the greatest ocean, surrounded by earthquakes and volcano lands. The place is like a central fire station, and there is some appeal to the imagination in possessing a world fire alarm center.

After alluding to several "disasters" (volcanic and earthquake) in the circum-Pacific regions, he states that these disasters "and a hundred others constitute an endless warfare, and what more fitting center for mobilization against it than the natural laboratory of the Island of Hawaii?" Jaggar clearly envisioned an observatory as needing to employ multiple scientific approaches and all available and emerging technologies in its studies. With its frequent eruptions, earthquakes, and tsunamis, the Island of Hawai‘i was the perfect locale for conducting continuous scientific observation to more fully understand eruptive and seismic phenomena and their associated hazards. HVO's studies of earthquake, volcanic, and tsunami hazards and associated mitigation strategies, with some case histories, are treated in the chapter by Kauahikaua and Tilling (this volume, chap. 10).

Post-Jaggar History of HVO

Jaggar served as HVO director through periods when the observatory was administered by the Weather Bureau (1919–24), the U.S. Geological Survey (1924–35), and the National Park Service until his retirement in 1940. In 1947, administration of HVO permanently returned to the U.S. Geological Survey and, in 1948, the HVO operation was relocated to its present site at Uēkahuna Bluff on the caldera's northwestern rim (fig. 1*B*); its facilities were gradually expanded with addition of a geochemistry wing in the early 1960s and the construction in 1985–86 of a much larger adjoining building with a viewing tower. For detailed accounts of the pivotal roles played by Jaggar, Perret, Thurston, and the HVRA in the founding of HVO and of the observatory's early history, see Macdonald (1953a), Apple (1987), Barnard (1991), Hawaiian Volcano Observatory Staff (2011), Dvorak (2011), Kauahikaua and Poland (2012), and Babb and others (2011).

Developing, Testing, and Using Volcano-Monitoring Techniques

Since the growth and spread of volcano surveillance throughout the world, experience clearly has shown that seismic and geodetic monitoring techniques are the most diagnostic and useful tools to detect eruption precursors (Tilling, 1995; Scarpa and Tilling, 1996; McNutt, 2000; McNutt and others, 2000; Dzurisin, 2007; Segall, 2010). By the early 20th century, the common association between premonitory seismicity and ground deformation had been documented (for example, Omori, 1913, 1914; Wood, 1913, 1915). As a specific example, after summarizing seismic and ground-tilt behavior at Kīlauea, *The Volcano Letter* of August 14, 1930, states (Powers, 1930, p. 3),

> The conclusion drawn from all this evidence is that lava pressure is increasing under Halemaumau. **It is impossible to say whether or not this will result in an eruption,** [bold in original] but it can be said confidently that conditions look more favorable now than at any time in the past several months.

On November 11, 1930, an 18-day eruption began in Halema‘uma‘u.

Throughout the 20th century, HVO has served as a developing and testing ground for volcano-monitoring instruments and techniques, many of which have been further adapted for use at other volcanoes worldwide. In recent decades, advanced satellite-based volcano-monitoring techniques—Global Positioning System (GPS), interferometric synthetic aperture radar (InSAR), and thermal imaging—have been successfully applied at Kīlauea and Mauna Loa, providing much more complete spatial and temporal time series of deformation patterns and lava-flow inundation than ever before. The data collected by HVO's long-term ground-based monitoring program, however, have proved to be invaluable for checking and validating the results obtained from space-age monitoring techniques. In summarizing HVO deformation studies and techniques employed during 1913–2006, Decker and others (2008, p. 1–2) emphasized that "Many of the techniques are complementary; for example, using GPS and satellite measurements of benchmark positions provides 'ground truth' for InSAR (satellite radar interferometry) maps." Below, we offer some examples of developments in instrumental and volcano-monitoring techniques during HVO's history.

Seismic Monitoring

The use of seismic waves to detect unrest at volcanoes began in the mid-19th century. A Palmieri (electromagnetic) seismograph at the Vesuvius Observatory detected precursory seismic activity before the 1861, 1868, and 1872 eruptions at Mount Vesuvius (Giudicepietro and others, 2010). The first seismometer in Hawai‘i was installed on O‘ahu in 1899 (Klein and Wright, 2000), and instrumental recording of earthquakes on the Island of Hawai‘i was initiated with the completion in 1912 of the Whitney Laboratory of Seismology (fig. 2)—a basement vault beneath HVO's main building. The first seismometers at HVO were two instruments imported from Japan (shipped directly to Hawai‘i) and one from Germany (shipped from Strasburg via Boston); some of these were modified later to better record volcanic seismicity at Kīlauea. The data from the seismographs that were collected in the HVO vault were flawed for a variety of reasons (for instance, building vibrations, nearby cultural noise, wide fluctuations in vault temperature) but still provided useful information (Apple, 1987; Klein and Wright, 2000). For example, these first instruments were sufficient in establishing that Hawaiian eruptions were preceded by increased seismicity and ground tilt changes (Wood, 1915).

During the early decades of seismic monitoring, HVO never operated more than five stations (two at Kīlauea's summit, one at ~3,300 m elevation on the eastern flank of Mauna Loa, and two outlying ones in Kealakekua and Hilo). Moreover, these early instruments were heavy and unwieldy, had low sensitivity, and lacked the capability to transmit data to the observatory. It was not possible to determine accurate earthquake locations because of the inadequate density of seismometers, imprecise timing mechanisms, and lack of direct data transmission. Nonetheless, the early seismic recordings generally sufficed to estimate relative intensity and distance to origin and to discriminate whether an earthquake was associated with Kīlauea, Mauna Loa, or Hualālai or was a teleseism (Apple, 1987; Wright, 1989; Wright and others, 1992a).

Seismic monitoring at HVO was upgraded substantially with the arrival in 1953 of seismologist Jerry P. Eaton, who introduced the smaller, more sensitive, electromagnetic seismometer and established the first telemetered seismic network at Kīlauea within a few years (Wright, 1989; Klein and Wright, 2000; Okubo and others, this volume, chap. 2). Signals from six seismometers were transmitted to the observatory via overland cables and recorded on smoke-drum seismographs. Data from this rudimentary network, combined with a crustal-velocity structure model also developed by Eaton, made possible routine determination of earthquake locations and magnitudes; Eaton's modernization of the network enabled HVO to produce catalogs of reliably located earthquakes by the 1960s (Wright, 1989). Equally important, Eaton's seismic network in Hawai‘i served as a prototype upon which a number of "modern" networks in other regions (for example, California) were based.

With expanded coverage, more sensitive instruments, and a more accurate seismic velocity model, the quality of the data catalog improved. By 1974, the HVO seismic network had grown to 34 seismic stations, and by 1979 all seismic data were processed by computer (Klein and others, 1987). The availability of high-quality data from the modern seismic network made it possible to extend the catalog of Hawaiian earthquakes back in time by estimating locations and magnitudes of reported historical events (Wyss and Koyanagi, 1992; Klein and Wright, 2000). The first digital seismometers were installed at Kīlauea as part of a joint United States-Japan seismic experiment in 1996 (McNutt and others, 1997); about 10 broadband seismometers remained operational at Kīlauea summit after the experiment but were not used in routine processing until 2007, when HVO's data acquisition software was upgraded from Caltech-USGS Seismic Processing (CUSP) to Earthworm (Okubo and others, this volume, chap. 2). The American Recovery and Reinvestment Act funding of 2009 allowed HVO to fully upgrade its seismic network with more broadband seismometers and digital telemetry. As of this writing (mid-2014), HVO's seismic network (fig. 3*A*) is among the densest volcano-monitoring networks in the world, consisting of 57 stations over the five volcanoes of the island, 21 of which use broadband digital instruments.

HVO's seismic-monitoring data constitute an integral component in chronological narratives and interpretations of all Hawaiian eruptions since the first instrument became operational. Okubo and others (this volume, chap. 2) review, in detail, the evolution of HVO's seismic monitoring systems with time, highlighting the significant findings from progressively improving data that sharpen our understanding of how Hawaiian and other basaltic volcanoes work.

Geodetic Monitoring

It is now well demonstrated that the surfaces of active volcanoes deform in response to inflation or deflation of subsurface magma reservoirs and hydrothermal systems (see, for example, Murray and others, 2000; Dzurisin, 2007). This phenomenon had been recognized but was poorly understood in the early 20th century; however, from its beginning in 1912, HVO used geodetic measurements to track ground deformation. Decker and others (2008) provide a detailed account of the methodologies—including some developed, adapted, or refined by HVO—that have been employed for deformation studies on active Hawaiian volcanoes. Drawing from this summary, we comment below on the historical importance of some of the early techniques and measurements and then consider satellite-based geodesy.

Tilt

The earliest tilt measurements were made after the discovery that the seismographs in the basement of HVO's first building (the "Whitney Vault") were affected by deflection (relative to the vault floor) of the horizontal pendulums, apparently in response to deformation of Kīlauea's summit. The deflection-induced offsets on the seismograms could be related to summit tilt (Apple, 1987). "Thus, the Hawaiian Volcano Observatory . . . inadvertently began to record tilt continuously . . . from 1913 to 1963" (Decker and others, 2008, p. 8). While crude, these inadvertent seismometric measurements well recorded the large tilt changes related to the 1924 explosive eruptions. Beginning in the 1950s, the quality of tilt measurements improved greatly with use of permanent and portable water-tube tiltmeters (Eaton, 1959) and by the installation in 1966 of a continuously recording mercury-capacitance tiltmeter in the basement of HVO's facilities on Uēkahuna Bluff (the "Uēkahuna Vault"; Decker and others, 2008).

Additional continuously recording electronic tiltmeters, including electronic borehole tiltmeters, were later installed at Kīlauea and Mauna Loa (fig. 3*C*). Four analog borehole tiltmeters operating along the Kīlauea East Rift Zone (ERZ) documented dike propagation and the onset of the Puʻu ʻŌʻō eruption in January 1983 (Okamura and others, 1988). The borehole tilt networks were expanded throughout the 1990s and into the 21st century, and during 2010–11, several advanced digital borehole tiltmeters were installed on Kīlauea and Mauna Loa (their broad frequency response allows them to record low-frequency seismic tremor and

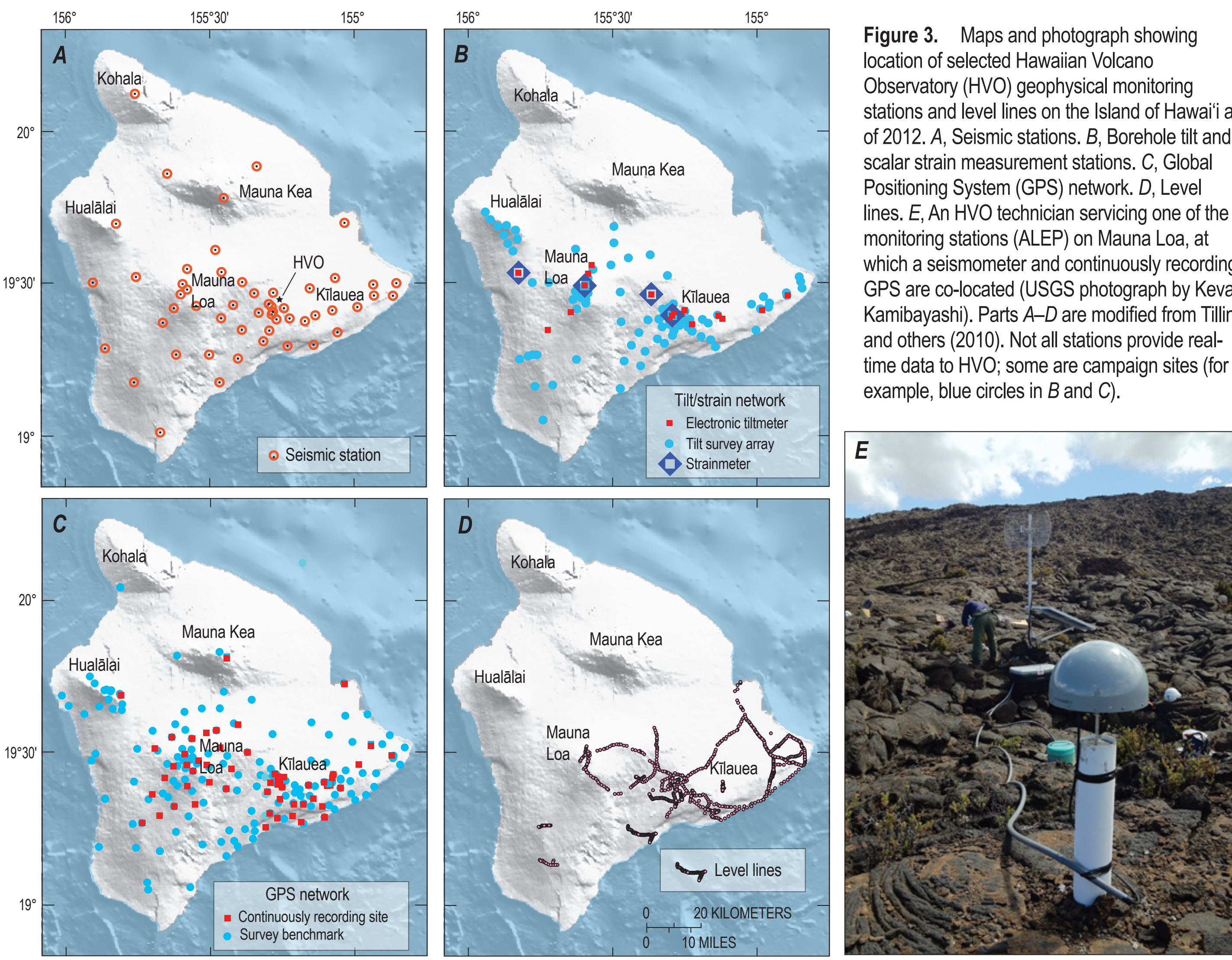

Figure 3. Maps and photograph showing location of selected Hawaiian Volcano Observatory (HVO) geophysical monitoring stations and level lines on the Island of Hawaiʻi as of 2012. *A*, Seismic stations. *B*, Borehole tilt and scalar strain measurement stations. *C*, Global Positioning System (GPS) network. *D*, Level lines. *E*, An HVO technician servicing one of the monitoring stations (ALEP) on Mauna Loa, at which a seismometer and continuously recording GPS are co-located (USGS photograph by Kevan Kamibayashi). Parts *A*–*D* are modified from Tilling and others (2010). Not all stations provide real-time data to HVO; some are campaign sites (for example, blue circles in *B* and *C*).

teleseisms and blurs the line between seismic and geodetic monitoring). Tilt measurements at Kīlauea's summit since 1912 (fig. 4) constitute the world's longest duration and most comprehensive time-series dataset for such measurements.

Electronic Distance Measurement (EDM)

Among the world's volcano observatories, HVO was a pioneer in using theodolites, or electronic distance measurement (EDM), to routinely measure horizontal displacements at deforming volcanoes, beginning in 1964 (Decker and others, 1966). A major advantage of EDM over traditional triangulation is the relative ease in measuring three sides of a triangle ("trilateration") to yield precise determination of horizontal displacement vectors. Trilateration surveys in the 1970s and 1980s were HVO's mainstays for tracking horizontal distance changes related to eruptions, intrusions, and earthquakes (Decker and others, 1987, 2008). HVO's network of EDM benchmarks, later also used for GPS monitoring (fig. 3*D*), grew significantly through the early 1990s. EDM data also conclusively showed that Kīlauea's south flank was moving seaward several centimeters per year (see "Flank Instability" section, below). The EDM technique is now used only for training purposes, to give students and scientists, mostly from developing countries, background about ground-deformation monitoring (see discussion in "Cooperative Research and Work with Other Organizations" section, below).

Satellite-Based Geodesy

During the past quarter century, satellite-based techniques (space geodesy) have increasingly been used to measure ground deformation related to a wide variety of dynamic earth processes, including fault movement/rupture and strain accumulation and release at volcanoes. To date, the two techniques most widely used to detect and image deformation at active volcanoes are the Global Positioning System (GPS) and interferometric synthetic aperture radar (InSAR). (For good summaries of the principles and applications of these techniques, see Dzurisin, 2007; Lu and Dzurisin, 2014.)

Because repeat GPS measurements can yield both vertical and horizontal displacements, the GPS technique quickly became the geodetic-monitoring tool of choice at Hawaiian and other volcanoes. Beginning in 1996, in cooperation with investigators at the University of Hawai'i, Stanford University, and other institutions, HVO established sites for continuous GPS measurement on Kīlauea, Mauna Loa, and Mauna Kea volcanoes. At present, HVO's continuous GPS monitoring network consists of 60 receivers (fig. 3*D*). In the 21st century, the combination of continuous and campaign GPS measurement, together with conventional geodetic methods, has provided greater time resolution for geodetic changes at Hawaiian volcanoes unattainable in the previous century. The comprehensive geodetic data now available make possible more

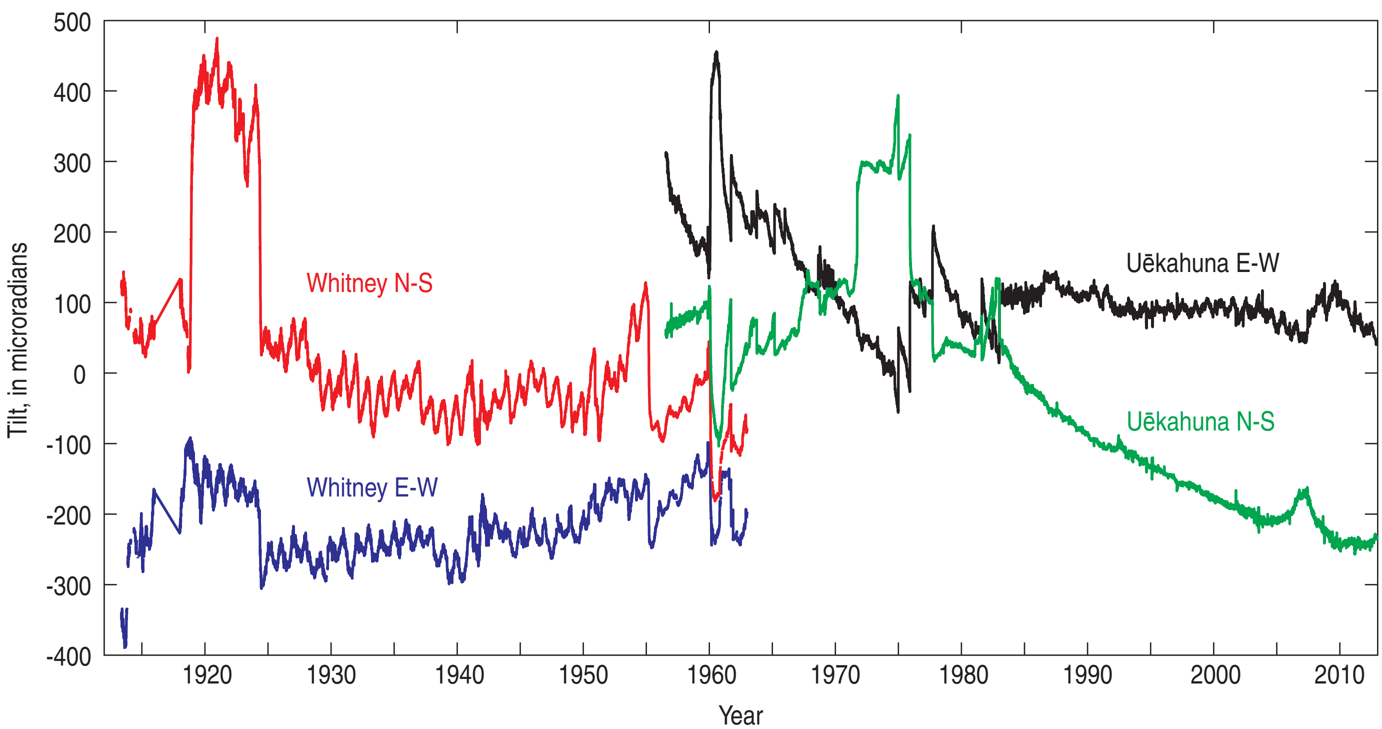

Figure 4. Graph showing fluctuations in summit tilt at Kīlauea Caldera during the period 1913–2011, as measured by the seismometric method in the Whitney Vault and by water-tube tiltmeters at Uēkahuna (see text for discussion). Tilt readings in both north-south and east-west directions are shown. The seismometric tilts have been converted to microradians (~0.00006 degree), the conventional measurement unit for tilt change. The seismometric record is offset from the water-tube tiltmeter record because they pertain to different geographical sites at Kīlauea's summit.

detailed and better constrained models of summit and rift zone magma reservoir, transport, and eruption dynamics at Kīlauea and Mauna Loa (see, for example, Cervelli and Miklius, 2003; Miklius and others, 2005; Poland and others, 2012; Wright and Klein, 2014; Poland and others, this volume, chap. 5). Moreover, continuous GPS measurements (fig. 5*A*) have made possible real-time tracking of ground deformation associated with magma movement, eruption dynamics, and the motion of Kīlauea's unstable south flank (see "How Hawaiian Volcanoes Work" section, below).

The potential of InSAR in volcano monitoring was first demonstrated by imaging the 1992–93 deflation at Etna Volcano, Italy (Massonnet and others, 1995). This technique is especially powerful in that it captures deformation of the entire radar-imaged ground area, rather than change at individual points, as measured by other monitoring techniques (for instance, GPS, EDM, tilt, and leveling). InSAR mapping was first tested at Kīlauea in 1994, but the interferograms contained large errors because of atmospheric effects related to Hawai‘i's tropical environment, resulting in ambiguous interpretation (Rosen and others, 1996). With time, however, the InSAR technique improved as atmospheric artifacts were more easily recognized and new techniques developed to mitigate such artifacts. InSAR is now a versatile tool routinely used for mapping volcano deformation at Kīlauea (fig. 5*B*) and Mauna Loa (for example, Amelung and others, 2007) and at volcanoes around the world (for example, Dzurisin and Lu, 2007, and examples summarized therein). The development in 2007 of airborne InSAR (a radar pod attached to fixed-wing aircraft) eliminated constraints of orbit paths and satellite repeat passage, thereby providing much greater flexibility in the acquisition of data. Airborne

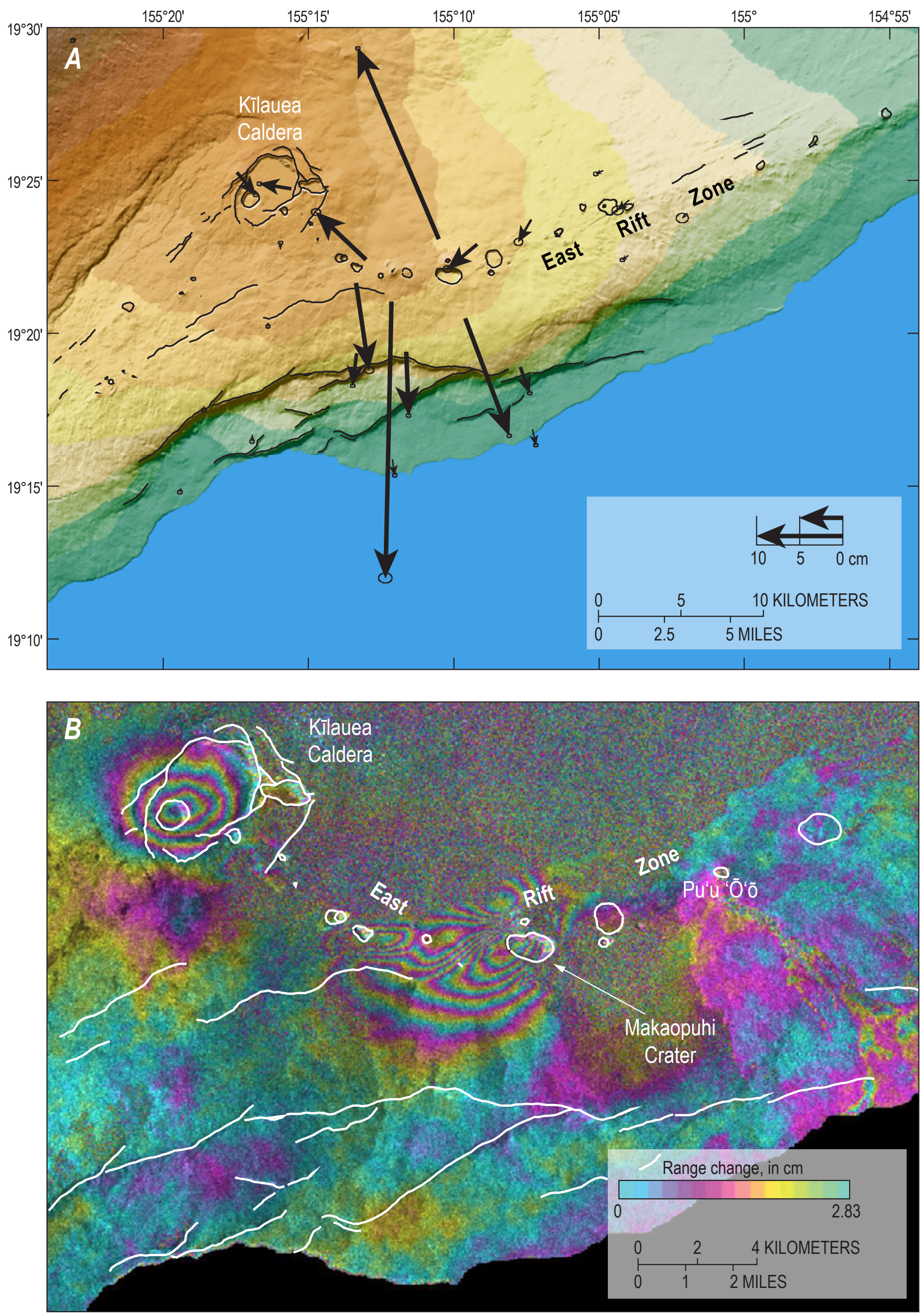

Figure 5. Map and InSAR (interferometric synthetic aperature radar) image showing horizontal and vertical ground deformation at Kīlauea Volcano. *A*, An example of geodetic monitoring results using continuously recording Global Positioning System (GPS) receivers of the Hawaiian Volcano Observatory (HVO), Stanford University, and the University of Hawai‘i. Vectors indicate the horizontal displacements produced by magma intrusion into Kīlauea's upper East Rift Zone and associated brief eruption during June 17–19, 2007. Station locations are at the tails of vectors, and circles indicate 95-percent confidence levels (modified by Asta Miklius from Montgomery-Brown and others, 2010, figure 3). *B*, An InSAR interferogram, derived from a pair of satellite radar images acquired by the European Envisat satellite 35 days apart for the same event in 2007. The patterns of fringes indicate subsidence of Kīlauea Caldera and a combination of uplift and subsidence near Makaopuhi Crater as magma from the summit reservoir intruded into the East Rift Zone (image by Michael Poland, USGS).

InSAR data were collected in Hawai‘i in 2010 and 2011, and the results were invaluable in documenting subsurface dike processes associated with the March 2011 Kamoamoa fissure eruption (Lundgren and others, 2013).

Precise Gravity Monitoring

Measuring changes in the acceleration of gravity, coupled with precise leveling, is the only known way to measure changes in subsurface mass associated with magma movement. The first reliable measurements of gravity changes were made in the 1970s. Jachens and Eaton (1980) analyzed gravity data for Kīlauea summit stations measured before and after a major summit deflation produced by the November 29, 1975, earthquake and interpreted the results to indicate a mass loss, probably from two sources in the south part of Kīlauea Caldera. Dzurisin and others (1980) exploited gravity measurements to conclude that the November 1975 earthquake of magnitude (*M*) 7.2 (Tilling and others, 1976) created void space in the summit area that completely filled with magma over the subsequent months, thereby setting the stage for two intrusions into the East Rift Zone in mid-1976.

Johnson (1992) interpreted gravity and leveling measurements at Kīlauea, specifically for the period 1984–86, and distinguished three variables that modulate deflation of the magma reservoir: volume and depth of magma transfer; pressure and volume of CO_2 gas; and spreading of the summit area. Kauahikaua and Miklius (2003) interpreted gravity and leveling trends from 1983 through 2002 in terms of mass-storage changes of Kīlauea’s magma reservoir. Johnson and others (2010) examined measurements from late 1975 to early 2008 over a broader network of measurement sites to document the refilling of void space inferred by Dzurisin and others (1980) beneath the summit created by the 1975 *M*7.2 earthquake (Tilling and others, 1976). In addition, Johnson and others (2010) suggest the 2008 Kīlauea summit vent probably tapped the magma that had accumulated since 1975.

Continuous gravity measurements started in 2010 at Uēkahuna Vault and on the caldera floor above the Halema‘uma‘u “Overlook vent” (as the 2008 summit eruptive vent has been informally named), and in 2013 at Pu‘u ‘Ō‘ō (Michael Poland, oral commun., 2013). These data have already documented a previously unknown oscillation with a period of 150 s that is almost certainly not seismic in nature. Carbone and Poland (2012) suggest that its origin may be linked to convective processes within the shallow magma reservoir. In addition, gravity changes detected during abrupt changes in lava level within the Overlook vent are consistent with the near-surface magma having a very low density, compatible with a gas-rich foam (Carbone and others, 2013).

Time-Lapse Photography

Localized deformation of the ground surface can also be captured in time-lapse photography at very fine spatial and temporal scales compared to any other geodetic monitoring technique. For example, photographic measurements made during 2011 at the Overlook vent within Halema‘uma‘u and at Pu‘u ‘Ō‘ō crater showed that the lava lake levels varied sympathetically, indicating that an efficient hydraulic connection linked Kīlauea’s simultaneous summit and East Rift Zone eruptive activity (Orr and Patrick, 2012; Patrick and Orr, 2012a). Significantly, these photographically documented lava level changes “mirror trends in summit tilt and GPS line length” (Patrick and Orr, 2012a, p. 66). Tilling (1987) previously reported a similar correlation—but based on limited and imprecise data—between Kīlauea’s summit tilt and the levels of active lava lakes at Mauna Ulu and ‘Alae. However, with acquisition of digital, high-resolution time-lapse photographic data now possible, detailed measurements of fluctuations in lava level can monitor localized changes in magma pressurization (inflation versus deflation) in the volcanic plumbing system feeding eruptive vents (Patrick and Orr, 2012a; Patrick and others, 2014, figs. 6, 7, and 9; Orr, 2014).

Volcanic Gas Monitoring

Sutton and Elias (this volume, chap. 7) summarize the history of volcanic gas studies at HVO during the past century. Here, we present a few selected highlights.

Regular measurements of volcanic gases, especially SO_2 and CO_2, became part of HVO’s monitoring program in the late 1970s. Initially, monitoring of gas composition was accomplished using direct sampling near eruptive vents for gas chromatographic analysis at HVO (Greenland, 1984, 1987a, 1987b; and references therein). It was during this time that remote-sensing techniques began to be used to monitor gas-emission rates—correlation spectrometry (COSPEC) for SO_2 and infrared spectrometry for CO_2 (Casadevall and others, 1987). Since 1987, huge strides have been made in the field of remote-sensing measurements—ground-, plane-, and satellite-based—of volcanic gases (see, for instance, Carn and others, 2003; Nadeau and Williams-Jones, 2008; and Carn, 2011). The COSPEC (fig. 6*A*) was the instrument used to make SO_2 emission measurements at Kīlauea through September 2004, when—after a period of comparison and calibration with newer instruments—it was replaced by a miniature ultraviolet spectrometer (nicknamed FLYSPEC; fig. 6*B*), which is much smaller and more portable (Elias and others, 2006; Horton and others, 2006). Another regular component of HVO’s gas monitoring program uses the Fourier transform infrared (FTIR) spectrometer (McGee and Gerlach, 1998; McGee and others, 2005). The FTIR is capable of analyzing many other species of volcanic gases in addition to SO_2 and CO_2, thereby making possible estimates of the ratios of other gas species not directly measured by FLYSPEC.

Over the past two decades, near-real-time remote-sensing measurements of gas emission—of SO_2 (regularly) and CO_2 (infrequently)—have become one of the primary tools, along with seismic and geophysical techniques, in HVO’s volcano-monitoring program for Kīlauea and Mauna Loa (see, for example, Elias and others, 1998; Sutton and others, 2001, 2003; Elias and Sutton, 2002, 2007, 2012). Indeed, the time-series data for SO_2 emission rates at Kīlauea (fig. 7) acquired from 1979 to the present constitutes the longest duration dataset of its type for any volcano in the world; CO_2 emission measurements at Kīlauea were added to the mix starting in 1995 and collected more frequently after 2004.

Since 1958, atmospheric CO_2 levels have been continuously monitored by the National Oceanic and Atmospheric Administration (NOAA) Mauna Loa Observatory (MLO) on the north slope of Mauna Loa (at 3,397 m elevation—above the inversion layer). Estimates of volcanic CO_2 emission can be obtained from analysis of the "excess" amounts above normal atmospheric levels captured during periods when wind directions bring emissions from known volcanic sources to the sensors (Ryan, 1995, 2001). For a detailed discussion of gas studies and their importance for HVO's overall volcano-monitoring program, as well as the most recent developments, see Sutton and Elias (this volume, chap. 7).

HVO's increased gas-measuring capability allows for more measurements (in different locations) to be made easily, and the availability of long-term data now permits identification of possibly significant changes in emission rate (in other words, greater than "background" variations) from long-measured sources. Beginning in 1983, the essentially continuous eruptive activity at Puʻu ʻŌʻō-Kupaianaha has been accompanied by relatively high rates of SO_2 emission, fluctuating between <500 and >3,000 metric tons of SO_2 per day (fig. 7*A*). This relatively high, nonstop rate of gas emission at Kīlauea—from both the summit and the East Rift Zone—has produced a persistent "vog" (volcanic smog) that poses a significant volcanic hazard for Hawaiʻi residents and visitors (Sutton and others, 1997). This problem worsened with the onset of the 2008-present Halemaʻumaʻu eruption at Kīlauea's summit, which greatly increased the SO_2 emission rate (fig. 7*B*) from a second location (in addition to the East Rift Zone eruptive vents, like Puʻu ʻŌʻō), exacerbating vog conditions in more communities, some much closer to the summit vent than Puʻu ʻŌʻō (for detailed discussion, see Kauahikaua and Tilling, this volume, chap. 10).

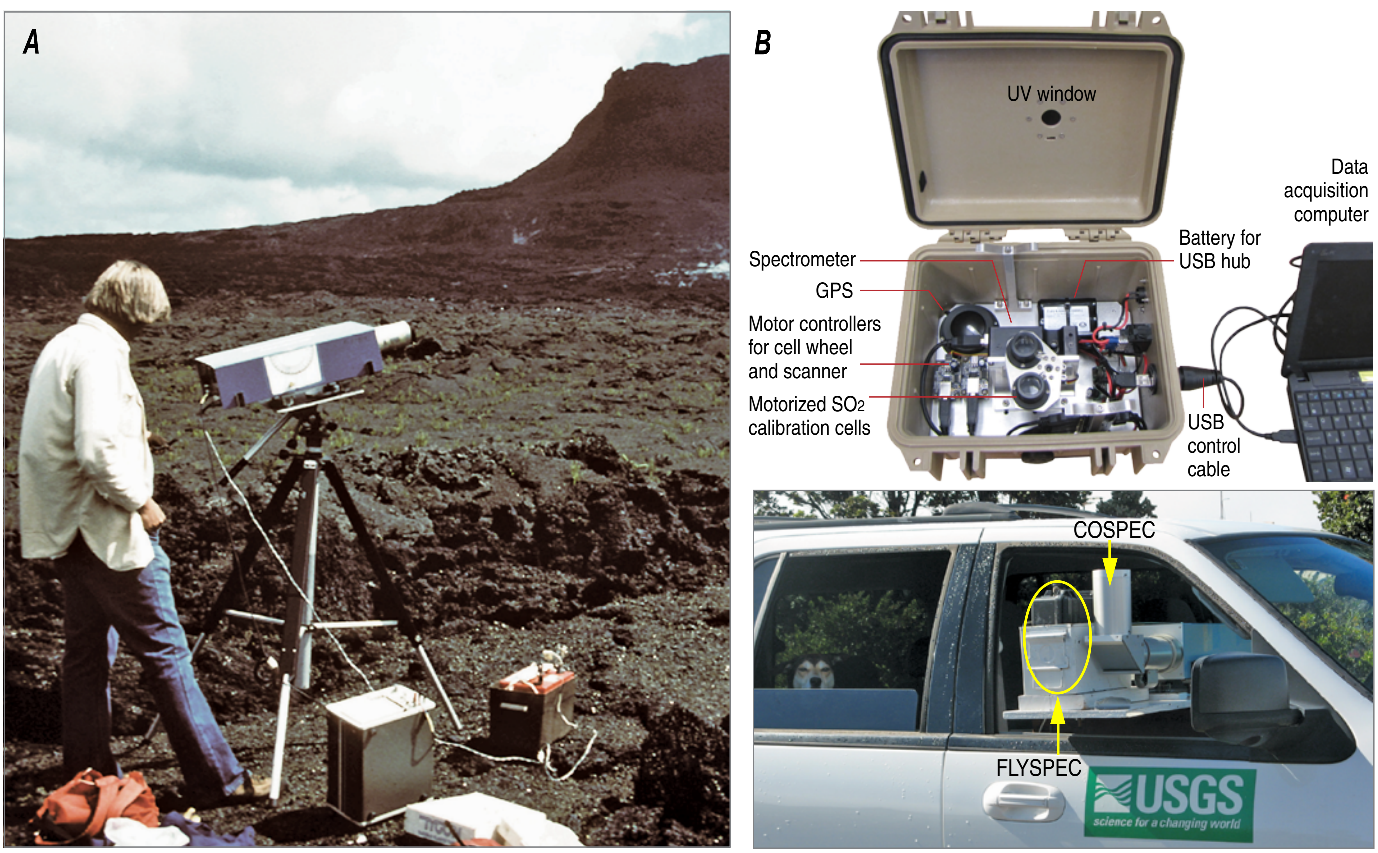

Figure 6. Photographs of spectrometers used by the Hawaiian Volcano Observatory (HVO). *A*, The correlation spectrometer (COSPEC), seen here in stationary operating mode at Puʻu ʻŌʻō, was the workhorse instrument used by HVO to measure SO_2 emission rates at Kīlauea through 2004 (USGS photograph by J.D. Griggs). It has been replaced by the lighter, less cumbersome, and lower-cost FLYSPEC, a miniature ultraviolet spectrometer. *B*, The compactness of the latest model of the miniature ultraviolet spectrometer can be appreciated from this schematic (top) of the measurement system (Horton and others, 2006, figure 1). Road-based configuration (bottom) for running the FLYSPEC and COSPEC instruments side-by-side for experiments conducted during 2002–03 (Elias and Sutton, 2007, figure 2*A*). For detailed discussion of FLYSPEC measurements, see Horton and others (2006), Elias and others (2006), and Sutton and Elias (this volume, chap. 7).

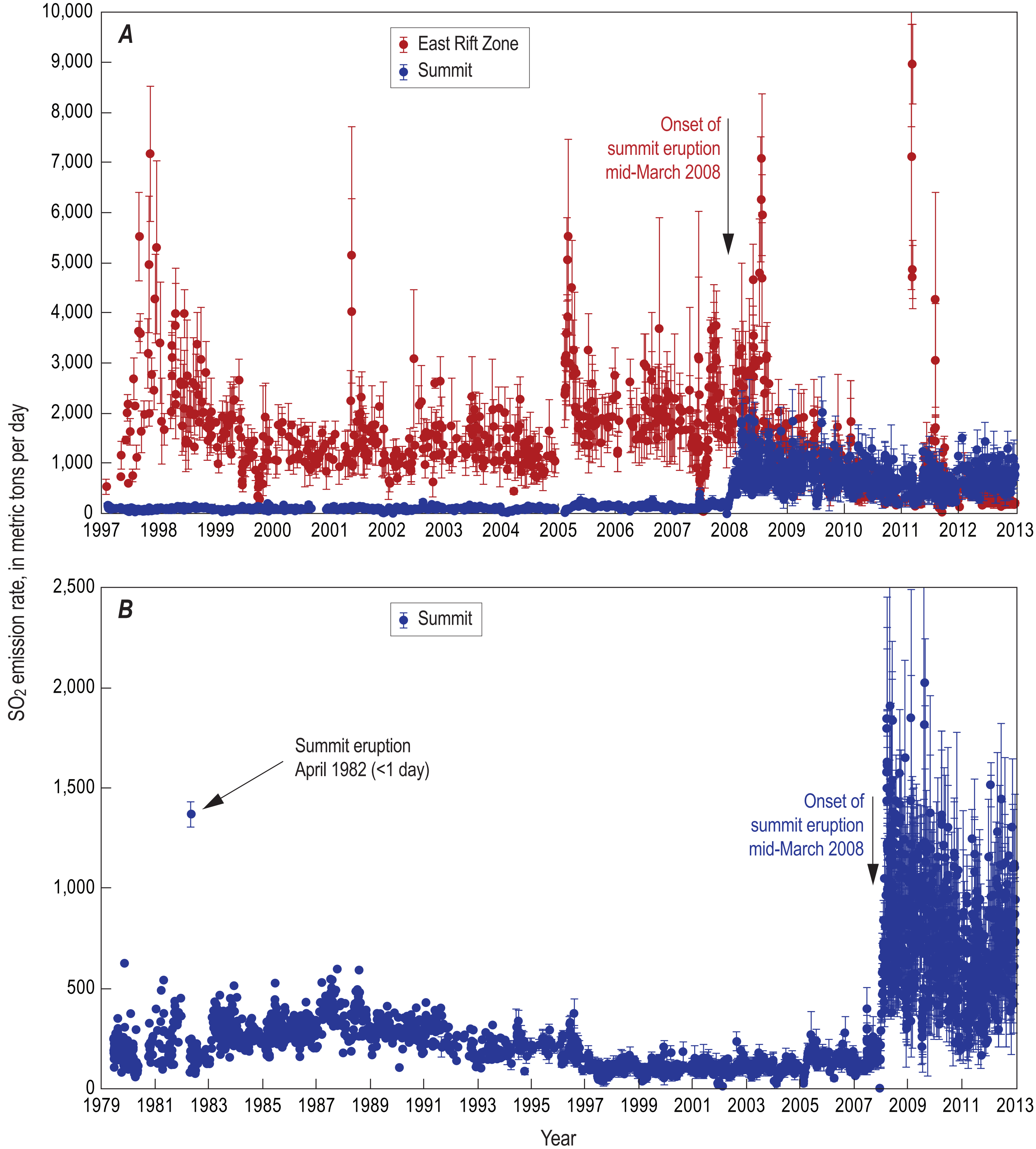

Figure 7. Graphs of SO_2 emission rates at Kīlauea during the period 1979–2013 (updated from Elias and others, 1998; Elias and Sutton, 2002, 2007, 2012). *A*, Comparison of emission rates for the Pu‘u ‘Ō‘ō-Kupaianaha eruption (East Rift Zone) and Kīlauea summit during the period 1997–2013. Spikes in rates reflect surges or new outbreaks during eruptive activity. *B*, Emission rates for Kīlauea summit for the period 1979–2013. During 1979–97, rates were higher and more variable than those during the 1997–2007 period, before sharply increasing with the onset of continuous eruptive activity in mid-March 2008 (summary data plots by Tamar Elias, USGS).

Petrologic-Geochemical Monitoring

When Gordon Macdonald joined the HVO staff in the early 1940s, he initiated what might be considered the forerunner of “petrologic-geochemical” monitoring of Hawaiian eruptions—the systematic sampling and analysis of eruptive products to examine temporal changes to composition as an eruption progresses. Beginning in 1952, every eruption at Kīlauea and Mauna Loa, ranging in duration from days to decades, has been “sampled at regular intervals to cover both the spatial and temporal distribution of eruptive products” (Wright and Helz, 1987, p. 628). Such systematic sampling (fig. 8) is especially important during prolonged eruptions, such as the ongoing Pu‘u ‘Ō‘ō-Kupaianaha eruption (1983 to present). Time-series compositional data complement those from seismic, geodetic, and gas monitoring to characterize preeruption conditions and processes within magma reservoirs, as well as syneruptive dynamics (for example, Thornber, 2003; Thornber and others, 2003). The availability of extensive time-series compositional datasets for Hawaiian lavas fostered the development of the breakthrough concepts of “olivine control,” “magma batches,” and “magma mixing” (see, for instance, Powers, 1955; Wright, 1971), which are now widely applied in igneous petrology, especially in studies of basaltic volcanism. The obvious synergy between HVO petrologic-geochemical monitoring and basic research is amply illustrated by the many advances in our petrologic understanding of basaltic volcanism, as reviewed by Helz and others (this volume, chap. 6).

Geologic, Petrologic, and Geochemical Investigations

The first geological studies of Hawaiian volcanoes were made during 1840–41, as part of the U.S. Exploring Expedition, commanded by U.S. Navy Lieutenant Charles Wilkes (Wilkes, 1844). These early scientific observations were led by James Dwight Dana, a 27-year-old, Yale-educated natural scientist who had worked at Mount Vesuvius in 1834. Dana is considered the first American volcanologist, and his expedition report “constitutes a virtual textbook of Hawaiian volcanology and geology” (Appleman, 1987, p. 1607). Clarence E. Dutton—the first USGS geologist to work in Hawai‘i—spent 5 months in the Hawaiian Islands in 1882 “for the purpose of studying the features and processes of a volcano in action, and thus obtaining the practical knowledge which is essential to the investigation of extinct volcanoes” (Dutton, 1884, p. xxvi) before starting a new mapping assignment in the Cascade Range of the Pacific Northwest. The work and findings of Dana (1849) and Dutton have guided subsequent geologic studies. In his memoir, Dana (1890) summarized concepts learned from study of Hawaiian volcanoes, listing topics needing further study in the preface of that volume (table 1). As is obvious from the now-abundant volcanologic literature, HVO and many other investigators continue to address many of these fundamental research questions—first emphasized by Dana more than a century ago—to better understand basaltic volcanism in Hawai‘i and, by extrapolation, elsewhere.

Figure 8. In the regular petrologic-geochemical monitoring of eruptive products, Hawaiian Volcano Observatory (HVO) scientists, using a steel cable with a hammerhead attached, collect a sample through a skylight of an active lava tube originating at Pu‘u ‘Ō‘ō vent. Molten lava adheres to the hammerhead dangling at edge of skylight above the flowing lava stream. (USGS photograph by J.D. Griggs, December 5, 1990).

Table 1. Some aspects of Hawaiian volcanism that geologist James D. Dana thought still needed investigation in 1890 (excerpted from Dana, 1890, p. vii–viii).

"But much remains to be learned from further study of the Hawaiian volcanoes. Some of the points requiring elucidation are the following:

- the work in the summit-crater between its eruptions;
- the rate of flow of lava-streams and the extent of the tunnel-making in the flow;
- the maximum thickness of streams;
- the existence or not of fissures underneath a stream supplying lava;
- the temperature of the liquid lava;
- the constitution of the lava at the high temperatures existing beneath the surface;
- the depth at which vesiculation begins;
- the kinds of vapors or gases escaping from the vents or lakes;
- the solfataric action about the craters;
- the source of the flames observed within the area of a lava lake;
- the differences between the lavas of the five Hawaiian volcanoes . . . ;
- the difference in kind or texture of rock between the exterior of a mountain and its deep-seated interior or centre . . . ;
- the difference between Loa, Kea, and Haleakala in the existence below of hollow chambers resulting form lava discharges . . .
- the movements of the lavas in the great lava columns, and the source or sources of the ascensive movement."

Observations of Kīlauea Lava Lake Activity

Because of its frequent and sustained effusive eruptions and relative accessibility, Kīlauea Volcano has served as a prime natural laboratory for systematic studies of active basaltic lava lakes. Table 2 is a compilation of episodes of lava-lake activity at Kīlauea, lasting 30 or more days, during the period pre-1823 to the present.

Between Jaggar's first visit to Kīlauea in 1909 with fellow MIT geologist R.A. Daly to early 1924, the continuously active lava lake at Halemaʻumaʻu Crater provided a natural and easily accessible focus for systematic visual observations of eruptive activity at Kīlauea. The accounts of the earliest observers were conveniently summarized in Brigham (1909) and Hitchcock (1911). Daly incorporated his 1909 lava-lake observations into a larger work on volcanism (Daly, 1911), concluding that (1) the circulation of lava in the shallow, saucer-shaped Halemaʻumaʻu lakes was driven by two-phase magmatic convection within a narrower conduit below; (2) lava fountains were the result of "explosive dilation" of entrained gas bubbles as magma rose within that conduit; (3) the lake surface was a "froth"; and (4) the predominant gas release was at lake edges, where lava pooled. Based on night-and-day observations in 1911, Perret (1913a,b,c,d) came to the conclusion that lava-lake circulation was driven by the sinking of cooled, degassed slabs at the eastern end of the lake into the same conduit from which fresh, vesiculating magma was rising before flowing westward along the bottom to emerge at the western end of the lake.

Jaggar's much longer series of lava-lake observations led him to more refined ideas of the active lava lake and associated processes within the Halemaʻumaʻu pit crater (Jaggar, 1920). He correctly concluded that gases are in solution in magma at depth ("hypomagma") and only start to vesiculate in the magma as it rises ("pyromagma"). Once the lava loses its gas while in the lake, it becomes denser and more viscous ("epimagma") and collects at the base and along the edges of the lake, as well as draining back into

Table 2. Eruptions at Kīlauea Volcano over the past ~200 years.

Eruption site	Year start	Duration (days)[1]	Selected references
Halemaʻumaʻu	Pre-1823	>35,000 (intermittent)	Jaggar (1947) Bevens and others (1988)
Halemaʻumaʻu	1934	33	Jaggar (1947)
No eruptive activity at Kīlauea during 1935–51			
Halemaʻumaʻu	1952	136	Macdonald (1955)
Kīlauea Iki	1959	36	Richter and Eaton (1960) Richter and others (1970)
Halemaʻumaʻu	1967	251	Kinoshita and others (1969)
Mauna Ulu	1969	875	Swanson and others (1979)
Mauna Ulu	1972	455	Tilling (1987) Tilling and others (1987a)
Mauna Ulu	1973	222	Tilling and others (1987a)
Pauahi	1979	30	Tilling and others (1987a)
Puʻu ʻŌʻō-Kupaianaha	1983	>11,500 (intermittent, ongoing)	Wolfe and others (1987) Wolfe and others (1988) Heliker and others (2003a) Orr and others (2012)
Halemaʻumaʻu		>2,400 (ongoing)	Hawaiian Volcano Observatory Staff (2008) Patrick and others (2013)

[1]Updated from Peterson and Moore (1987, table 7.3).

the hypomagma at depth. In addition, Jaggar hypothesized that deformation around and within the lake occurred by pressurization of the epimagma rather than the solid rock surrounding the crater and lake. Jaggar made many direct measurements of the lava lakes (Jaggar, 1917a,b), confirming that they were shallow (only ~14–15 m deep) and hotter at the bottom than at the surface (confirming Perret's circulation model). Lake depths were determined by insertion of steel pipes, into which Seger cones were lowered to estimate temperatures (see Apple, 1987, fig. 61.5; also see discussion in "Field Measurements of Lave Temperature" section, below). The time series of lava-lake elevations compiled by Jaggar was later used by Shimozuru (1975) to demonstrate a semidiurnal oscillation correlated with Earth tides.

The 1969–74 Mauna Ulu eruptions produced the first sustained lava-lake activity in a rift zone of Kīlauea during historical time. During the 1969–71 activity, nearly continuous lava lakes exhibited "gas pistoning"—an episodic release of gas accumulated beneath the lake's crust—that was first described by Swanson and others (1979). During 1972–74, fluctuations of the surface height of the Mauna Ulu lava lakes correlated with variations in Kīlauea's summit tilt, indicating an efficient hydraulic linkage between the summit magma reservoir and the active lava lakes (Tilling, 1987). Later, gas-piston behavior was also commonly observed within pits in the floor of Puʻu ʻŌʻō crater (for example, Orr and Rea, 2012). Although not a lake per se, a perched lava channel that formed at Puʻu ʻŌʻō in mid-2007 also exhibited gas-piston-like gas release cycles (Patrick and others, 2011a) and seeps of much denser, more pasty lavas from its base ("epimagma" in Jaggar's terms).

The return of prolonged lava-lake activity to Halemaʻumaʻu in 2008 and to Puʻu ʻŌʻō in 2011 has provided new opportunities to quantify and refine the observations made throughout HVO's history. Webcam records of active lava-lake activity have allowed categorization and quantification of typical lake behaviors, for example, hours-long rise/fall events during which lava levels gradually rise while gas emissions and seismic tremor levels drop, followed, in turn, by a quick lava-level drop and resumption of gas emissions and tremor; summit lava lake levels that track summit tilt records; and variation of lake-circulation patterns associated with the location of spattering sinks (as first described by Daly, 1911, and Perret, 1913a,b). Continuous gravity measurements during lava lake level changes suggest that at least the upper few hundred meters of the magma column is a foam with a density of about 1,000 kg/m^3 (Carbone and others, 2013).

Because Kīlauea lava lakes are located within a dense seismic network, recent lake observations are closely tied to unique seismic signatures. For example, the continued stoping of the conduit in which the Halemaʻumaʻu lava lake sits frequently produces rock falls directly into the lava lake. These rock falls, in turn, commonly produce a characteristic composite seismic signature that starts with a high-frequency signal (presumably the rock breakage) that grades into long-period (LP) frequencies (interaction with the lava lake) and, ultimately, into a very-long-period (VLP) signal that can last for several minutes (possibly related to deep pressure oscillations within the magma column; Patrick and others, 2011a). Moreover, the rock falls into active lava lakes are known to trigger explosive events (Orr and others, 2013) and initiate rise/fall events.

Origin and Fractionation of Hawaiian Magmas

The earliest geochemical investigations at Hawaiian volcanoes involved the sampling and analysis of volcanic gases—all at Kīlauea except for two samples from Mauna Loa—by A.L. Day, E.S. Shepherd, and T.A. Jaggar during the period 1912–19 (Day and Shepherd, 1913; Shepherd, 1919, 1921). Some of these early collections of gas from Halemaʻumaʻu are still considered among the best in the world in terms of sample purity and analytical precision (Gerlach, 1980; Greenland, 1987b). After these notable investigations, the study of eruptive volcanic gases then languished for decades, only to be resumed sporadically in the 1960s, mostly centered on specific short-lived eruptions or intrusions, including the beginning of the Puʻu ʻŌʻō eruption of Kīlauea and the 1984 eruption of Mauna Loa (Greenland, 1987a). For informative summaries of gas studies through the mid-1980s, the interested reader is referred to Greenland (1987a,b, and references therein). Beginning in the 1990s, systematic studies of the composition and rate of gas emission—using continuously recording optical or multispectral remote sensing of gas species—became an integral component of HVO's current volcano-monitoring and research program (see Sutton and Elias, this volume, chap. 7).

Other than HVO's volcanic gas studies during its early decades, however, "systematic collection and characterization of samples from eruptions, either megascopically, or by petrographic and chemical analysis" were lacking for much of the early 20th century (Wright, 1989, p. xix). It was not until the early 1940s, with the arrival of Gordon Macdonald, that regular collection of lava and tephra samples for laboratory analysis was inaugurated at HVO; he was the first to make a comprehensive petrologic and geochemical study of Hawaiian lavas (Macdonald, 1949a,b). In the 1950s Howard A. Powers introduced the now commonly used magnesia-variation diagrams, olivine-control lines, and the concepts of magma batches and magma mixing in analyzing chemical variations in erupted lava (Powers, 1955). Illustrative examples of plots of times-series compositional data for MgO and other oxides (bulk lava or glass) are used in Helz and others (this volume, chap. 6, their figures 3, 6, and 11). Perhaps unique for investigations of basaltic volcanism, shallow magma crystallization and fractionation processes have been documented directly by petrologic-geochemical studies of samples collected by drilling into passive lava lakes (see "Drilling Studies of Passive Historical Lava Lakes," below, and Helz and others, this volume, chap. 6, for additional discussion). Figure 9 petrographically demonstrates the progressive crystallization with decreasing temperature of the still-molten portion of the solidifying 1965 lava lake in Makaopuhi Crater (Wright and Okamura, 1977).

Powers was the first to recognize that the historical lavas of Kīlauea and Mauna Loa are petrographically and chemically distinct. Building on Powers's pioneering work, Wright (1971) produced a definitive compilation of the composition of Kīlauea and Mauna Loa lavas using all chemical and petrographic analyses available at the time. He proved that Mauna Loa lava compositions showed no correlation with time of eruption, nor with vent location, whereas Kīlauea lavas could be compositionally grouped according to eruption age and vent site (summit vs. rift zones). The work of Wright and his associates during the 1970s (for instance, Wright, 1971; Wright and Fiske, 1971; Wright and others, 1975; Wright and Tilling, 1980) set the stage for many subsequent petrologic-geochemical studies germane to the origin and fractionation of Hawaiian basalt (see, for example, Garcia and Wolfe, 1988; Garcia and others, 1989, 1992, 1998, 2000). For comprehensive reviews of petrologic-geochemical studies of Hawaiian lava, the interested reader is referred to the many summary works (for example, Wright and Helz, 1987; Rhodes and Lockwood, 1995; Tilling and others, 1987b; Helz and others, this volume, chap. 6, and references therein).

Geological Mapping of Hawaiian Volcanoes

As noted by Wright (1989), except for partial maps of the lava flows of the 1840 Kīlauea eruption (Wilkes, 1844) and maps of some other historical eruptions produced by the Territorial Government Survey Office (Brigham, 1909; Hitchcock, 1911), early studies of Hawaiian volcanism lacked accurate and complete geologic maps. Beginning in the late 1920s, geological reports and accompanying maps for many of the Hawaiian Islands were produced by USGS geologists Harold T. Stearns and his associates, particularly Gordon Macdonald (see Sherrod and others, 2007, and references therein). The geologic map for the Ka‘ū District (Stearns and Clark, 1930) inaugurated the era of systematic geologic mapping in Hawai‘i, and Stearns and Macdonald (1946) compiled the first geologic map of the entire Island of Hawai‘i. Moreover, published accounts of eruptions at Kīlauea and Mauna Loa since the 1950s include reasonably good maps of erupted lava flows (for example, Swanson and others, 1979; Tilling and others, 1987a; Wolfe and others, 1987; Lockwood and others, 1987; Heliker and others, 2003b). Equally and perhaps more important, the newer mapping also delineated deposits of prehistoric eruptions, thereby allowing longer term reconstruction of eruptive history and hazards assessment (for instance, Peterson, 1967; Walker, 1969; Lipman and Swenson, 1984; Holcomb, 1987; Lockwood and Lipman, 1987; Lockwood and others, 1988; Moore and Clague, 1991; Buchanan-Banks, 1993; Neal and Lockwood, 2003). Assignments of absolute or relative ages to prehistoric lavas were made increasingly possible by careful mapping of

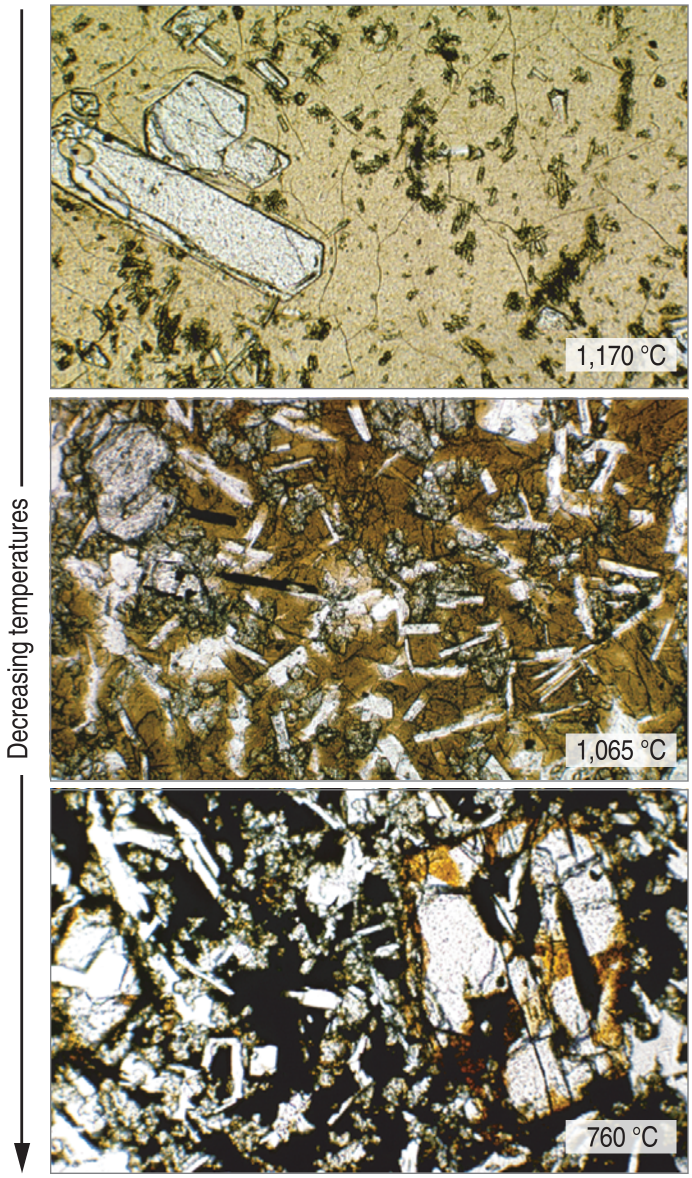

Figure 9. Photomicrographs (field of view ~1.2 mm) of samples collected by drilling through the crust of the cooling 1965 lava lake in Makaopuhi Crater (Wright and Okamura, 1977). The lava-lake drilling operations at Makaopuhi were similar to those conducted in 1975 for Kīlauea Iki lava lake (see fig. 20). The samples, which represent the still-molten portion of the lava lake at the time of sampling and at the in-hole temperatures indicated, show increasing crystallinity and sequential appearance of mineral phases with decreasing temperature. The progressive darkening of the glassy matrix reflects the presence of submicroscopic Fe-Ti-oxide grains and imperfect quenching (USGS photomicrographs by Richard S. Fiske; image from Tilling and others, 2010).

stratigraphic relationships and refinements in radiometric and paleomagnetic dating methods during the latter part of the 20th century (discussed below).

In the mid-1980s, HVO launched the Big Island Map Project (BIMP) to update the geologic map of the Island of Hawaiʻi, based on maps generated from 1975 to 1995 by more than 20 geologists from the USGS and various universities. The new compilation (Wolfe and Morris, 1996a; Trusdell and others, 2006) represented a quantum advance over the 1946 map in its detailed portrayal of the distribution and ages of prehistoric, as well as historical, eruptions (fig. 10). In addition, this compilation also includes location maps of all radiocarbon dating sites and samples collected for major-element chemical analysis (Wolfe and Morris, 1996b). The new mapping confirmed the geologic youthfulness of Mauna Loa and Kīlauea volcanoes inferred by earlier investigators. About 90 percent of Mauna Loa's surface is covered by lava younger than ~4,000 years old; Kīlauea's surface is even younger, with ~90 percent plated with lavas younger than 1,100 years (Holcomb, 1987; Lockwood and Lipman, 1987; Wolfe and Morris, 1996a). The original geologic mapping by Stearns and colleagues, updated in places by various geologists, including new Haleakalā mapping by USGS geologist Dave Sherrod, and the BIMP data over the intervening years, was registered against modern topographic maps, compiled and published as a state geologic map in modern geographic information systems (GIS) formats by Sherrod and others (2007). More detailed geologic mapping of Mauna Loa volcano, to be published at a 1:50,000 scale in five sheets, is currently underway (F.A. Trusdell, oral commun., 2012).

Radiometric and Paleomagnetic Dating of Lava Flows

Geological mapping at Hawaiian volcanoes benefited greatly from the advent and development of radiometric and paleomagnetic dating methods in the 20th century. Potassium-argon age determinations were crucial in establishing the age progression of the Emperor Seamount–Hawaiian Ridge volcanic chain (for example, Clague and Dalrymple, 1987; Langenheim and Clague, 1987; Clague and Sherrod, this volume, chap. 3). For dating the lavas erupted at Hawaiʻi's active volcanoes, however, radiocarbon (^{14}C) and paleomagnetic dating techniques have proven the most useful. During the first 75 years of HVO's history,

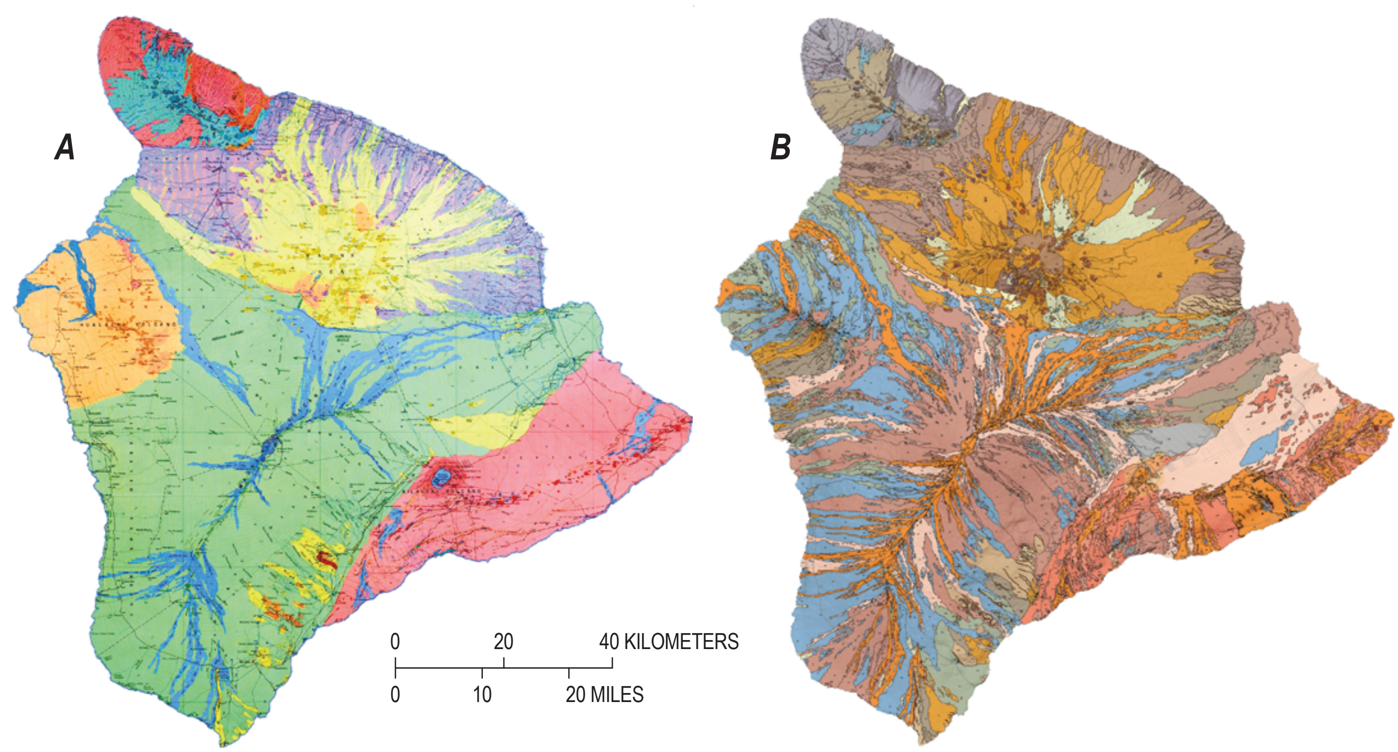

Figure 10. Geologic maps of the Island of Hawaiʻi. *A*, The first geologic map for the entire island (published scale 1:125,000), by Stearns and Macdonald (1946), who based their compilation on all then-existing geologic information. Although remarkable and useful in its time, this map lacked geologic definition and age data for the prehistoric volcanic deposits that underlie most of the island. *B*, The geologic map (published scale 1:100,000) compiled in 1996 by Wolfe and Morris (1996a), was the culmination of the Big Island Map Project (see text). This newer map clearly shows in much greater detail the distribution of the prehistoric deposits, reflecting the improved knowledge gained from mapping and dating studies conducted since 1946 (images from Babb and others, 2011).

many hundreds of radiocarbon dates on carbon-bearing samples (see Rubin and Suess, 1956; Rubin and others, 1987) were used in the preparation of Hawaiian geologic maps and the Wolfe and Morris compilation (1996a,b). Since 1987, many more radiocarbon dates have been obtained and used in the preparation of updated geologic maps and refined eruption frequencies for Hawaiian volcanoes (for instance, Sherrod and others, 2006, 2007; Trusdell and Lockwood, in press).

Oftentimes, finding carbon-bearing materials in the field suitable for dating is a challenge. From practical experience gained during the mapping of Mauna Loa, HVO scientists learned to identify the most favorable field settings to find datable carbon (see Lockwood and Lipman, 1980), which has benefited investigators studying some other basaltic volcanoes (for example, in the Canary Islands and the Azores). Paleomagnetic dating of lavas, by matching the preserved magnetic direction in lava with the record of the secular variation in the Earth's magnetic field, has been used with good success in Hawaiʻi (for instance, Holcomb and others, 1986; Holcomb, 1987; Lockwood and Lipman, 1987). This method is premised on determination of the directions in remnant magnetization of well-dated (generally by radiocarbon) Hawaiian samples that span a range of geologic time. Lavas of unknown age can be dated or time-bracketed by comparing their magnetization directions with the history of secular variation of the magnetic field (for example, Holcomb and others, 1986; Hagstrum and Champion, 1995; Clague and others, 1999; Sherrod and others, 2007). Dozens of new radiocarbon ages, combined with paleomagnetic data, were obtained to augment field studies in recent reconstructions of the eruptive history of geologically recent explosive activity at Kīlauea (for instance, Fiske and others, 2009; Swanson and others, 2012a).

How Hawaiian Volcanoes Work

From century-long observations of Kīlauea's changing eruptive activity between the summit and rift zones and decades-long monitoring data and topical research, we have a general conceptual model of the subsurface magmatic systems that sustain Hawaiian volcanism (see, for example, Decker, 1987). Although specifics about the deep (>20 km) source regions are still poorly resolved, this model depicts magma generation and ascent in the mantle, its transport to and storage within one or more shallow reservoirs, and ultimately its eruption at the surface. In this section, we touch upon some selected attributes and operative processes of Hawaiian volcanic plumbing systems; the other chapters in this volume treat in greater detail, and for differing time scales (geologic vs. historical), how Hawaiian volcanoes have worked in the past and are working at the present time.

Shallow Magma Reservoirs in Shield Volcanoes

The first inferences about Kīlauea magma chambers came from an analysis of leveling data acquired before and after the explosive eruptions of May 1924. These data documented dramatic subsidence of the caldera floor associated with the retreating lava column and related decreases in a subsurface pressure source at a depth of 3.5 km below the south part of Kīlauea Caldera. "The changes of the pressure of the spherical sources may correspond perhaps to the decrease of the hydrostatic pressure of magma reservoirs below the area and may have been caused by the intrusion or the extrusion of magma from the reservoirs" (Mogi, 1958). Later, using data collected by HVO and other scientists through the 1950s, Eaton and Murata (1960, fig. 5) proposed the first dynamic model for the magmatic system of Kīlauea. This model, based primarily on seismic and other geophysical data, involved the following elements: (1) a magma-source region deeper than 60 km; (2) poorly defined pathways ("permanently open conduits") for magma to rise into the crust; and (3) collection and storage of magma in a shallow (<5 km) summit reservoir for a finite time, from which magma later is erupted at the summit or intruded and possibly erupted along a rift zone. The basic features of this now half-century-old "classic" model (fig. 11) still apply, but decades of additional data and subsequent analyses (for example, Dzurisin and others, 1984; Ryan, 1987; Delaney and others, 1993; Tilling and Dvorak, 1993; Dvorak and Dzurisin, 1997; Cervelli and Miklius, 2003; Wright and Klein, 2006, 2014; Poland and others, 2012, this volume, chap. 5) have sharpened the model and introduced some important refinements. Variations of the Eaton-Murata model include the concept that Kīlauea's summit region may contain more than one shallow reservoir beneath the surface (for example, Fiske and Kinoshita, 1969), that secondary shallow reservoirs operate within the rift zones, and that magma pathways between the summit and rift zones may extend to greater depths than previously inferred. Poland and others (this volume, chap. 5, fig. 10) introduce a new model consistent with all that has been learned from recent decades of monitoring and modeling studies.

On the basis of differences in lava chemistry and patterns of eruptive behavior, nearly all post-1950 studies favor the view that the volcanic systems of Kīlauea and Mauna Loa apparently operate independently, even though they may tap, at depth, the same magma-source region. A study by Miklius and Cervelli (2003), however, suggests that, during 2001–02, a "crustal-level interaction"—though not necessarily a physical connection—may have linked these two volcanoes, and Gonnermann and others (2012) suggest a zone of porous melt accumulation in the upper mantle beneath both volcanoes that can transmit pressure variations between the two systems. Because the subsurface configurations of sustaining volcanic systems figure directly or indirectly in many studies of Kīlauea and Mauna Loa eruptions (for example, Decker and others, 1987; Heliker and others, 2003b; Poland and others, 2012, this volume, chap. 5; and references cited therein), we do not discuss them further here.

Long-Term Inflation-Deflation Cycles

As is now well known, the premonitory indicators of a Hawaiian eruption typically include heightened seismicity, inflationary ground deformation, and increased gas emission. As the shallow summit reservoir experiences magma influx and (or) hydrothermal pressurization, the volcano undergoes swelling or inflation. The inflation, in turn, deforms the volcano's surface, and this can be tracked in real time by geodetic monitoring, particularly variation in summit tilt. For Hawaiian volcanoes, preeruption inflation is generally gradual and can last for weeks to years. Once an eruption begins, however, the summit reservoir typically undergoes rapid contraction or deflation as pressure is suddenly relieved. During deflation, changes in tilt and in vertical and horizontal displacements of benchmarks are opposite to those during inflation. Kīlauea's behavior during and between eruptions is remarkably regular, generally characterized by the so-called inflation-deflation cycle, first recognized in 1930 and perhaps earlier (Jaggar, 1930). These cycles are observed for nearly every Hawaiian eruption or intrusion regardless of size (fig. 4). The largest tilt change (nearly 300 microradians), to date, for an inflation-deflation cycle was recorded for the Kīlauea Iki eruption in 1959; however, similar cycles can involve much smaller tilt changes (<20 microradians), as during episodes 1–20 (1983–84) of the ongoing Puʻu ʻŌʻō activity (Wolfe and others, 1988, figure 1.2).

Effusive Eruptions

Except for the 1924 explosive activity and minor ash emissions since 2008 at Kīlauea's summit, only effusive eruptions have occurred during HVO's first 100 years of existence. Consequently, volcano monitoring and research efforts on Hawaiian volcanoes have focused overwhelmingly on eruptive processes and products of nonexplosive historical eruptions, and a vast body of scientific literature on effusive volcanism in Hawaiʻi has accrued accordingly. These extensive data have prompted the worldwide use of the adjective "Hawaiian" to describe effusive or "gentle" eruptions wherever they happen—in other words, assigned with rankings of 0 to 1 in the Volcanic Explosivity Index (VEI) of Newhall and Self (1982). Because "Hawaiian-style" eruptive activity has received much scientific attention (for example, Decker and others, 1987; Cashman and Mangan, this volume, chap. 9, and references therein), there is no need for us to elaborate here. In contrast, however, recent studies indicate that, before 1800, explosive eruptions at Kīlauea were common and powerful.

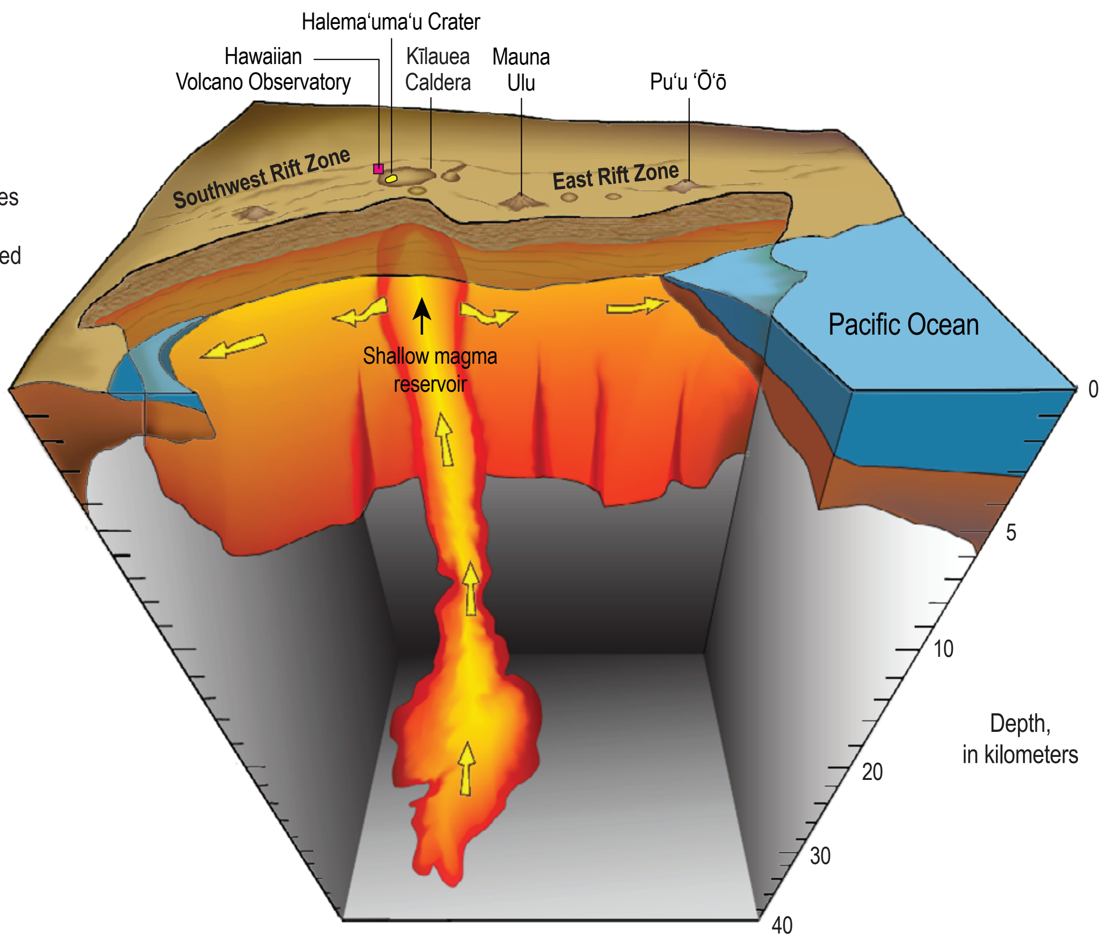

Figure 11. Cartoon of the "classic" model of Kīlauea's volcanic plumbing system, showing magma input from depth, the shallow reservoir, and the volcano's two rift zones (highly simplified from Ryan, 1987, figure 52.29, and as used in Tilling and others, 2010).

Explosive Eruptions

Recognizing pyroclastic deposits in addition to lava flows at Kīlauea and elsewhere in Hawai‘i, early observers and investigators reasoned that Hawaiian volcanoes have erupted explosively in the past (for instance, Ellis, 1825; Emerson, 1902; Hitchcock, 1911; Perret, 1913e; Powers, 1916; Stone, 1926; Wentworth, 1938; Powers, 1948). Indeed, Hitchcock (1911, p. 167) concluded that “Kilauea . . . has not always been the tame creature of today” (as quoted in Swanson and others, 2012a, p. 8). A map showing the generalized distribution of the known ash deposits of Hawai‘i was published by Wentworth (1938, fig. 6); however, to date, other than in the Kīlauea region, pyroclastic deposits have not been well studied. The extensive and deeply weathered ash deposits (“Pāhala Ash”) southwest of Kīlauea were originally thought to have issued from a buried caldera in the Pāhala area. It is now thought that these deposits may have been produced from explosive activity of Kīlauea Volcano (Sherrod and others, 2007). Beginning in the 1980s, studies of the products of explosive Kīlauea eruptions have shown that Kīlauea is much more explosive, energetic, and hazardous than anyone but the early geologists considered (Decker and Christiansen, 1984; McPhie and others, 1990; Mastin, 1997; Mastin and others, 1999, 2004; Fiske and others, 2009; Swanson and others, 2011a,b, 2012a,b).

The May 1924 eruptions at Halema‘uma‘u (fig. 12*A*)—Kīlauea’s only significant explosive activity during recorded history—occurred after the withdrawal 3 months earlier of the lava lake, and they were well documented by HVO (Jaggar, 1924; Jaggar and Finch, 1924). The cause for this eruption is interpreted to be the interaction of groundwater with Kīlauea’s shallow magma reservoir (see, for example, Decker and Christiansen, 1984; Dvorak, 1992). Yet this eruption was much, much smaller than the phreatomagmatic eruption in 1790 C.E. (McPhie and others, 1990; Mastin, 1997; Mastin and others, 1999, 2004). Base surges associated with this powerful explosive event caused many fatalities, which have been estimated decades after the eruption to range from 80 to >5,000 (Swanson and Christiansen, 1973; Swanson and others, 2011b). Even the minimum-fatalities estimate would make Kīlauea historically the deadliest of all U.S. volcanoes. Recent detailed geologic and dating studies reveal that the 1790 event was only one of many explosive eruptions throughout a 300-year period between about 1500 and 1800 C.E. (Fiske and others, 2009; Swanson and others, 2011a,b, 2012a,b). These ongoing studies have led to a new interpretation of Kīlauea’s long-term volcanic behavior: during the past 2,500 years of its eruptive history, centuries of effusive eruptions have alternated with centuries of dominantly explosive ones when there exists a deep summit caldera (Swanson and others, 2011a,b). Moreover, the new data about pre-1924 pyroclastic deposits also have resulted in two findings that entail implications for volcanic hazards (see Kauahikaua and Tilling, this volume, chap. 10): Kīlauea erupts explosively about as often as does Mount St. Helens in the Cascade Range of Washington; and at least six of the pre-1924 explosive eruptions were highly energetic, sending centimeter-size lithic clasts to jetstream heights (Fiske and others, 2009; Swanson and others, 2011b).

Flank Instability

Repeat regional triangulation measurements during the late 19th and early 20th centuries (for example, Wilson, 1927, 1935; Wingate, 1933) hinted that some benchmarks on Kīlauea Volcano were not fixed. Although the instability of Kīlauea’s south flank was recognized by Moore and Krivoy (1964), the actual model of seaward displacement of the south flank by rift dilation was first presented by Fiske and Kinoshita (1969). Since then, past and contemporaneous volcano flank movement has been confirmed by further geologic studies and abundant geodetic measurements (see, for example, Owen and others, 1995, 2000).

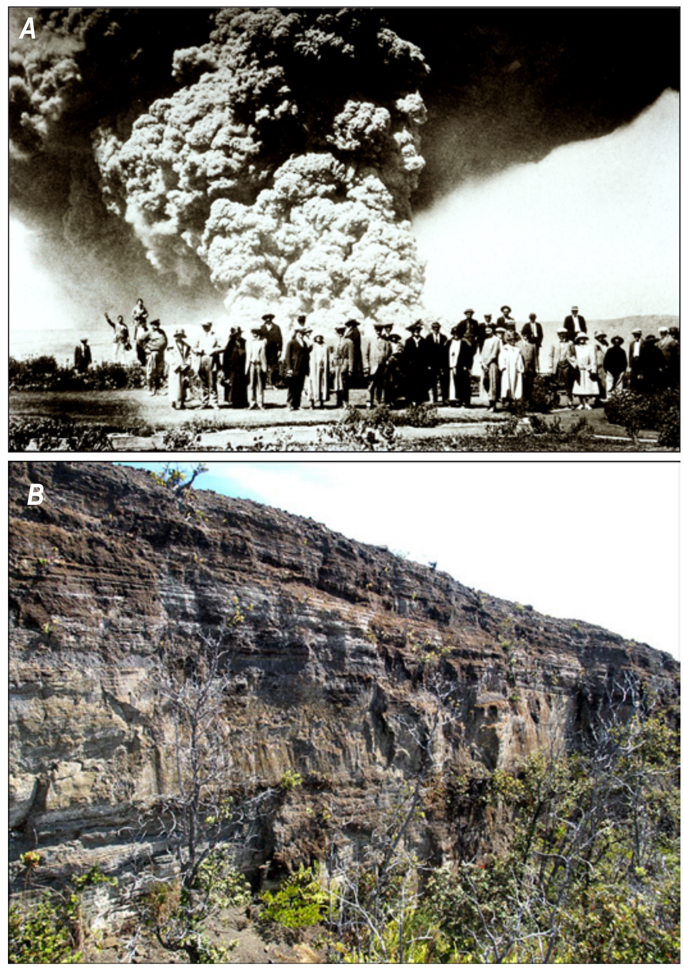

Figure 12. Photographs evidencing explosive behavior by Kīlauea Volcano. *A*, A crowd of visitors posing in front of the May 24,1924, explosive eruption plume from Halema‘uma‘u Crater (photograph courtesy of the Bishop Museum, Honolulu). Such explosive activity occurs when magma in the shallow summit reservoir interacts with groundwater. A person who ventured too close to take a picture was killed by a falling volcanic block. *B*, Pyroclastic deposits are well exposed in this cliff (~12 m high) southwest of Keanakāko‘i Crater, Kīlauea summit. These strata are part of a phreatomagmatic sequence (the “Keanakāko‘i Tephra” of Swanson and others, 2012a) produced by explosive activity much more powerful than the 1924 explosive eruption (see text; USGS photograph by Donald A. Swanson).

Tracking Flank Movement

As HVO's ground-deformation networks expanded and became more sophisticated, beginning in the 1970s, EDM and later GPS data demonstrated that this persistent seaward displacement occurs at average rates of several centimeters per year (fig. 13). The first comprehensive study of volcano flank movement by Swanson and others (1976), made possible by the development of a two-color, long-distance laser EDM for making much longer shots between benchmarks, concluded that the driving force for flank displacements was intrusion of magma into the rift zones. During catastrophic flank motion events, such as the *M*7.7 earthquake in November 1975 (Tilling and others, 1976, Nettles and Ekström, 2004), the sudden seaward flank displacements are much greater than those measured during "normal" volcanic activity (Lipman and others, 1985). Since then, many other studies—involving both ground- and space-based geodetic techniques—have generally reinforced these findings but differ in details of the conceptual models for flank displacements (for example, Lipman and others, 1988, 1990, 2002; Delaney and others, 1990, 1993; Cayol and others, 2000; Denlinger and Morgan, this volume, chap. 4; Poland and others, this volume, chap. 5).

Slow Slip Events

First reported in 2001 for the Cascadia subduction zone (Dragert and others, 2001), aseismic slip events are now recognized as common in subduction regimes around the world (see Beroza and Ide, 2011). Cervelli and others (2002a, p. 1015) recognized very similar sudden aseismic slip of Kīlauea's south flank in 2000, based on data from the continuous GPS network—the first such "recording of a silent earthquake in a volcanic environment." The 2000 slow slip event was equivalent to an earthquake with a moment magnitude of 5.7 but without the seismic shaking. Since this initial discovery, several more "slow slip" events on Kīlauea's south flank have been recognized, including a family of periodic events that occur every 2.2 years, give or take a month or two (Brooks and others, 2006; Poland and others, 2010). Each event is also associated with characteristic seismicity within the south flank (Segall and others, 2006a,b; Wolfe and others, 2007; Montgomery-Brown and others, 2009). A slow slip event in mid-2007 was thought to be triggered by a rift-zone dike intrusion by Brooks and others (2008, p. 1177), who suggested that "both extrinsic (intrusion-triggering) and intrinsic (secular fault creep) fault processes" can produce slow slip events at Kīlauea.

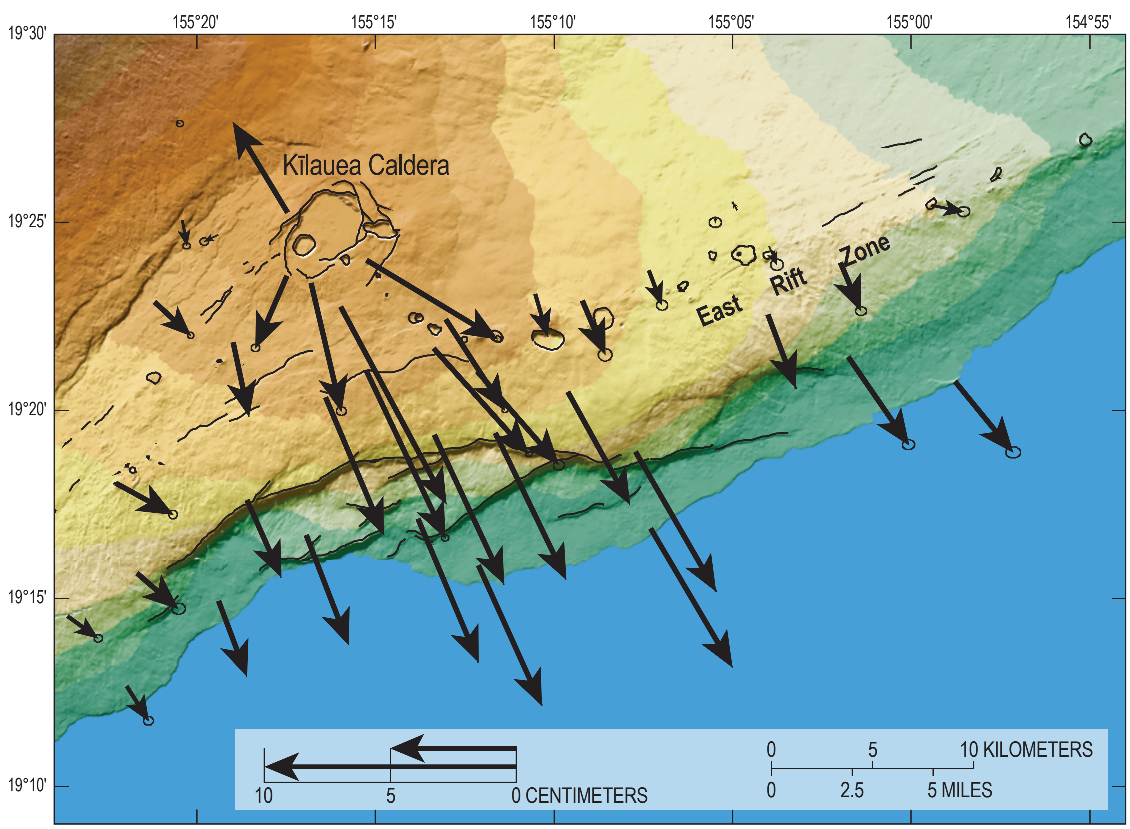

Figure 13. Map of Kīlauea showing continuously recording Global Positioning System (GPS) measurements obtained by the Hawaiian Volcano Observatory (HVO) geodetic networks during 2003–06. Station locations are at the tails of vectors, and circles indicate 95-percent confidence levels. The vectors show the horizontal movement of the ground surface during that period. They indicate net inflation of the summit region, as well as document the persistent, ongoing seaward displacement of Kīlauea's mobile south flank at rates of several centimeters per year (image by Michael Poland and Asta Miklius, USGS).

Geophysical Investigations of Subsurface Volcano Structure

The International Geophysical Year (1957–58) and the prospect of siting a deep research drill hole north of Maui spurred geophysical work on all the islands by HVO and University of Hawaiʻi at Mānoa scientists in the early 1960s. The drilling project, dubbed the "Mohole," was scrapped by lack of funding, but the scientific gains from the geophysical work were profound. Using a recently expanded and updated seismic network at Kīlauea Volcano, Eaton and Murata (1960) determined a basic seismic velocity structure for the Island of Hawaiʻi from P-wave arrival times while Kinoshita and others (1963) mapped the gravity variations caused by the island's substructure. The results of these studies, together with follow-up seismic studies (summarized by Hill and Zucca, 1987), revealed that the weight of the island's volcanoes depresses the oceanic crust below, causing it to flex. The internal structure of the volcanoes was consistent with a model of dense cores beneath summits and rift zones. More recently, detailed gravity mapping (Kauahikaua and others, 2000) and seismic tomography (Okubo and others, 1997) revealed discernible variations within those dense cores.

In 1978, the USGS conducted several airborne magnetic and very-low-frequency (VLF) electromagnetic resistivity surveys over the Island of Hawaiʻi (Flanigan and Long, 1987). These surveys indicated that Kīlauea's East Rift Zone is characterized by a highly magnetized shallow linear zone superposed over a deeper, broad unmagnetized body. Hildenbrand and others (1993) reinterpreted the magnetic data in terms of magnetic properties of basalts and concluded that the deep, unmagnetized body was hydrothermally altered rock, and that variations in the highly magnetized shallow zone defined cooling intrusions.

All of these geophysical data, combined with the results of resistivity soundings and self-potential surveys, defined the hydrothermal systems of Kīlauea Volcano (Kauahikaua, 1993). High-level groundwater within the summit region and convection within the aquifer in the vicinity of thermal sources in the summit and rift zones produce large self-potential electrical anomalies at the surface (Zablocki, 1978). Bedrosian and Kauahikaua (2010) recently revisited the use of electromagnetic resistivity and self-potential monitoring to geophysically characterize the Halemaʻumaʻu Overlook eruptive vent area.

Evolution of Volcanic Landforms

Hawaiian eruptions produce stunning examples of volcanic landforms and associated features, including shields, cones, craters, flow fields, lava lakes, lava tubes, lava deltas, and earthquake faults. Since the beginning of HVO, scientists have documented well—and often in real time—the processes and products resulting in the formation of many volcanic landforms. These are recorded and published in various venues, ranging from HVO's early serial publications (compiled in Fiske and others, 1987; Bevens and others, 1988) and annotated bibliographies and pictorial histories (Macdonald, 1947; Wright and Takahashi, 1989; Wright and others, 1992) to the general scientific literature. In the discussion below, we highlight a few selected landforms whose construction and evolution were well documented by HVO staff. Knowledge gained from studies of these historical examples can constrain interpretations regarding the origins of similar landforms created in the geologic past in Hawaiʻi and elsewhere, or on other planetary bodies.

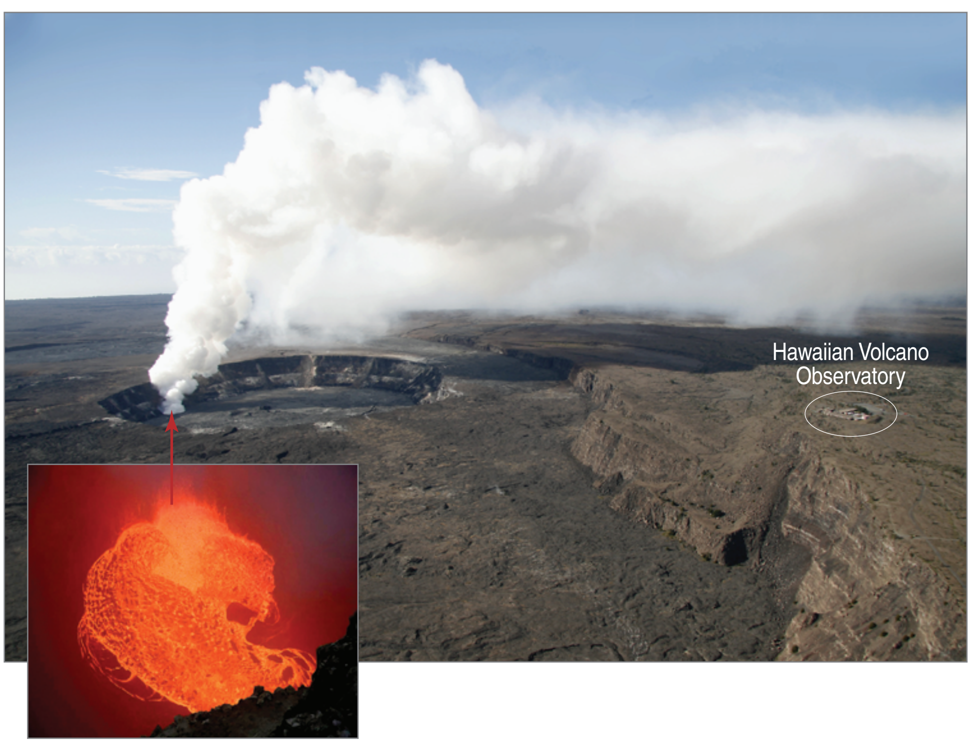

Figure 14. Photographs showing the eruption within Halemaʻumaʻu Crater that began in mid-March 2008. Right: Aerial view (looking south) in November 2008 of the eruption plume from the vent within Halemaʻumaʻu Crater; the Hawaiian Volcano Observatory (HVO) on the rim of Kīlauea Caldera is circled. This summit activity has continued into 2014. Left: Nighttime view in January 2010 of the active lava pond in the progressively enlarging vent (here ~120 m across). USGS photographs by Tim Orr.

Halemaʻumaʻu Crater

The formation of Halemaʻumaʻu pit crater within Kīlauea's summit caldera predated the start of scientific observations in the 19th century. Nonetheless, changes with time in Halemaʻumaʻu's configuration and lava-lake activity within it were noted in the accounts of the early explorers and settlers. It was recognized that the crater occupied the highest area of the caldera floor, which represented the surface of the summit of a broad, nearly flat shield.

In response to rapid magma withdrawal preceding the 1924 explosions, the crater floor dropped about 200 m below the rim; after the explosions, it was observed that the rubble-filled crater floor had dropped another 200 m (Jaggar and Finch, 1924). The 1924 events doubled the width of Halemaʻumaʻu to more than 900 m. Lavas from post-1924 eruptions at Halemaʻumaʻu have refilled much of the crater, such that its floor was raised to the current level of about 85 m below the present-day rim. The Overlook eruptive vent of the 2008–present summit activity, which now has become the longest-lived summit vent since 1924 (Hawaiian Volcano Observatory Staff, 2008), is centered within a smaller pit within Halemaʻumaʻu (fig. 14). The volume of material lost by collapse during the 1924 explosive eruption was more than 250 times the volume of lithic tephra ejected (Jaggar, 1924). A similar relation characterized the mid-March 2008 start of the Halemaʻumaʻu Overlook eruption, in which the estimated volume of the collapse also far exceeded the volume of ejecta (Houghton and others, 2011; Swanson and others, 2011b). Does this relationship, for two comparatively small historical explosive eruptions, also hold for much larger explosive events that have occurred in the geologic past?

Mauna Ulu and Kupaianaha Lava Shield Vents

Before the 1983–present Puʻu ʻŌʻō-Kupaianaha eruption, the 1969–74 eruption at Mauna Ulu (Hawaiian for "growing mountain") had been the longest-lived historical flank eruption—a distinction now held by continuing activity at Puʻu ʻŌʻō. Episodic overflows from the Mauna Ulu lava lake built a lava shield (fig. 15) that reached a maximum height about 121 m above the pre-1969 surface; moreover, overflows from the adjacent ʻAlae lava lake constructed a smaller shield, whose summit attained a height nearly 90 m above the surrounding surface (Holcomb and others, 1974; Swanson and others, 1979; Tilling and others, 1987a). Several other lava shields are found at Kīlauea along its two rift zones, including Kanenuiohamo (dated by radiocarbon analysis at 750–400 years before present; Sherrod and others, 2007), Heiheiahulu (~1750 C.E.; Trusdell and Moore, 2006), and Maunaiki (1919–20). It was not until the 1969–74 Mauna Ulu eruption, however, that modern scientific observations could be made to document, in detail, the beginning and growth history of a volcanic shield. The observations of the processes and durations involved in the development of Mauna Ulu and ʻAlae (Swanson and others, 1979; Tilling and others, 1987a) could be compared with studies of a later shield (built during 1986–92), when eruptive activity shifted 3 km downrift from the Puʻu ʻŌʻō vent to another site of outbreak. Repeated overflows from the new active lava pond fed by this new vent (later named Kupaianaha) constructed a shield that attained a maximum height of ~58 m above the preeruption surface (Heliker and Mattox, 2003).

Figure 15. Aerial photograph looking west on September 8,1972, of the two volcanic shields (Mauna Ulu in background, and the smaller ʻAlae shield in foreground) that developed during the 1969–74 eruption on Kīlauea's upper East Rift Zone. Both were built by repeated overflows from active lava lakes, as can be seen happening here from the perched lava pond at ʻAlae. The liquid lava-pond surface of ʻAlae (about 200 m across) indicates scale (USGS photograph by Robert I. Tilling).

The Complex Cone at Puʻu ʻŌʻō

The 1983–present Puʻu ʻŌʻō-Kupaianaha eruption—the longest lived flank eruption at Kīlauea in more than 500 years—has provided an unprecedented opportunity for making detailed observations of the evolution of a complex basaltic cone (in other words, one not predominantly composed of cinder). Growth and collapse of the cone during its first 20 years of eruption are summarized by Heliker and others (2003a). Built from the combined accumulations of fountain-fed lava flows, agglutinated spatter, and rootless flows, the Puʻu ʻŌʻō cone quickly attained its maximum height (255 m) by mid-1986. When the Kupaianaha vent formed in July 1986, cone growth ceased at Puʻu ʻŌʻō. In July 1987, Puʻu ʻŌʻō abruptly collapsed to form a steep, narrow, 100-m-deep crater, which deepened to 180 m by December 1988 and was enlarged by piecemeal rock falls and collapses of the crater walls. An active lava pond was observed intermittently as Kupaianaha erupted through February 1992 (Heliker and others, 2003a).

With the demise of the Kupaianaha vent, the eruption returned to Puʻu ʻŌʻō, where, over the next 20 years, the activity was dominated by a wide variety of processes, including (1) crater floor and wall collapses and subsequent filling with lava; (2) construction of small (“mini”) shields by flank vents that undermined the west and south flanks, leading to further cone collapse; and (3) episodic crater overflows (Heliker and others, 2003a; Poland and others, 2008). In 1997, another major collapse took place at the summit of the cone (fig. 16), and, by late 2002, the cone’s highest point was only 187 m above the preeruption surface. Many of the crater floor collapses correspond in time to intrusions up or down the rift zone. By 2011, the central crater was greatly elongated along the rift axis, the summit had lowered by more than 84 m from its highest elevation, and much of the east, west, and south flanks of the cone were buried by lava flows. As of this writing (mid-2014), the story of Puʻu ʻŌʻō continues to unfold (Orr and others, 2012); it is likely that the ongoing eruption at Puʻu ʻŌʻō will continue to modify the cone’s configuration by similar processes, perhaps ultimately leading to its total collapse and complete burial by new overflows.

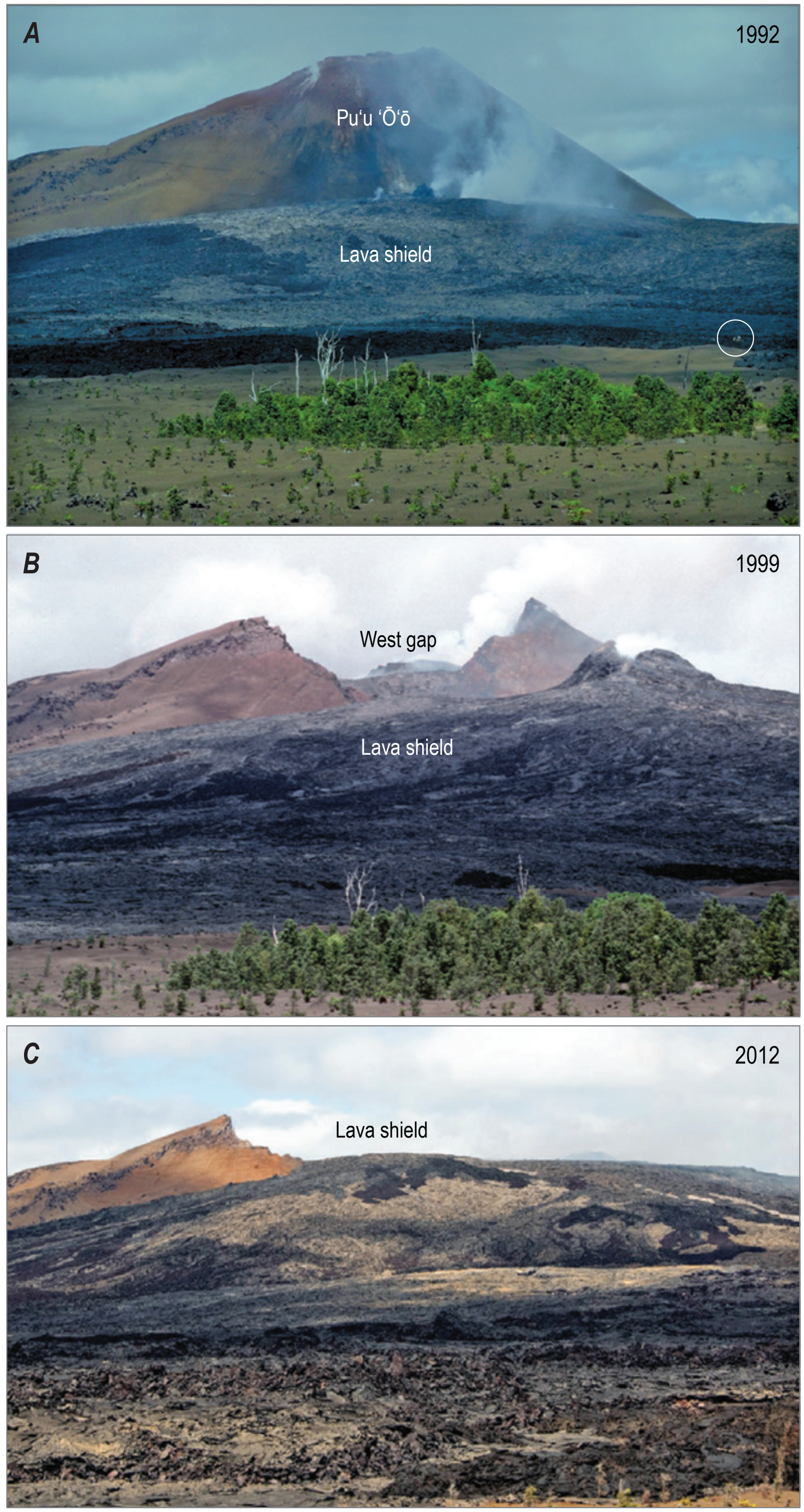

Figure 16. Photographs of the volcanic landforms built at the Puʻu ʻŌʻō vent as they evolved over time. *A*, View of the Puʻu ʻŌʻō cone in June 1992 at its maximum height (~255 m). An unnamed lava shield that had developed against the cone’s west flank during the previous 4 months is visible in the middle ground. People (circled) indicate scale of the landforms (USGS photograph by Tari Mattox). *B*, Same view of the Puʻu ʻŌʻō cone in 1999 after a major collapse of its summit and west flank, forming the prominent “west gap” (USGS photograph by Christina Heliker). *C*, Same view in 2012 after additional piecemeal smaller collapses, continued shield growth, and accumulation of episodic crater overflows. The cone has become a much less imposing landmark (USGS photograph by Tim Orr).

Lava Tubes

Lava tubes are common volcanic landforms on Hawaiian volcanoes (fig. 17), but the processes of their development were not studied "live" until the 1969–74 Mauna Ulu eruption (Swanson and others, 1979; Tilling and others, 1987a). Sustained lava flows produced during this eruption allowed, for the first time historically, systematic and repeated field observations of lava-tube formation and evolution. Peterson and others (1994) concluded, from observations at Mauna Ulu, that lava tubes can form by four principal processes, and that their development was favored by low to moderate volume rates of flow for sustained periods of time. The subsequent, and even longer-duration, Puʻu ʻŌʻō-Kupaianaha eruption (1983–present), provided HVO and other scientists unprecedented opportunities to observe active lava tubes and to extend and refine the early findings from studies during Mauna Ulu (see Heliker and others, 2003b, and references therein). During the 40-plus years since the Mauna Ulu eruption, the key role played by lava tubes in effusive basaltic volcanism has been thoroughly investigated in Hawaiʻi and documented in numerous summary works (for example, Peterson and Swanson, 1974; Swanson and others, 1979; Greeley, 1987; Tilling and others, 1987a; Peterson and others, 1994; Greeley and others, 1998; Heliker and others, 2003a; Helz and others, 2003; Kauahikaua and others, 2003; Cashman and Mangan, this volume, chap. 9; and references therein). Later (see "Development of Lava Flow Fields" section, below) we focus on the importance of lava tubes in the development of lava flow fields.

Perched Lava Ponds and Channels

Perched lava ponds and channels share a similar origin—episodic overflows of their banks raise the surface of flowing lava progressively higher than the surrounding ground (for example, Wilson and Parfitt, 1993). The formation and activity of a striking perched channel were documented in detail by Patrick and others (2011a). This channel formed in 2007 on relatively flat ground within 1.4 km of a new vent downrift of Puʻu ʻŌʻō, and repeated lava overflows from it raised the lava surface nearly 45 m above the surrounding terrain at an average rate of about 0.3 m per day. Integrated monitoring data and field observations detailed a process never before seen for a lava channel: cyclic lava spattering at intervals of 40–100 minutes along the channel margins typically led to sudden lava-level drops of ~1 m, accompanied by seismic tremor bursts with peak frequencies of 4–5 Hz. This pattern was interpreted by Patrick and others (2011a) to reflect a gas pistoning process driven by gas accumulation and release beneath the lava crust of the active channel. The recent studies at Kīlauea (for example, Hawaiian Volcano Observatory Staff, 2007a,b; Patrick and others, 2011a; Patrick and Orr; 2012b) arguably represent the most comprehensive documentation to date—replete with detailed chronologies and illustrative photographs and diagrams—of the formation of perched lava ponds and channels and their evolution.

Figure 17. Photograph of the interior of Thurston Lava Tube (Hawaiʻi Volcanoes National Park), looking toward an exit (photograph courtesy of Peter Mouginis-Mark, University of Hawaiʻi at Mānoa). The tube cavity here is about 4 m high. This is an easily accessible, and heavily visited, example of an inactive lava tube; compare with the active lava tube shown being sampled in figure 8.

Rootless Shields and Shatter Rings

The Puʻu ʻŌʻō-Kupaianaha eruption has afforded multiple opportunities to study the formation of some smaller scale landforms, such as hornitos, elongate tumuli, rootless shields, and shatter rings (Kauahikaua and others, 1998, 2003; Orr, 2011a; Patrick and Orr, 2012b). Unlike large lava shields (for example, Mauna Ulu and Kupaianaha) that are directly linked to a deep-seated (>1 km) vent, a rootless shield is fed by, and built above, an active lava tube. It forms at a breakout along the tube, generally associated with resumption of active flow within the tube following an eruptive pause (Kauahikaua and others, 2003). A perched lava pond quickly develops above the breakout point, and overflows from that in all directions construct a shield-like structure. First seen in 1999, such features have been observed several times since then, most notably in 2002, 2003, and during 2007–11, and can build as high as 20 m above the surrounding surface. The largest one, to date (formed in 1999), had a diameter of more than 500 m and was topped by a flat, lava-ponded surface 175 m across (Kauahikaua and others, 2003). After becoming inactive, rootless shields collapse and reveal hollow interiors, suggesting that they contained shallow reservoirs filled with lava before draining. This hypothesis was confirmed several times when the side of some actively growing shields during 2007–08 collapsed and produced fast-moving lava flows as they drained (Patrick and Orr, 2012b).

First noticed in the 1990s (Kauahikaua and others, 1998, 2003), shatter rings also can form over active lava tubes carrying variable amounts of lava that alternately push the tube roof up when the tube is full and then let it down as the lava flux decreases. The repeated up-and-down flexing of the tube roof eventually fractures the roof in an oval shape defined by a ring of rubble with a fractured pāhoehoe surface in the middle (Kauahikaua, 2003, figs. 6–8). Actively deforming shatter rings sound like rocks constantly grinding against each other. Lava in the tube can break out to the surface through the rubble rings, typically while the roof is being pushed upward. Orr (2011a) documents the shatter-ring process and provides a comprehensive list of other flow fields in the world that have shatter rings. He suggests that recognition of shatter rings on other planets would be evidence that lava tube systems were once active there.

Lava Deltas

The prolonged Mauna Ulu and Puʻu ʻŌʻō-Kupaianaha eruptions sent many tube-fed pāhoehoe lava flows into the ocean, thereby affording HVO scientists ample opportunity to track the detailed growth and collapse of lava deltas and to study accompanying explosive hydrovolcanic activity (for example, Peterson, 1976; Mattox and Mangan, 1997; Kauahikaua and others, 2003; Sansone and Smith, 2006). One of the main factors that promotes or limits delta growth is the steepness of the hydroclast-mantled submarine slope, which determines its ability to support the seaward extension of the leading edge of the overlying lava flows. Tube-fed lava flows have entered the ocean about 70 percent of the time during 1986–2010; the two longest duration ocean entries each lasted 22 months (Laeapuki in May 2005–March 2007 and Waikupanaha in March 2008–January 2010; Tilling and others, 2010). Upon entry into the ocean, the hot lava is shattered by coming into contact with cold seawater, can be reworked by surf action, and is easily erodible. If lava entry is sustained, however, the fragmental debris can accumulate in the littoral zone, forming a bulwark of new land—enlarging and extending the shoreline seaward—over which additional lava advances to form lava deltas.

Recent studies have documented the rapid changes that lava deltas can undergo after their formation. As an example, the east Laeapuki lava delta had grown to about 44 acres in size by mid-November 2005 and then abruptly collapsed into the sea on November 28 to produce the largest lava-delta collapse observed to date (the collapse was captured on time-lapse video; see Orr, 2011b). With continued lava entry at the same location, the delta quickly rebuilt (fig. 18) to reach 64 acres in size by March 2007. Then, within a few months, the delta began a series of collapses, such that by June 2010, none of the originally huge east Laeapuki lava delta remained (Tilling and others, 2010). We present this example to emphasize that, without regular direct observations, the complete history of the dynamic but short-lived evolution of this lava delta would have been difficult, if not impossible, to reconstruct from the now-available field evidence. Current studies of lava deltas by HVO provide potentially useful information (for example, vent effusion rate, mode of lava transport to ocean, duration of ocean entry) for deciphering the formation and histories of prehistoric lava deltas in Hawaiʻi or at other island volcanoes (for instance, in the Canaries or the Azores, Stromboli, Iceland, and the Aleutians).

Volcano Experiments and Topical Studies

The initiation of regular observation and measurement of volcanoes, while rooted in the early 20th century movement to establish volcano observatories, also has facilitated research that has transformed volcanology into the multidisciplinary science that it is today. With its high eruption frequency and relatively easy and safe accessibility to an ample supply of molten or freshly erupted solidified lava, Kīlauea is a natural laboratory for conducting experimental or specialized studies. Apple (1987) gives a highly readable summary about some of the earliest volcano "experiments"—mostly involving temperature measurements—conducted by Jaggar and his collaborators. Because of HVO's isolated island location, these early experiments necessarily depended on materials, equipment, and techniques that were available, or could be readily adapted, in Hawai‘i. In this section, we will revisit some topically driven studies undertaken during the past century with the aim of better understanding basaltic volcanism. The scientific literature contains results of these topically focused studies conducted by HVO and other scientists during the past century; here, we present only selected highlights.

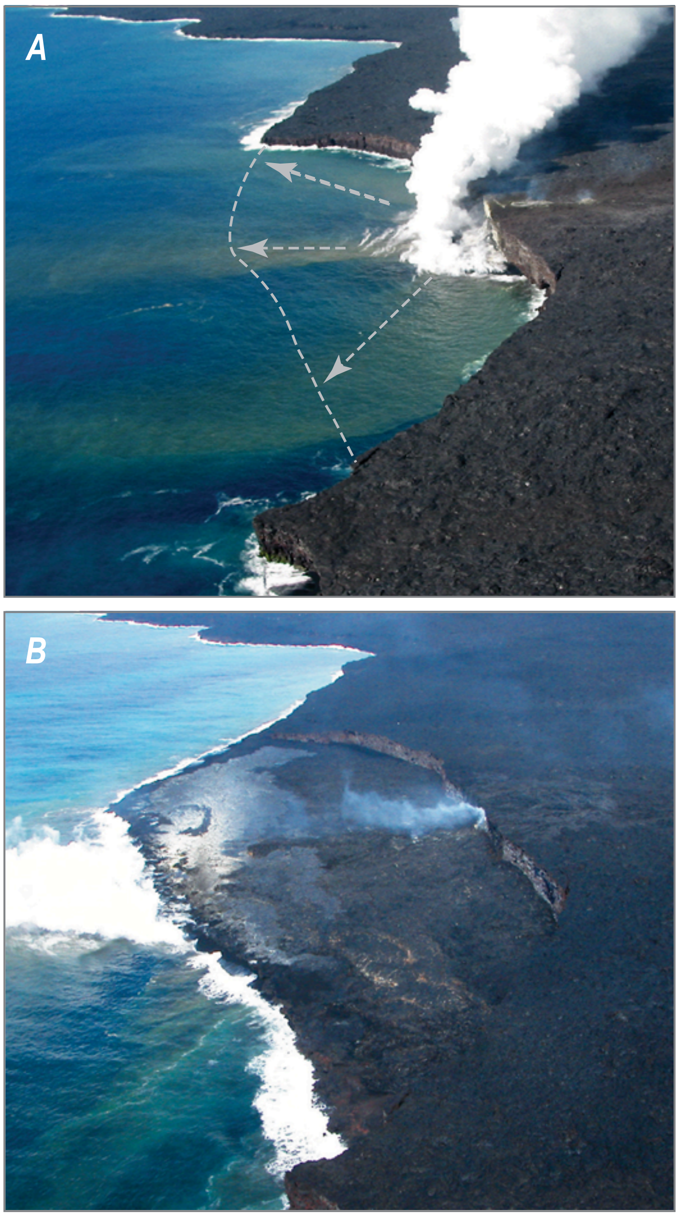

Figure 18. Oblique aerial photographs of lava-delta growth where lava enters the sea. *A*, Looking towards the west along Kīlauea’s south coast in early December 2005, showing the arcuate, newly exposed sea cliff four days after the collapse of the actively growing lava delta (approximated by dashed line) at east Laeapuki (USGS photograph by James Kauahikaua). *B,* With continuing lava entry into the sea, by late April 2006 the lava delta was rebuilt and larger in size than before the collapse (USGS photograph by Tim Orr).

Field Measurements of Lava Temperature

Even before HVO was formally established, a field experiment was undertaken in 1911 by Frank Perret and E.S. Shepherd to measure directly the temperature of the active lava lake at Halema‘uma‘u. The technique involved lowering a “special resistance thermometer” (a platinum thermocouple in an iron casing) into the molten lava lake by means of a specially designed cable-trolley system built across the lava lake (fig. 19*A*). After many logistical difficulties with the cable system and the loss of two thermometers, a reading of 1,010 °C was registered from the still-working third and last thermometer immersed about 0.6 m under the lava-lake surface (see interesting accounts by Perret, 1913f; Jaggar, 1917a; and Apple, 1987). Subsequent studies have shown that this temperature is too low for liquid basalt, reflecting chemical reactions of volcanic gases with the thermocouple elements that affected calibration. Nonetheless, the Perret-Shepherd experiment represented a historic scientific achievement in its time—the first in-place temperature measurement and sampling (fig. 19*B*) of liquid lava ever made at any volcano.

Temperature estimates of liquid lava were also made by thrusting steel pipes down to different depths below the surface of the active lake. At the end of the pipe was a cylinder containing six Seger cones, which are mixtures of clay and salt with variable known melting points used by ceramicists as temperature indicators. The pipe was inserted to a known depth and held in place for 6 minutes and then withdrawn—with pasty lava adhered to the part of the pipe that penetrated into still-molten material. Then, each of the Seger cones was examined to ascertain which had melted and which had not, thereby determining the thermal gradient within the examined depth interval (~1.5 m), assuming thermal equilibrium was attained (Jaggar, 1917a; Apple, 1987, fig. 61.5). The thermal gradients obtained by HVO in 1917 doubtless were imprecise by today’s standards, but they nevertheless constituted the first and only attempt ever made to determine the shallow thermal gradient for an active lava lake.

Because of the logistical difficulties attendant upon these earliest measurements of the temperature of liquid lava, HVO later relied on more robust thermocouples, optical pyrometers, and other hand-held instruments for field measurements of lava temperature. As geothermometric techniques became better calibrated, they have been increasingly used to determine lava temperatures of glassy water-quenched samples collected during the course of an eruption (for example, Helz and others, 1995, this volume, chap. 6), obviating the need for direct temperature measurements in the field.

In 1922, HVO conducted the first scientific drilling studies in solidified lava, using both churn-drill and rotary-drill rigs and imaginative adaptations of automobiles to haul drilling water and supplies to drill sites. Four holes were completed during this experiment, ranging in depth from 7 to 15 m, for temperature measurements in solidified lava at several sites at Kīlauea's summit. None of the measured bottom-hole temperatures exceeded 97 °C (Jaggar, 1922). Later, Jaggar planned to have a summit network of shallow (3 m) boreholes, intended for periodic remeasurements to collect long-term data to track temporal changes in the temperature of the bedrock. After drilling 30 holes for this network, however, the effort was abandoned in 1928, presumably because the results were inconclusive (Apple, 1987). While these early drilling experiments and the resulting temperature measurements produced few lasting scientific results, they provided an important conceptual framework for subsequent modern scientific drilling studies at Kīlauea.

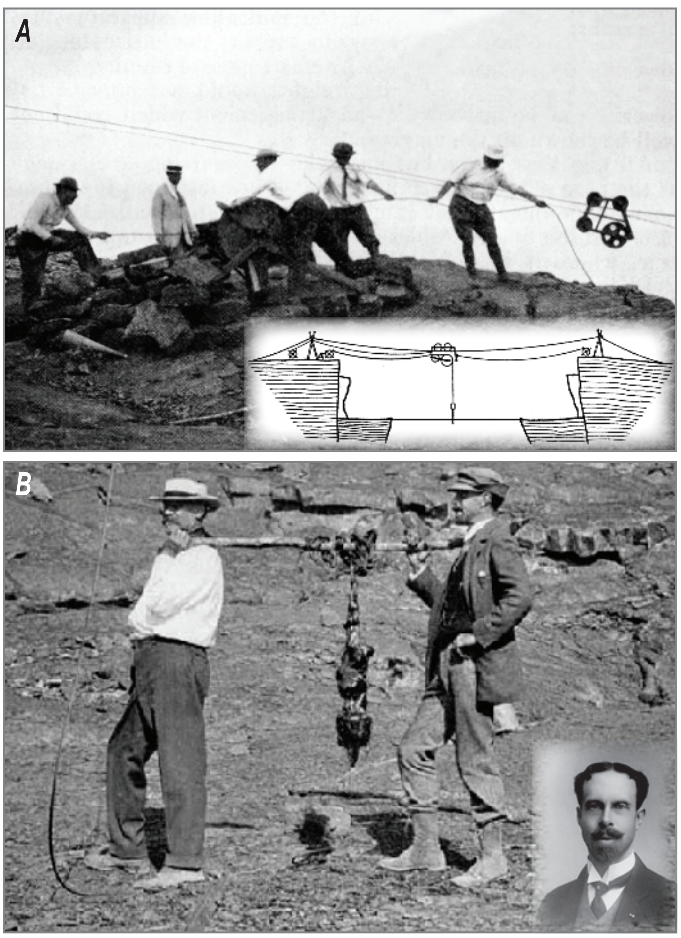

Figure 19. Photographs recording early adventures in studying and sampling molten lava at Kilauea. *A*, The cable-trolley system used by Frank Perret in 1911 for temperature measurement and sampling of lava from the active Halemaʻumaʻu lava lake. (Inset sketch and photograph are from Perret, 1913f, figs. 1 and 2, respectively.) *B*, Perret (right) and an assistant carry a sample of quenched molten lava collected by means of a pot and chain attached to the spanning cable of the apparatus shown in *A* (taken from Perret, 1913f, fig. 3). Inset (lower right corner) is a portrait of Perret in 1909 (photograph from Library of Congress).

Drilling Studies of Passive Historical Lava Lakes

Beginning in 1960, HVO conducted pioneering drilling studies of three historical passive lava lakes: Kīlauea Iki (erupted in 1959), ʻAlae (erupted in 1963), and the west pit of Makaopuhi (erupted in 1965). Of these, only the Kīlauea Iki lava lake has not been buried by younger lavas.

Five holes were drilled into the solidifying crust of Kīlauea Iki between April 1960 and December 1962 (Rawson, 1960; Ault and others, 1961; Richter and Moore, 1966). On July 25, 1960, the hole jointly drilled by the Lawrence Radiation Laboratory and HVO was the first to penetrate the crust, marking the first-ever drilling experiment specifically designed to directly measure temperature and sample the molten lava and associated volcanic gas. Owing to the crude and improvised equipment used, the first drillings at Kīlauea Iki encountered problems in the high-temperature environment. The early lessons learned regarding drilling techniques, however, were later applied to successful subsequent drilling studies at ʻAlae, Makaopuhi, and Kīlauea Iki (fig. 20). Because it was the largest and has remained accessible for study, the Kīlauea Iki lava lake was drilled repeatedly (in 1967, 1975, 1976, 1979, 1981, and 1988) to document its prolonged cooling history (Helz and Taggart, 2010; Helz and others, this volume, chap. 6). On the basis of its thermal history, Kīlauea Iki probably fully crystallized by 1995. The samples and temperature data collected from these drilling studies have provided significant insights into the cooling, crystallization, and differentiation of basaltic magma (for example, Peck and others, 1966; Richter and Moore, 1966; Wright and others, 1976; Wright and Okamura, 1977; Peck, 1978; Wright and Helz, 1987; Helz, 1987a,b, 2009; Jellinek and Kerr, 2001; Helz and others, this volume, chap. 6).

In-Place Measurements of Molten Lava Properties

Boreholes drilled into cooling lava lakes provided entryways for instruments and other experimental devices for making measurements from the solidified surface at ambient temperature, down to the still-molten lava at magmatic temperature at the bottom of the hole. As examples, we briefly comment on two unique experiments: one conducted in the 1965 lava lake within Makaopuhi Crater (Shaw and others, 1968) to measure lava viscosity and another in the 1959 Kīlauea Iki lava lake to measure magnetic susceptibility (Zablocki and Tilling, 1976).

Directly measuring viscosity involved the insertion of a stainless steel spindle into the melt via a casing that was forced through the crust, which was ~4.4 m thick at the time of the measurements. The spindle was rotated by application of known torque using a system of weights and pulleys (Shaw and others, 1968, figs. 2 and 3), and the number of revolutions of the rotating spindle was measured by means of a stopwatch. The entire operation to obtain a measurement—drilling, emplacement of the spindle, time required for readings, and withdrawal of the spindle—needed to be completed in one day, because if the hole was left open overnight, it became impossible to insert the spindle the next day due to the "hardening" of the crust-melt interface zone, and if the spindle was left too long in the hole, it would become encased in lava and could not be recovered. The simple but functional viscometer invented for use at Makaopuhi made possible the first-ever field measurement through a borehole of the viscosity of tholeiitic basaltic melt. The field data, combined with laboratory data to higher temperatures, indicated a Newtonian viscosity of about 4,000 poises for the equilibrium phase at 1,130 °C.

During the February–March 1975 drilling at Kīlauea Iki, two of the three holes were used to measure magnetic susceptibility (Zablocki and Tilling, 1976). As with the field measurements of viscosity at Makaopuhi, the situation at Kīlauea Iki also required some special adaptations. Because of the high temperatures (>900 °C) in the holes, the in-hole sensing element had to be thermally insulated to maintain a constant 100 °C; this was achieved by placing the sensor in a water-filled, open-ended ceramic tube wrapped in thin asbestos sheets. Moreover, because the depths of the 1975 drill holes (~44 m) were much deeper than those in the pre-1975 lava-lake drillings, it was necessary to devise a special flexible thermocouple system that was manually lowered and raised in the hole by means of a sheave to measure the temperature profile. For details about both the magnetic susceptibility and the thermocouple probe, see Zablocki and Tilling (1976, especially fig. 2). Measurements made in June 1975 showed that the minimum temperature at which magnetic susceptibility drops to zero is about 540 °C—a temperature that accords well with the range of Curie temperatures obtained in laboratory heating experiments of basaltic core samples. This particular special study at Kīlauea Iki represents "the first in-situ, 'real time,' determination of the apparent Curie temperatures of cooling basaltic lava." (Zablocki and Tilling, 1976, p. 487).

The slowly cooling molten lava body within Kīlauea Iki Crater also provided an ideal setting for geophysical studies to determine its electrical properties. Anderson (1987) reported on the electrical structure of the crust above the molten lava, and Frischknecht (1967) used surface electromagnetic soundings to determine molten lava conductivity to be about 2 ohm-meters. Various electromagnetic and magnetic techniques were used to map the edges of the molten lava and document the contraction of the cooling edge with time (Smith and others, 1977).

Figure 20. Photographs of drilling operations at Kīlauea Iki lava lake in 1975. *A*, General view of the drill rig. It and other heavy equipment were lowered into the crater by helicopter. *B*, The top of drill hole 75–2 and view looking down the drill hole (~ 6 cm in diameter) from the surface to hole bottom (~40 m), where still-molten 1959 lava glows at ~1,110 °C. (USGS photographs by Robin T. Holcomb).

Underwater Observations of Active Lava Flows

Fluid lava erupted or flowing under water can produce “pillow lavas,” which have been studied and mapped in many submarine volcanic environments, but their actual formation had never been directly observed in real time anywhere in the world before 1970. During lava entries into the ocean associated with long-lived flank eruptions, such as the Mauna Ulu (1969–74) and Puʻu ʻŌʻō-Kupaianaha (1983–present) activity, scuba-diving observers were able to watch and film (fig. 21) the formation of pillow lava at the submerged fronts of actively advancing flows (for example, Moore and others, 1973; Moore, 1975; Tepley, 1975; Tribble, 1991; Sansone and Smith, 2006). These real-time observations of pillow-lava formation have generally confirmed the origin and emplacement mechanisms inferred from studies of ancient pillow lavas in Hawaiʻi and elsewhere. Recent submarine studies (Takahashi and others, 2002) confirm Moore and Fiske’s (1969) assertion that the bulk of the below-sea part of a Hawaiian volcano is composed of pillow lavas. In addition to pillow-lava formation, Tribble (1991) also, for the first time, witnessed live the development of submarine channelized flows and submarine slope failures.

Lava-Seawater Interactions and Ocean-Entry Gas Plumes

The decades-long duration of the 1983-to-present eruption of Kīlauea has afforded ample opportunity to study lava-seawater interactions. Direct observations of the hydrovolcanic explosive activity produced upon lava entry into the ocean have improved our understanding of the processes that produce black sand beaches and littoral cones, common features along Hawaiʻi’s coasts (for instance, Moore and Ault, 1965; Jurado-Chichay and others, 1996). Mattox and Mangan (1997) documented the conditions under which lava entered the ocean explosively and found that it required relatively high rates of lava flux into the water.

When molten lava enters the ocean, the ensuing reaction with chlorides in the seawater can produce highly acidic steam plumes, sometimes called “laze” (lava haze). The plumes have been found to contain hazardously high concentrations of hydrochloric acid (pH 1.5–2), after Hawaiʻi Volcanoes National Park personnel complained about their frequent exposure to laze while on duty in the lava-entry areas (Sutton and others, 1997; Johnson and others, 2000; Sansone and others, 2002; Edmonds and Gerlach, 2006).

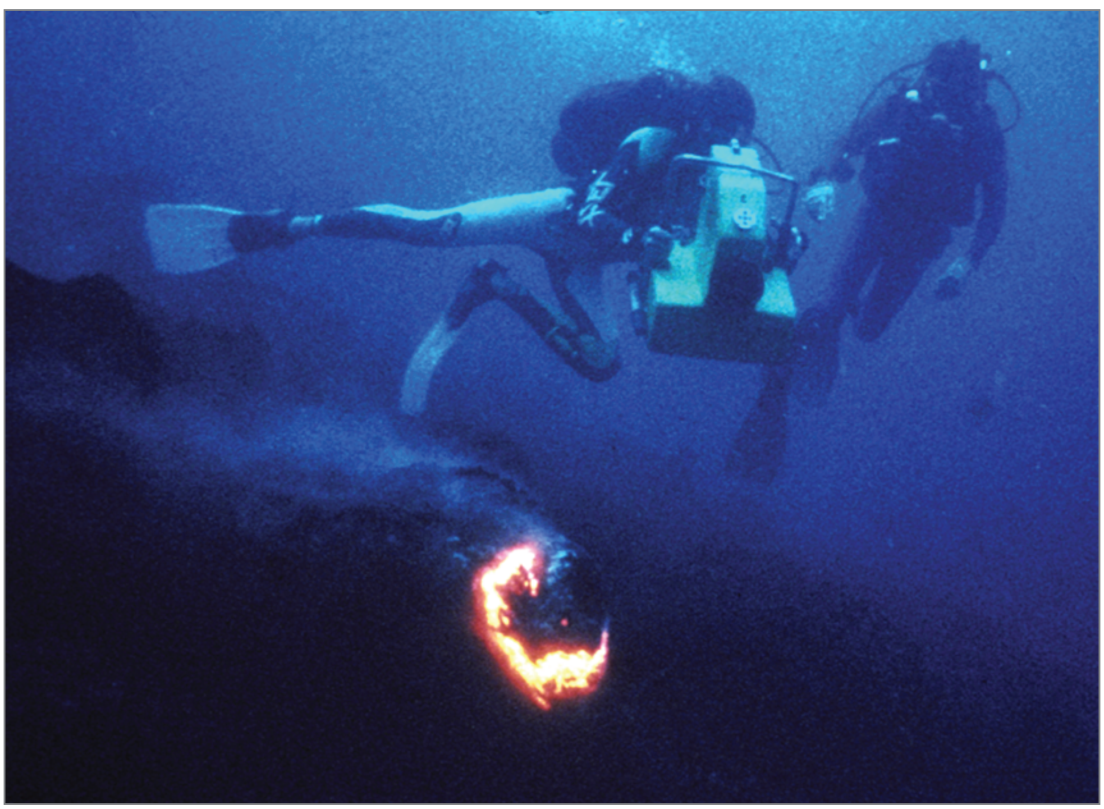

Figure 21. Photograph of scuba divers filming an underwater lava flow during the Puʻu ʻŌʻō-Kupaianaha eruption—the first such filming was done earlier, during the 1969–74 Mauna Ulu eruption. In this image, the crust of chilled lava is breaking open to reveal the advancing bright-orange molten lava inside (copyrighted photograph courtesy of Sharkbait World Pictures, Kailua-Kona, Hawaiʻi).

Use of Digital Cameras, Webcams, and Video to Precisely Document Eruptive Processes

Throughout HVO's history, sketches, photographs, and movies were the mainstays for documenting eruptive activity at Kīlauea and Mauna Loa, and time-lapse photography was first used to record lava-lake activity during the 1969–74 Mauna Ulu eruption. Beginning in 2004, webcams, time-lapse digital photography, and forward-looking infrared (FLIR) images have come into wide and increasing use (see, for example, Orr and Hoblitt, 2008; Hoblitt and others, 2008, Orr and Patrick, 2012; Orr and Rea, 2012; Patrick and Orr, 2012a; Patrick and others, 2014; Orr, 2014). These techniques have allowed volcanic processes to be "seen" and compared in near real-time with geophysical monitoring data as never before. Additionally, as emphasized by Patrick and others (2014), thermal cameras sometimes can also "see" through thick volcanic fume, thereby providing views of eruptive activity not possible by means of visual webcams and the naked eye. Figure 22 compares visual, FLIR, and composite images of lava flows. An added bonus is that direct views of Hawaiian eruptive activity can now be shared with the world via the Internet. For example, from the HVO Web page, it is possible to access the live views from webcams (including one at Mauna Loa's summit), as well as to view time-lapse digital photography of different types of eruptive activity at various sites (Orr, 2011b). In part from analysis of these new data streams, Patrick and others (2011b) used detailed timing of Halemaʻumaʻu's degassing pulses related to tremor bursts and small explosive events at or near the top of the lava column to show that they produced very-long-period signals at about 1-km depth.

Development of Lava Flow Fields

During the prolonged Mauna Ulu (1969–74) and Puʻu ʻŌʻō-Kupaianaha (1983–present) eruptions, extensive lava flow fields developed by the emplacement of multiple fluid flows—fed via long-duration surface channels or lava tubes—traveling great distances from the source vents to the coastal plains. The mechanisms and dynamics of lava flow emplacement are treated thoroughly by Kauahikaua and others (2003) and by Cashman and Mangan (this volume, chap. 9, and references therein), but we reemphasize below some processes well studied in Hawaiʻi. Systematic observations of flow dynamics, combined with detailed mapping of flow advances during the growth of lava-flow fields at Kīlauea, provide comprehensive case histories for comparing and contrasting the development of complex lava-flow fields—prehistoric and historical—at other volcanoes (for example, Calvari and Pinkerton, 1998; Guest and others, 2012; Solana, 2012; Branca and others, 2013).

Pāhoehoe-ʻAʻā Transition

The distinctive differences in appearance between pāhoehoe and ʻaʻā lavas naturally drew the attention of early observers of Hawaiian eruptions. They recognized that these two contrasting types of lava could occur during the same eruption, and even along a single active flow; thus, their origin could not be explained by any inherent differences in the magma before eruption. As annotated by Wright and Takahashi (1989, p. 6), the earliest published account of the origin of ʻaʻā was by W.D. Alexander (1859), who, while observing the 1859 eruption of Mauna Loa, likened ʻaʻā formation to "graining" of sugar. Alexander's notion of "sugaring" was later followed up scientifically by Jaggar (1947) and Macdonald (1953b), who hypothesized that ʻaʻā formation involved volcanic degassing and change of viscosity.

Scientific interest in the pāhoehoe-ʻaʻā transition was rekindled, beginning with the 1969–74 Mauna Ulu eruption. During this eruption, many long lava flows over gentle and steep slopes afforded abundant opportunities to observe, in real time, transitions between the two types. Peterson and Tilling (1980) proposed a semiquantitative model relating viscosity and rate of shear that featured a "transition threshold zone" (TTZ) separating the pāhoehoe and ʻaʻā flow regimes. During flow, once a discrete infinitesimal element of lava crosses the TTZ, pāhoehoe changes to ʻaʻā (Peterson and Tilling, 1980, fig. 9). The original Peterson-Tilling model has been substantially modified and quantified by many subsequent studies (for example, Kilburn, 1981, 1993, 2000; Lipman and Banks, 1987; Wolfe and others, 1988; Cashman and others, 1999). Some of the most recent studies (for instance, Hon and others, 2003; Kauahikaua and others, 2003) argue that the pāhoehoe-ʻaʻā transition is not always irreversible, as originally contended by Peterson and Tilling (1980); ʻaʻā-pāhoehoe transitions do indeed occur, as shown during the Puʻu ʻŌʻō-Kupaianaha eruption. Considerable scientific debate continues about the rheological nature and styles of transitions between ʻaʻā and pāhoehoe during a single active flow (see Cashman and Mangan, this volume, chap. 9). Most eruptions at Kīlauea and Mauna Loa produce ʻaʻā flows initially but quickly transition to pāhoehoe flows for the remainder of activity. The ratio of duration in these phases historically has ranged from 1:7 (Mauna Ulu eruption) to 1:18 (1859 Mauna Loa eruption). Using these historical ratios, staff member Jack Lockwood speculated in an internal HVO communication in early 1987: "If historical ʻaʻā/pāhoehoe chronological ratios of previous long-lived Hawaiian flank eruptions persist, the sustained pahoehoe production eruption which began in July 1986 ("Phase 48") could last from 24 to 63 years! This is, of course, outrageous; we know of no historical example of such long-lived activity—but is it really impossible?" (Lockwood, 1992, p. 6). Lockwood's line of reasoning was met with considerable skepticism at the time, but now—in hindsight—seems remarkably prescient and entirely plausible as we enter the 31st year of near-constant lava effusion on Kīlauea's East Rift Zone (Orr and others, 2012).

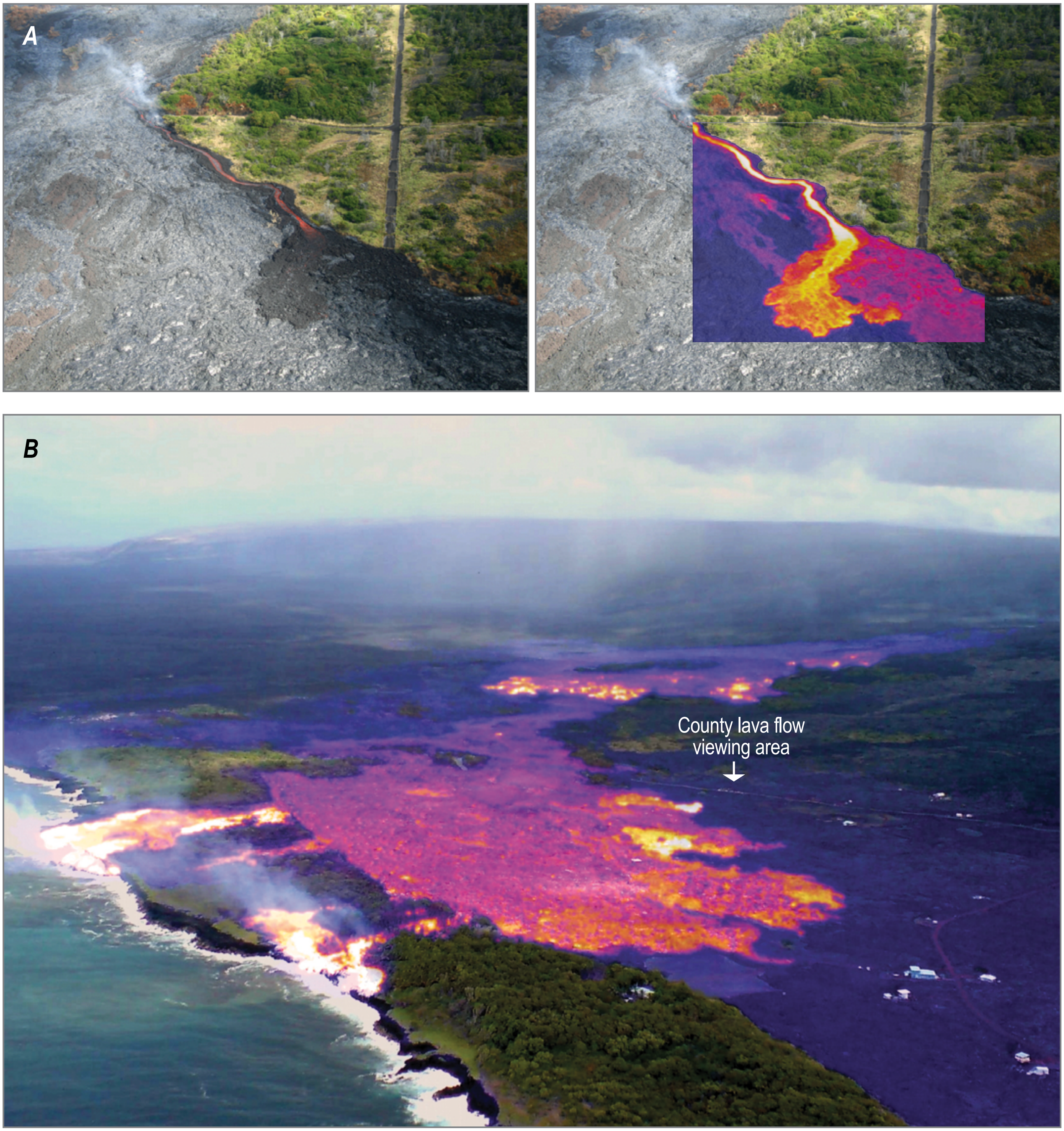

Figure 22. Images illustrating the use of forward-looking infrared (FLIR) imaging to monitor active lava flows. *A*, Comparison of conventional photographic image (left) of active lava flow from Pu‘u ‘Ō‘ō with an FLIR image of the same flow (right), with the yellow-orange colors showing more clearly its hottest (most active) parts (USGS images, March 14, 2008). *B*, Example of composite conventional photograph and FLIR image of active lava flow from Pu‘u ‘Ō‘ō at ocean entry; such composite images have been popular with emergency-management officials and the general public (USGS image, July 30, 2010).

Lava-Tube Systems

With sustained effusive eruptive activity, well-integrated lava-tube systems commonly develop during the emplacement of lava flow fields. These systems thermally insulate lava flowing within the tubes, thereby allowing the lava to travel great distances and ultimately enter the ocean. The ability of fluid lava to flow great distances in this way contributes to the low-angle slopes that characterize Hawaiian and other shield volcanoes. HVO studies of lava-tube behavior have largely settled an oft-debated question: can the molten lava flowing through tubes erode down through its base? The answer is "yes," by thermal and (or) mechanical processes, and the erosion rate has been observed to be as high as 10 cm/day for several months (Kauahikaua and others, 1998a, 2003). The key role played by the tubes in facilitating long-distance lava transport and in emplacing flow fields has been thoroughly studied in Hawai‘i, and we refer the interested reader to the numerous summary works (for example, Peterson and Swanson, 1974; Swanson and others, 1979; Greeley, 1987; Tilling and others, 1987a; Peterson and others, 1994; Heliker and others, 2003b; Helz and others, 2003; Kauahikaua and others, 2003; Cashman and Mangan, this volume, chap. 9; and references therein).

Inflation of Pāhoehoe Flows

Inflation features in pāhoehoe flows were first recognized during the 1919–20 Maunaiki eruption and described by Finch and Powers (1920, p. 41) as "A large schollendome [equant tumulus] . . . had been built up . . . occupied by recently solidified lava that had risen from below as was shown by its flat topped filling." Prominent tumuli were also recognized on the floor of Kīlauea Caldera but were attributed to the action of gas pressure. This endogenous mechanism in the development of pāhoehoe flow fields was recognized by Holcomb (1987) while mapping recent Kīlauea lava flows; he labeled them "inflated." The dominant mode of emplacement of pāhoehoe flows entering the coastal community of Kalapana on Kīlauea's south flank in 1990 also involved endogenous growth or "inflation." Molten lava that flows or spreads into solidifying crust at a flow front lifts its surface at decreasing exponential rates (for example, Walker, 1991; Hon and others, 1994; Cashman and Kauahikaua, 1997; Kauahikaua and others, 1998, 2003; Hoblitt and others, 2012). Once this mechanism was understood, the hazards posed by pāhoehoe flows could be better estimated using the rate of increasing height of inflating lava flows rather than only the proximity of infrastructure to recently active lava flows. The extensive documentation of the flow-inflation process at Kīlauea has contributed directly to studies of the processes and duration of the emplacement of continental flood basalts (for example, Columbia River Basalt, Deccan Traps), other hot-spot shield volcanoes (for example, Iceland), and the submarine basaltic flow fields that make up the ocean floor (for instance, Hon and others, 1994; Self and others, 1998; Thordason and Self, 1998; Sheth, 2006; and references therein).

Deep Scientific Drilling Studies

Beginning in the 1970s, several deep (>1 km) holes were drilled on the Island of Hawai‘i to learn more about the deeper parts of volcanic edifices and magmatic/hydrothermal systems not accessible to direct surface-based studies. These drilling studies, which were funded by the National Science Foundation (NSF), were led by investigators in academia, but HVO and other USGS scientists participated, directly or indirectly, in the acquisition of in-hole data, analysis of core samples, and interpretations of the findings.

Drilling into Kīlauea Caldera

In collaboration with HVO, the Colorado School of Mines secured NSF funding for the purpose of drilling a research borehole into the inferred hydrothermal convection cell above the shallow magma reservoir beneath the summit of Kīlauea Volcano. A preliminary time-domain electromagnetic survey of the summit caldera and areas over the summit magma reservoir identified a likely drilling target in the form of a shallow high-conductivity anomaly in the southern portion of the caldera (Jackson and Keller, 1972). Drilling during April–July 1973 reached a depth of 1,262 m and encountered elevated temperatures (maximum 137 °C at hole bottom) but no magma (Zablocki and others, 1974; Keller and others, 1979). The drill hole did confirm the existence of a shallow groundwater table about 500 m below the ground surface (700 m above sea level). The complicated nature of the hole's thermal profile (Zablocki and others, 1974, fig. 3) reflects hydrothermal circulation, with a largely convective regime in the depth interval 500–950 m and a largely conductive regime beneath that.

The summit drill hole was left open to allow further studies of the water table, including the episodic collection of water samples during 1973–76 (McMurtry and others, 1977; Tilling and Jones, 1995, 1996), in 1991 (Janik and others, 1994), and during1998–2002 (Hurwitz and others, 2002, 2003; Hurwitz and Johnston, 2003) for laboratory analysis. These samples were unique in that they constituted the only analyzed samples of thermal water from directly above Kīlauea's summit magma reservoir. Tilling and Jones (1995, 1996) were the first to report on the water chemistry of these samples and noted temporal changes in composition related to possible rainfall dilution and to increased partial pressure of CO_2 related to volcanic degassing accompanying the December 31, 1974, eruption. The well was cleaned out in 1998 and the sampling resumed during 1998–2002. Analysis of waters showed continued temporal compositional variations (fig. 23), as well as a change in water level interpreted as response to a nearby magma intrusion. For detailed discussions of the temporal changes in water chemistry, well level, and borehole temperatures through 2002, see Hurwitz and others (2002, 2003) and Hurwitz and Johnston (2003).

Hawai‘i Scientific Drilling Project (HSDP)

The primary justification for this NSF-funded project was to better characterize and understand the mantle plume inferred to sustain the Hawaiian hot spot within the context of plate tectonics (Stolper and others, 1996a; for details about the HSDP, see http://hawaii.icdp-online.org). As emphasized by Stolper and others (1996b, p. 11593), “Hawaii was a natural target since as the best studied volcanic construct on Earth, it is the archetype of ocean island volcanism and provides the best possible scientific framework for a major project of this sort.” We fully concur with this rationale. Two holes have been drilled as part of the HSDP—a 1,052-m-deep “pilot hole” (HSDP1) completed in 1993, and the HSDP2 hole, drilled to a depth of 3,110 m in 1999 and later, during 2004–07, to a depth of 3,508 m. In all, 4,600 m of rock core were collected (mostly from Mauna Kea volcano), spanning in geologic age from perhaps 700 ka to ~200 ka. Taking into account plate motion during this interval, the HSDP cores represent “the first systematic cross-sectional sampling of a deep mantle plume” (Stolper and others, 2009, p. 13). In-hole observations and measurements made during the drilling, together with petrologic, geochemical-isotopic, and geochronological studies of the core samples, have yielded unprecedented data on the internal structure, hydrogeologic regime, and evolution of a large ocean-island volcano. HSDP studies (still continuing) have contributed significantly to knowledge about intraplate magmatism, mantle plume dynamics, volcano growth and subsidence, and other key aspects of Hawai‘i’s geologic evolution (see, for example, Beeson and others, 1996; DePaolo and Stolper, 1996; DePaolo and others, 1996, 2001; Stolper and others, 1996a,b, 2009; Garcia and others, 2007; Jourdan and others, 2012).

Geothermal Development in Hawai‘i

National interest in developing alternative energy sources, including geothermal, was spurred by the 1973 oil crisis that adversely impacted daily life in the United States. Although geothermal exploration in Hawai‘i had begun as early as 1961 (Macdonald, 1973), it greatly accelerated in the 1970s with the inception of the Hawai‘i Geothermal Project (HGP) in 1973 (Thomas, 1990; Moore and Kauahikaua, 1993). The early geothermal studies in Hawai‘i were led by the University of Hawai‘i at Mānoa (UHM), but many of them were done in collaboration with HVO scientists. The statewide inventory of geothermal resources (Thomas, 1984, 1986) incorporated several USGS- and UHM-led studies defining potential resources in Hawai‘i. The high-temperature resources were generally within the rift zones of active volcanoes on the Island of Hawai‘i, while the lower temperature resources were distributed on the older islands. In 1976, as part of the HGP, a public-private partnership developed Hawai‘i’s first geothermal well (HGP-A), in Kīlauea’s lower East Rift Zone (Thomas, 1987, figure 56.1). With the installation in 1981 of a wellhead generator on this well, the partnership operated an experimental 3-megawatt power plant during 1982–90, before being replaced in 1990 by the commercial Puna Geothermal Venture (Boyd and others, 2002). Additional exploratory wells have been drilled in Puna, and at present about 30 megawatts of electricity (MWe) are being produced and fed into the local utility grid (Ormat Technologies, Inc., 2012).

To better understand the geochemical and structural conditions of Kīlauea’s East Rift Zone (ERZ), and to monitor changes in the hydrothermal system, three cored scientific observation holes (SOH 1, SOH 2, and SOH 4), ranging in depth from 1.7 to 2.0 km, were drilled between 1989 and

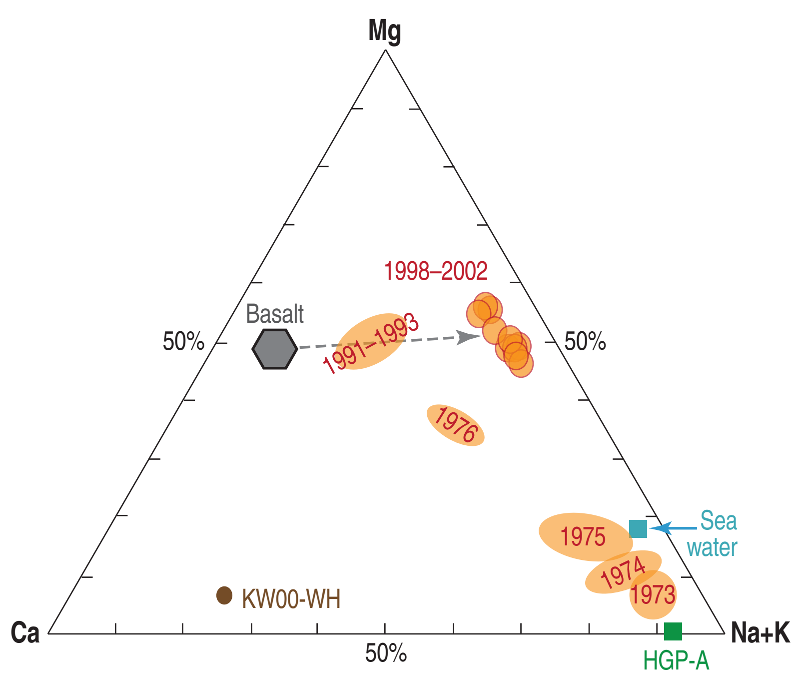

Figure 23. Triangular diagram showing the cation composition of water samples from Kīlauea. Plotted are relative proportions of calcium (Ca), magnesium (Mg), and sodium (Na) and potassium (K). Circles and ovals are waters collected from the deep drill hole at the summit of Kīlauea between 1973 and 2002 (from Hurwitz and others, 2003, fig. 5). Solid dot (KW00-WH) is water from cistern at wellhead, solid squares represent seawater and water from geothermal well HGP-A on Kīlauea’s lower East Rift Zone (Thomas, 1987), and the hexagon (basalt) is bulk average of Kīlauea summit basalt. Significance of these compositional and temporal variations is discussed by Tilling and Jones (1996) and by Hurwitz and others (2003).

1991 into the lower ERZ (Olson and Deymonaz, 1992; Olson and others, 1990). Studies of core from these holes have characterized the hydrothermal alteration mineralogy of the ERZ geothermal area (Bargar and others, 1996) and contributed to an improved understanding of the magmatic history of the ERZ (Quane and others, 2000). The routine commercial drilling of an injection well in 2005 in the Puna geothermal field penetrated dacitic melt (~1,050 °C) at a depth of 2,488 m, marking one of the very rare instances when molten material has been encountered accidentally in geothermal drilling (Teplow and others, 2009).

The potential of the geothermal resource at Kīlauea could be as great as 500 to 700 MWe (Olson and others, 1990)—but can the full exploitation of this significant resource be balanced with the high threat of volcanic hazards in Hawai‘i (Hawaiian Volcano Observatory Staff, 2012a)? With the initiation of exploitation of geothermal resources, HVO scientists have cautioned that, in developing the high-temperature resources, it is necessary to recognize the inherent hazards posed by frequent eruptions in Hawai‘i, especially on Kīlauea's ERZ (see, for example, Moore and Kauahikaua, 1993; Moore and others, 1993; Kauahikaua and others, 1994).

Cooperative Research with Other Organizations

Because they are frequently active, relatively accessible, and generally safely approachable, Hawaiian volcanoes always have been attractive research targets, and consequently their study has produced thousands of publications. Many of the scientific studies involve only HVO and allied USGS researchers, but the overwhelming majority of the publications are products of collaborative work between HVO/USGS personnel and scientists of other organizations—universities and other research centers, national and international. This collaboration would come as no surprise to Jaggar, who, from the very beginning, advocated and supported collaborative scientific research: "A volcano observatory must see or measure the whole volcano inside and out with all of science to help" (Jaggar, 1941). By "all," Jaggar clearly had in mind all fields of science, and all scientists whose expertise and work would contribute to an improved understanding of how volcanoes and earthquakes work. While Jaggar was a visionary scientific thinker, he also had common sense and realized that HVO would need all the help it could get to fulfill its scientific vision. It is far beyond the scope of this paper to detail HVO's rich history of collaborative research during the past 100 years. Nonetheless, in the discussion to follow, we highlight a few examples (mostly since the 1950s) of joint research with scientists of other organizations.

During HVO's early years, HVO collaborated with, and greatly benefited from, Fusakichi Omori and other Japanese colleagues in setting up the Whitney Laboratory of Seismology and the initiation of seismic monitoring at Kīlauea. Later, under the Japan-United States Cooperative Science Programme, a team of Japanese scientists lived and worked at HVO for about 8 months during 1963–64, during which time two eruptions occurred on Kīlauea's East Rift Zone (Aloi Crater, August 1963; Nāpau Crater, October 1963). By coincidence, also in August 1963, a Japanese training vessel (*Kagoshima Maru*) was visiting Hawai‘i, and an informal agreement was made with the ship's captain to conduct a bathymetric survey of Papa‘u Seamount offshore of Kīlauea's south flank (James G. Moore, oral commun., 2012). During the survey, two HVO staff (James Moore and Harold Krivoy) worked aboard the ship to assist with a depth recorder, and Dallas Peck and other HVO staffers installed and oversaw three transit stations on shore to track the ship's position every 10 minutes. This target-of-opportunity study resulted in the first offshore studies of Kīlauea's south flank; the bathymetric map obtained (Moore and Peck, 1965), together with seafloor mapping by the U.S. Navy around the Hawaiian Islands in the late 1950s (the *Pioneer*/*Rehoboth* surveys), contributed to the discovery of Hawaiian submarine landslides, first described by Moore (1964). Following joint studies of the Aloi and Nāpau eruptions and the bathymetric survey collaboration with Japanese scientists—formal and informal—continued for years afterward, including a visit in 1965 by several HVO staff to Japanese volcano observatories at Asama, Aso, and Sakurajima. During this visit, Taal Volcano (Philippines) began to erupt, and James Moore and Kazuaki Nakamura traveled to the Philippines to assist local colleagues making key observations, including the documentation of pyroclastic base-surge phenomena (Moore and others, 1966).

This bilateral program with Japan in the mid-1960s exemplifies HVO's collaborative research (for example, Minakami, 1965; Peck and Minakami, 1968; Aramaki and Moore, 1969). Since then, HVO has participated in cooperative studies with researchers from many scientific institutions (including, but not limited to, the University of Hawai‘i at Mānoa, University of Oregon, Stanford University; Monterey Bay Aquarium Research Institute; Smithsonian Institution; and University of Massachusetts). These joint studies have focused on many aspects of Hawaiian volcanism, including petrologic-geochemical dating studies of eruptive products; lava-tube processes and lava-flow emplacement (for example, Cashman and others, 1999; Kauahikaua and others, 1998, 2003); Kīlauea's pre-20th century explosive eruptive activity (for instance, Fiske and others, 2009; Swanson and others, 2011a,b; 2012a,b); Mauna Loa Volcano (Rhodes and Lockwood, 1995; and references therein); slow slip dynamics of Kīlauea's south flank (for example, Cervelli and others, 2002a; Wolfe and others, 2007; Brooks and others, 2008; Montgomery and others, 2009, 2010; Poland and others, 2010); and seismic tomography of the Hawaiian hot spot (for instance, Wolfe and others, 2009, 2011). Using data from the broadband seismic network around Kīlauea's summit, HVO and USGS investigators, working with national and international collaborators, have made significant contributions to volcano seismology. A sampling of such studies include modeling sources of shallow tremor at Kīlauea (Goldstein and Chouet, 1994); seismic refinement of the three-dimensional velocity structure of the Kīlauea Caldera (Dawson and others, 1999); and analyses of long-period (LP) and very-long-period signals to characterize seismic source regions and hydrothermal systems beneath Kīlauea Caldera (Ohminato and others, 1998; Almendros and others, 2001, 2002; Saccorotti and others, 2001; Kumagai and others, 2005). This collaboration continues with studies of the seismicity of the 2008 summit lava lake (Chouet and others, 2010; Dawson and others, 2010).

Another very productive collaborative research took place during 1998–99 between scientists of the USGS, University of Hawai‘i, Monterey Bay Aquarium Research Institute, and several Japanese universities, under the auspices of the Japanese Marine Science and Technology Center (JAMSTEC). A number of cruises using the latest techniques in submarine geological studies, including the RV *Kaiko* (a remotely operated vehicle or ROV) and the then-deepest diving manned submersible (the *Shinkai 6500*) examined the deep submarine flanks of several Hawaiian volcanoes. The results were published in a monograph of the American

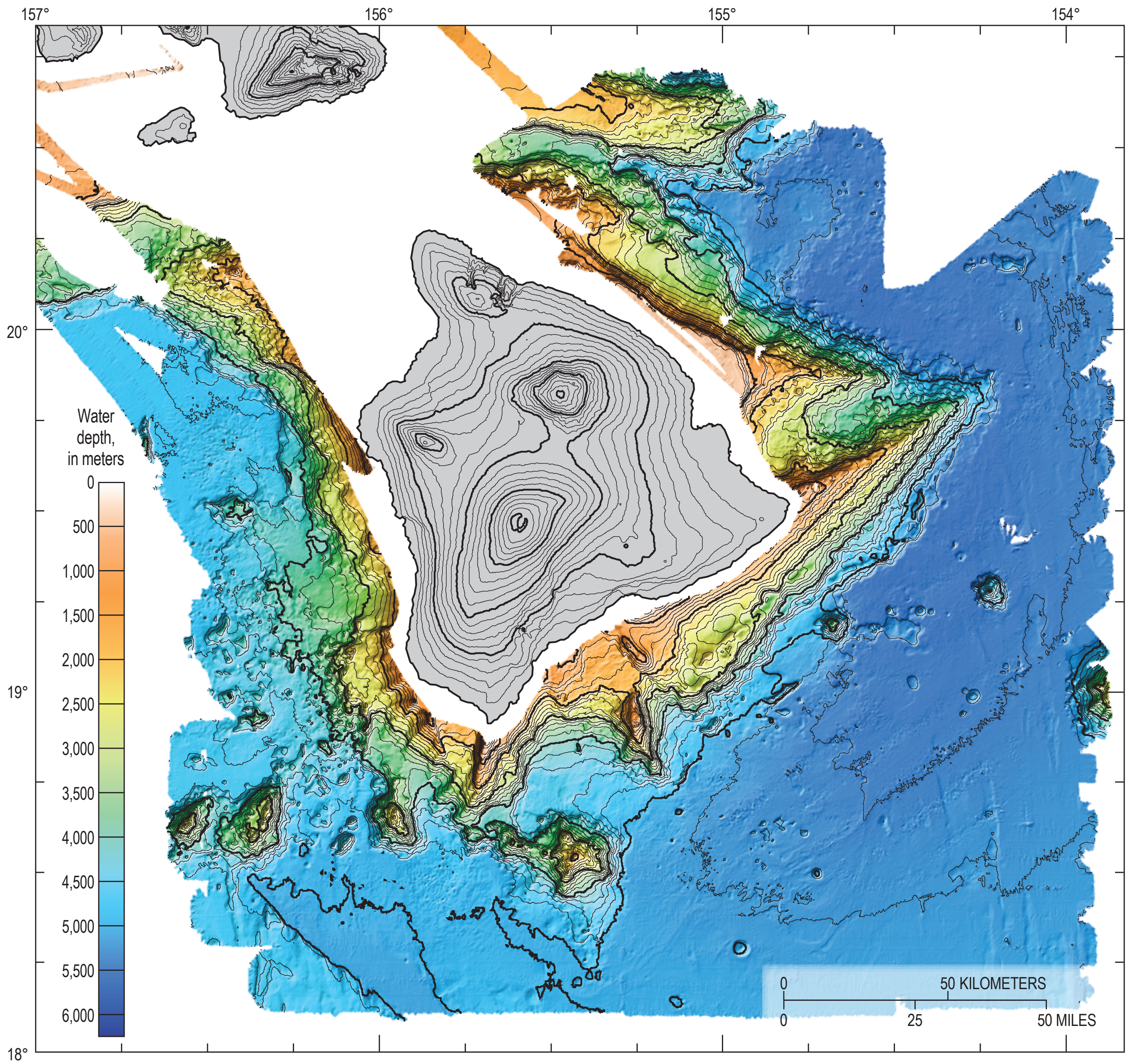

Figure 24. Map showing the bathymetry of the sea bottom around the Island of Hawai‘i. Contour interval is 200 m. This bathymetry became much better mapped with high-resolution data obtained during the 1998–99 cooperative research between Japanese and U.S. scientists (see text). This image is modified from one of many illustrations in the CD–ROM accompanying the monograph by Takahashi and others (2002).

Geophysical Union (Takahashi and others, 2002), which includes 27 papers germane to the deep underwater geology around the Hawaiian Ridge. In addition, this volume is accompanied by a CD-ROM that contains high-resolution images of bathymetry (fig. 24), spreadsheets of the analytical data for samples collected, and other useful compilations.

HVO has also participated in other cooperative efforts that did not necessarily result in scientific publications. For example, in 1965, HVO conducted a field seminar for a group of National Aeronautic and Space Administration (NASA) astronauts slated for upcoming Moon landings of NASA's Apollo Program. Hawai'i provided an excellent place for such astronaut training because of its well-displayed volcanic features that could be compared and related to similar features on the lunar surface. Because of its frequent and, sometimes, prolonged eruptions, Kīlauea constitutes an accessible global resource for learning or teaching about volcanism. Consequently, HVO has interacted informally with many students, educators, and visiting scientists, seeking to collect samples, exchange ideas, or to test hypotheses or teaching curricula. Over the decades, many volcanologists from other countries have interned among HVO staff to learn monitoring techniques. In this regard, to take best advantage of HVO's staff and resources, former Scientist-in-Charge Robert W. (Bob) Decker founded the Center for the Study of Active Volcanism (CSAV; http://www.uhh.hawaii.edu/~csav/) in 1989 at the University of Hawai'i at Hilo. CSAV is a training and outreach program and operates an international training course, intended primarily for scientists and science-support personnel in countries that have active or potentially active volcanoes. Present and past HVO staff members serve as instructors, and HVO provides some logistical support.

Communication of Scientific Information and Public Outreach

One of HVO's main goals was—and remains—to "keep and publish careful records" (Jaggar, 1913, p. 4) of the observations of eruptive and associated activities at Hawaiian volcanoes. From 1912 through 1955, in addition to publications in peer-reviewed scientific journals, this was accomplished regularly by the observatory's several serial publications (Special Reports, Weekly Reports, Monthly Bulletins, and Volcano Letters). These early publications presented chronological narratives of the visible eruptive activity, as well as associated seismic, geodetic, and other data. Some also contained discussions of volcanic and earthquake activity elsewhere in the world. After 1955, however, chronological narratives and results of volcano-monitoring and topical studies—geologic, geophysical, and geochemical—of Hawaiian volcanism have been presented in USGS publications, journal articles, and books, now numbering many thousands. Suffice it to say, the volcanic behavior of Kīlauea and Mauna Loa since the early 20th century has been extraordinarily well documented.

For all the science accomplishments at HVO in the past century, the support and survival of the observatory also required communicating and sharing information and interpretations of Hawai'i's eruptions and restless activity with fellow scientists and the public. Jaggar was well aware of the importance of keeping the general public informed; thus, he regularly spoke publicly and wrote many articles for newspapers about the activities at Kīlauea and Mauna Loa. Indeed, the all-inclusive communication of scientific information was a central theme of HVO long before the term "public outreach" was coined.

Print Publications

Jaggar (1912, p. 3) advocated that "Results obtained in connection with all subjects of investigation should be promptly published in the form of bulletins and memoirs." Even before it occupied its first permanent building in 1912, the new observatory made public its scientific findings on a regular basis. A weekly update on Kīlauea Volcano activity was started by Frank Perret, who wrote six weekly articles issued between August 15 and September 17, 1911, for *The Pacific Commercial Advertiser,* published by Lorrin A. Thurston. When Jaggar arrived the following January, he immediately resumed the weekly updates, with the first issued on January 25, 1912. Weekly Reports and Bulletins became Monthly Bulletins that were published by the Hawai'i Volcano Research Association, with the last issue covering the month of July 1929. *The Volcano Letter*, a monthly publication that included both scientific articles and updates of volcanic and earthquake activity, started being issued in late 1925 and continued until mid-1955. All of these early serial publications of HVO are readily accessible in several comprehensive volumes of collected works (Fiske and others, 1987; Bevens and others, 1988; Wright and Takahashi, 1989; Wright and others, 1992).

Once it became a permanent part of the USGS in 1947, HVO began publishing more technical summaries with annual reports from 1948 to 1955, quarterly reports from 1956 to 1958, and annual seismic summaries that included volcanic details starting in 1956 and continuing today as an annual seismic catalog. After the cessation in 1955 of *The Volcano Letter*, however, there was no regular popular medium through which even local residents could keep up with Hawaiian volcanic and earthquake activity, except for the frequent press releases directly related to increased or new activity and possible imminent hazards. As a result, the USGS, including HVO, later began to publish Fact Sheets—involving one or two pages of well-illustrated, nontechnical discussion—on popular topics (http://hvo.wr.usgs.gov/products/#factsheets).

While Bob Decker was a professor of geology at Dartmouth University, he wrote and submitted a weekly "Volcano Watching" article to the *Hawaii Tribune-Herald* during the year 1975. These articles were collated and formed the basis for a general-interest book about Hawaiian volcanism (Decker and Decker, 1980). Decker later served as HVO Scientist-in-Charge (SIC) during 1979–84. This weekly newspaper series was reinstituted in its present form (now called "Volcano Watch") in November 1991 by David A. Clague, HVO SIC during 1990–96, and continues to be written by HVO scientists and published in local newspapers and posted on the Internet (Hawaiian Volcano Observatory Staff, 2000). Each Volcano Watch includes an article about a geologic topic of relevance to volcano enthusiasts and Hawai‘i residents, as well as an update on current volcanic activity and descriptions of felt earthquakes. Through early 2013, more than 1,000 Volcano Watch articles have been written and shared with local residents via newspapers and with a broader audience via HVO's Web site.

While these popular publications were being produced, HVO staff continued to keep their "careful records" in the form of Record Books that included daily observations and photos from 1912 to 1955, as well as internal weekly, monthly, bimonthly, and quarterly reports starting in 1967 that were meant to document important details. While not official publications, these serve as resources for further research and as starting materials for formal publications.

HVO Web Site

HVO's first Web site was initiated by several HVO staff in 1997 and consisted of infrequent updates on volcanic activity with some volcano background information. Within a year, a new Web site was launched to include near-monthly updates of Kīlauea's eruptions, including images, graphics, and maps, and background information on Hawai‘i's active volcanoes and earthquakes. The site continues to evolve with daily updates (more frequently, as needed, with rapidly changing activity), real-time monitoring data and webcams of erupting vents and flow fields, time-lapse digital photography of remarkable activity, background volcano information, types of hazards, photo field tours, and more. The HVO Web site continues to get several hundred thousand hits per day, but that number dramatically increases up to several million per day when activity picks up or a new eruption commences.

Public Education and Outreach

From the beginning, HVO has endeavored to routinely and effectively communicate the results of its work to the scientific community, Federal and local government agencies, news media, and the general public. As discussed previously, HVO uses many existing avenues of communication—print and electronic—to disseminate scientific information, and the observatory anticipates greater use of social media outlets in the future.

Volcano Awareness Month

In addition to ongoing efforts throughout the year, Hawai‘i's volcanoes received a boost in attention during the month of January, beginning in 2010, when Hawai‘i County Mayor Billy Kenoi declared it "Volcano Awareness Month." The motivation for this specific designation is to enhance public awareness of Hawaiian volcanoes and associated hazards in particular and volcanic phenomena in general. Each January, many lectures, movies, excursions, and other volcano-related activities, in which HVO and affiliated scientists are heavily involved, are scheduled for the education and enjoyment of the public. (For a representative listing of activities, see Hawaiian Volcano Observatory Staff, 2012b). In connection with Volcano Awareness Month, an eight-page newspaper insert was produced in 2010 that included short articles on current activity and other topics of relevance to Hawai‘i residents who live on active volcanoes. On January 21, 2012, as part of the year-long celebration of its centennial, HVO held an open house that drew more than 1,400 visitors and at which was premiered a new general-interest booklet that recounts the story of HVO and of its century of scientific accomplishments and public service (Babb and others, 2011).

Is Public Outreach Working?

Given the considerable outreach efforts on the part of HVO, how aware are Hawai‘i residents about volcanic eruptions and hazards? A recent survey reported that residents of the Kona area (west Hawai‘i) exposed to lava flows from Mauna Loa and Hualālai "have received little or no specific information about how to react to future volcanic eruptions or warnings, and short-term preparedness levels are low" (Gregg and others, 2004, p. 531). In contrast, residents on the east side of the Island of Hawai‘i, who are frequently exposed to volcanic activity, are better informed and prepared to respond to a volcanic emergency (western Hawai‘i residents have not witnessed any volcanic activity since the 1950 eruption of Mauna Loa). Although greater efforts can be made to increase public awareness of volcano hazards in western Hawai‘i, the studies of Gregg and others (2004, 2008) may simply reflect basic human behavior, as demonstrated in nearly all volcanic regions of the world: the people directly affected by frequent eruptions naturally become more knowledgeable and, hence, better prepared to cope with future eruptive activity. Another contributing factor is that detailed guidance or plans of action about how to react, or what to do, during a volcanic crisis traditionally have not been given until a crisis begins to unfold. In recent decades, increased attention has been paid to studies of how people in various countries and cultures perceive volcanic risk and how they respond during volcanic crises (for example, Gaillard and Dibben, 2008). The findings of such studies vary in emphasis and specificity, but they all share a common thread: scientists are not, and cannot be, solely responsible for enhancing public awareness of volcanic hazards. Rather, meeting this challenge requires a close partnership between scientists, government authorities, and other stakeholders to develop and implement effective risk-reduction strategies, tailored to the local jurisdiction. Specifically regarding Hawai‘i, HVO must maintain its present level of islandwide public outreach but, at the same time, strive to work more closely with State and County government officials to find ways to change the current perception of volcanic risk held by western Hawai‘i residents. Those residents need to be better prepared, should Hualālai reawaken or an eruptive outbreak occur on Mauna Loa’s western flank.

Some Notable Developments Since HVO’s 75th Anniversary

In commemoration of HVO’s 75th anniversary, the USGS published the massive, two-volume Professional Paper 1350 (Decker and others, 1987), which contained 62 papers that presented results from diverse studies conducted by HVO and affiliated scientists through the mid-1980s. This comprehensive volume may be likened to a time capsule of the state-of-the-art knowledge about Hawaiian volcanism, acquired using the monitoring techniques and research disciplines available to HVO and, indeed, to the global volcanologic community at the time. In writing the introductory chapter to this current volume, we have chosen to use for our timeframe the entire first 100 years of HVO’s tracking of eruptions and earthquakes (Babb and others, 2011; Kauahikaua and Poland, 2012)—taking a largely retrospective look at the work of the observatory and its accomplishments that are not, or barely, discussed in the excellent historical summary by Apple (1987). Nonetheless, given the post-1987 explosive growth in instrumentation, technology, and computer-based data processing and modelling, remote sensing, satellite-based geochemical and geodetic monitoring, and basic knowledge of physical volcanology, we believe it is instructive to highlight some major developments during the past quarter century at Kīlauea and Mauna Loa volcanoes, and in HVO’s capabilities to study them. Some aspects of these developments (summarized in table 3) have been discussed in the preceding sections of this chapter, but some are noted here for the first time. In any case, it is clear from table 3 that many powerful tools and techniques used in studying volcanic phenomena (for instance, GIS, GPS, InSAR, remote gas measurements, broadband seismometers, digital borehole tiltmeters and strainmeters)—which we now take for granted—have only become available and applied in recent decades. As examples, the first GPS measurements were not made in Hawai‘i until 1987 (Dvorak and others, 1994), and data from digital broadband seismometers were unavailable before 1987 and hence not considered in the comprehensive summary of Kīlauea’s seismicity by Klein and others (1987). Such seismic data nowadays are necessary prerequisites for quantitative seismological studies of volcanoes (for example, Chouet, 1996, 2003).

Looking to the Future

With HVO’s first 100 years now past, what might we expect in the future? Unless plate-tectonic dynamics inexplicably change or cease to operate—a highly unlikely eventuality—Hawaiian volcanoes, especially Kīlauea, will continue to erupt frequently. Given the new interpretation of Kīlauea’s history of centuries-long alternation between effusive and explosive volcanic behavior (see “Explosive Eruptions” section, above), however, it is an open question whether future activity will be a continuation of the current mode of dominantly effusive eruptions or whether the volcano will enter a long period of explosive eruptions, as during 1500–1800 C.E. In any case, we can expect HVO and affiliated scientists to continue to use and improve existing approaches and tools in studying future eruptions, whatever their nature. We can also expect to see greater use of new, emerging monitoring techniques and improved means to share and communicate scientific information, some of which we touch upon in the discussion below.

Lava Flux Monitoring

The rate at which lava is erupted is a critical measure of an eruption’s status. The most widely used technique at HVO to estimate lava production is to repeatedly map the lava-flow area and estimate thicknesses across the area, from which an erupted volume can be calculated. Because reliable estimation of lava flux rates is such an important monitoring goal, a few new techniques have been developed, and the most promising ones are briefly summarized below.

Electromagnetic (EM) techniques have always offered great promise for volcano studies. Because hot, molten magma has a high electrical conductivity compared to cold, solidified lava, the differences between hot and cold domains should be easily detectable and mappable. In practice, however, the results of EM surveys in structural studies have been mixed, because groundwater-saturated lavas have moderately high conductivities compared to dry lavas (see, for example, Jackson and Keller, 1972). Nonetheless, shallow-depth EM techniques have proved to be very useful in mapping the molten interiors of active lava flows and lava tubes (for example, Kauahikaua and others, 1998).

Under specific circumstances, the flux of lava flowing through a tube can be measured with the very low frequency (VLF) technique, which uses the electromagnetic fields created by remote powerful radio transmitters. If an open skylight is available so that a flow velocity for the lava can be measured, a VLF profile obtained at that location can be interpreted as a cross-sectional area of the molten lava in the tube which, when multiplied by the lava velocity, yields the lava flux through the tube. Monitoring the decreasing lava flux through Pu‘u ‘Ō‘ō’s master tube in the early 1990s led to a forecast that its feeding vent(s) would shut down soon; within a month of the forecast, the vent actually did become inactive (Kauahikaua and others, 1996).

Table 3. Some major developments or events at Kīlauea and Mauna Loa volcanoes and at the Hawaiian Volcano Observatory since its 75th anniversary (Diamond Jubilee) in 1987 (compiled from diverse sources).

Development(s) or event(s)	Relevance / significance / importance	Selected references (and references therein)
Continuation of the Pu‘u ‘Ō‘ō-Kupaianaha eruption into the 21st century.	The longest duration, nearly continuous, rift-zone eruption at Kīlauea in more than 600 years, affording unprecedented opportunities to study a wide variety of processes and products of effusive basaltic volcanism.	Wolfe (1988) Heliker and others (2003b) Orr and others (2012)
Growth and collapse of the complex cone at Pu‘u ‘Ō‘ō 1983–2002.	The evolution of this prominent volcanic landform—one of the most recent in the United States—is exceptionally well documented, both visually and instrumentally.	Heliker and others (2003a)
Detailed documentation of eruption dynamics in the development of extensive lava-flow fields, 1983–present, extending and refining the findings from previous studies during the 1969–74 Mauna Ulu eruption.	The prolonged and still-continuing Pu‘u ‘Ō‘ō-Kupaianaha eruption has provided unprecedented opportunities to make detailed studies of the key processes involved in the development of extensive lava-flow fields. Such processes include formation of complex lava-tube systems, pāhoehoe-‘a‘ā transitions, inflation of pāhoehoe flows and sheets, construction of perched lava ponds and channels, and building and collapse of lava deltas.	Heliker and others (2003b) Kauahikaua and others (2003)
Greatly increased magma supply to Kīlauea during 2003–07.	Long inferred to vary little over decadal time scales, the magma supply rate to Kīlauea at least doubled during 2003–07 relative to previous rate estimates. This finding was made possible by a combination of detailed geodetic, geochemical, and gas-emission data.	Dvorak and Dzurisin (1993) Poland and others (2012) Poland and others (this volume, chap. 5)
Since mid-March 2008, renewed eruptive activity and operation of an active lava lake at Kīlauea summit.	The opening of the new vent within Halema‘uma‘u represents the first summit eruptive activity since 1982. The ongoing lava-lake activity marks the longest duration summit eruption since 1924 and the first in which two vents—at the summit and rift zone—were simultaneously active for many years. The summit vent opened following the increased magma supply 2003–07.	Hawaiian Volcano Observatory Staff (2008) Patrick and others (2013)
Long-term net subsidence of Kīlauea summit with the onset of the Pu‘u ‘Ō‘ō-Kupaianaha eruption in 1983, interrupted by a conspicuous inflation period during 2003–07.	This long-term summit subsidence was the longest in duration since continuous measurement of tilt began in 1912. The location of maximum subsidence (~2 km south of Halema‘uma‘u) dropped by more than 1.5 m between 1983 and 2003.	Tilling and others (2010) Poland and others (2012) (see also fig. 4, this chapter)
Changing magma supply rate to Mauna Loa? Reversal of overall Mauna Loa summit deflation trend since 1994 with renewed inflation beginning in May 2002. But then inflation decreased.	The rate of renewed inflation reached a maximum during 2004 before declining, perhaps suggesting that Mauna Loa's magmatic system was also affected by the mantle-driven surge during 2003–07 in magma supply to Kīlauea. Can this coincidence be taken as indirect evidence that the two systems somehow interact?	Miklius and others (2002) Hawaiian Volcano Observatory Staff (2003) Miklius and Cervelli (2003) Gonnermann and others (2012) Poland and others (2012)
The series of Japan-U.S. cooperative deep-water research cruises during 1998–99 produced much new bathymetric and geologic data about the deep submerged flanks of Hawaiian volcanoes, especially Kīlauea.	Scientific information from these cooperative studies has added a submarine perspective in understanding the emplacement of pāhoehoe flows, morphology of rift zones, ancestral growth of Kīlauea, volcano flank stability, and other aspects of Hawaiian volcanism.	Takahashi and others (2002) Clague and Sherrod (this volume, chap. 3)

Table 3.—Continued.

Development(s) or event(s)	Relevance / significance / importance	Selected references (and references therein)
Recent discovery that Kīlauea's volcanic behavior has been frequently, and sometimes energetically, explosive in the recent geologic past.	The new interpretation that Kīlauea can alternate in volcanic behavior between centuries-long dominantly effusive eruptions (19th century–present) and centuries-long explosive eruptions (1500–1800 C.E.) shatters the long-held thinking that it is a "benign" volcano. This discovery has potentially serious hazard consequences for the summit area.	Fiske and others (2009) Swanson and others (2011a,b) Swanson and others (2012a,b)
Regular measurement of emission rate of SO_2 at Kīlauea summit since 1979 and the continuous monitoring of SO_2 emission at both summit and East Rift Zone since 1997.	In addition to contributing to an improved understanding of Hawaiian volcanism, HVO's continuous monitoring of SO_2 emissions at Kīlauea—comprising the longest duration dataset of its kind—is critical for the assessment of the health hazards posed by vog (volcanic smog) to Hawai'i's residents and visitors.	Sutton and others (1997) Elias and Sutton (2012) Sutton and Elias (this volume, chap. 7) Kauahikaua and Tilling (this volume, chap. 10)
Miniaturization of instrumentation and improvements in gas-emission measurements using remote-sensing techniques.	The availability of lightweight, easily portable, and low-cost instruments and continuously recording systems have revolutionized volcanic gas monitoring of volcanoes in Hawai'i and elsewhere.	Elias and others (2006) Horton and others (2006)
Beginning in the early 1990s, installation of a subset of digital broadband seismometers as part of HVO's telemetered seismic network.	Data from the broadband network have enabled tomographic studies of Kīlauea's shallow magmatic system, precise determinations of the locations and mechanisms of long-period (LP) and very-long-period (VLP) events, and correlations with observed rock falls and related degassing bursts in the active vent in Halema'uma'u Crater.	Dawson and others (1998, 1999, 2010) Chouet and others (2010) Patrick and others (2011b) Orr and others (2013) Okubo and others (this volume, chap. 2)
Precise determination of lava flow paths and refined frequency of inundation by lava of specific areas.	Geologic and dating studies have enabled more detailed characterization of the frequency of inundation by lava flows in specific areas downslope from potential eruptive vents. Such information has important implications for lava-flow hazards assessments. Specific pathways are predicted using digital elevation models (DEM) once a vent location or lava flow front is known. Although improved geologic and age data are useful for assessing hazards probabilities, they do not determine "precise" flow paths.	Kauahikaua (2007) Trusdell and others (2002) Kauahikaua and Tilling (this volume, chap. 10)
Use of digital time-lapse visual and thermal cameras in systematically documenting eruptive processes at erupting vents, along lava channels and flows, and where lava enters the ocean.	The level of detail in near-real time with Global Positioning System (GPS) timing affords detailed documentation of eruptive processes and their resultant products that can be compared precisely with geophysical data.	Orr and Hoblitt (2008) Patrick and others (2011a,b) Orr (2014)
Transition from "classical" to space geodesy in the monitoring of Hawaiian volcanoes.	Beginning in the late 1980s, HVO has been the proving ground for the testing and use of geodetic techniques for ground-deformation monitoring in real or near-real time. This has made possible the documentation of short-term processes not detected by previous infrequent campaign-style techniques.	Decker and others (2008) Dzurisin (2007) Poland and others (this volume, chap. 5)

Lava flux also can be estimated through knowledge of the sulfur dioxide emission rate, assuming that a fixed relation exists between the mass of SO_2 emitted and the mass of lava. Applying this approach to Puʻu ʻŌʻō activity during the period 1997–2002, Sutton and others (2003) compared total volume estimates derived from SO_2 emission rates with those from VLF measurements and found that they agreed within 10 percent.

Another promising tool may be the detection of lava and the estimation of eruption rate through the thermal radiance of the flowing lava itself. Harris and others (1998) first used Landsat satellite data to estimate instantaneous lava effusion rates at Kīlauea to test this idea. Wright and others (2001) provided a slightly different view, measuring average effusion rates by quantifying the area of lava flows. Thermal detection and tracking of changes during eruption was highly useful in establishing the correct timeline of a remote fissure eruption in 1997 (Harris and others, 1997). The most recent innovation in applying thermal radiance techniques is the use of handheld thermal cameras (for example, at Piton de la Fournaise; Coppola and others, 2010); however, this approach has not yet been tested in Hawaiʻi. In 2010, HVO began using stationary infrared cameras to monitor Kīlauea's eruptive vents, and work is in progress toward creating software alarms that trigger on detection of high radiant temperatures (M. Patrick, oral commun., 2011; Patrick and others, 2014).

Mapping Active Lava Flows

Much of the work that HVO's geologists do during any eruptive crisis is mapping lava flows for the purpose of documenting their progress, especially the rate and direction of their advance, and estimating their discharge. Through the 1990s, flow mapping was done by traditional geologic mapping methods (aerial photographs) and surveying techniques (for instance, Wolfe and others, 1988). After GPS satellite transmission scrambling was turned off in May 2000, mapping accuracy of handheld GPS receivers improved to less than 10 m horizontally, but it was still necessary to carry the GPS receiver along the flow contacts and transfer the data into a GIS software system from which maps could be made. In the recent mapping and observations of active lava flows, the use of digital time-lapse photography, video, and thermal images has been highly instructive (for example, Patrick and others, 2011a,b; Patrick and Orr, 2012a; Orr and others, 2013).

Techniques using a pair of synthetic aperture radar (SAR) images are best known for their excellent resolution of ground deformation by interferometry (InSAR; see, for example, Dzurisin and Lu, 2007; Lu and Dzurisin, 2014, and references therein). Changes between SAR image acquisitions, however, can also delineate areas of incoherence, which denote regions of changing ground properties—for example, with resurfacing of the ground by new lava. This technique can be used to document recent lava flow activity in areas previously covered by older lava. Zebker and others (1996) demonstrated that such SAR incoherence maps do an excellent job of tracking active lava flows, and possibly effusion rates (given field-measured flow thicknesses), at Kīlauea. More recent work (Dietterich and others, 2012) further improves the technique and better demonstrates its ability to track active flows. This new spaced-based technique will never totally replace traditional ground mapping because of the inherent delay (latency) in round-trip transmission of satellite data, but SAR mapping may be very useful at active volcanoes where ground access is difficult and (or) dangerous.

Ambient Noise Seismic Tomography and Monitoring

Traditional seismology is based on the recording, processing, and interpretation of seismic signals—earthquakes, tremors, and teleseisms are among the most common types of seismic energy that travels through the Earth. But these signals are mixed with seismic "noise." One of the main sources of ambient seismic noise is ocean waves, and techniques have been developed recently to use this noise as a source for monitoring subsurface activity. Brenguier and others (2007, 2008, 2011) and Duputel and others (2009) have used ambient seismic noise to successfully monitor Piton de la Fournaise, a frequently active shield volcano on the French island of La Réunion in the Indian Ocean. As of this writing (mid-2014), seismologists at HVO and the University of Hawaiʻi are developing the tools to use this emerging technique as another way to continuously monitor the seismic properties of the subsurface.

The year 2012 marked the start of a 5-year program of scientist exchanges with the Observatoire Volcanologique du Piton de la Fournaise, and one of the goals of this program will be the transfer of modern monitoring techniques in both directions. Such an exchange should further the development of ambient noise monitoring techniques at both observatories.

Unmanned Aircraft Systems (UAS)

Until recently, unmanned aircraft systems (UAS)—commonly called drones—have been used almost exclusively for military and espionage purposes. In recent years, however, UAS have been increasingly deployed for some specific civilian applications (for example, remote-sensing studies, fighting of wildland fires, tracking hurricanes, surveillance of pipelines) where there is a need for rapid, low-cost reconnaissance of large areas at no health or safety risk to personnel (see, for instance, Merlin, 2009). The USGS has used UAS in various biological or environmental projects (see http://uas.usgs.gov/) and even collaborated with Advanced Ceramics Research to use UAS for monitoring lava dome growth at Mount St. Helens, Wahsington, in 2004 (Patterson and others, 2005; Smith and others, 2009). To date, UAS have not been employed at Hawaiian volcanoes; although HVO scientists are eager to find and test possible applications for UAS platforms in volcano monitoring and research, at the moment we are only in the early planning stages until uncertainties about available sensors are resolved. HVO has been involved, however, in a few innovative collaborative projects using meteorological balloons in connection with studies of volcanic gas distribution on a regional scale (for example, Donovan, 2008). In addition, airborne SAR acquisitions of Kīlauea have been made by NASA's Jet Propulsion Laboratory (Lundgren and others, 2013) using an instrument that is intended to one day fly on board UAS.

Greater Use of Social Media in Communicating Hazards Information

Early in its history, HVO's hazard assessments and related information were first made public by direct telephone communication and further disseminated by newspaper publication. From the 1980s until 2005, direct faxes to the emergency-management officials were also used to spread the word. The next major change in communication strategy was HVO's adoption of the communication potential of the Internet in 1997. HVO's original Web site hosted limited material, mostly hazards-related information releases, monthly updates on volcanic and earthquake activity, listings of new publications, and the like. The Web site content is now much more comprehensive, posting real- and near-real-time monitoring data, up-to-date lava flow maps, locations of current earthquakes, photographs, and many links to other information about Hawaiian volcanoes. Emergency managers (for example, Hawai‘i Volcanoes National Park, County of Hawai‘i, and State of Hawaii) continue to be updated directly via phone calls and e-mails. In fact, any person interested can subscribe to the USGS Volcano Notification Service to automatically receive e-mail volcano alerts from HVO or any other USGS volcano observatory by signing up at http://volcanoes.usgs.gov/vns/.

With the advent of social media outlets, such as Twitter and Facebook, anyone can sign up and post text, photographs, and video that can be shared with a specified set of fellow users ranging from everyone to only your closest friends. An added advantage is the ability to be alerted automatically to changes in the Facebook or Twitter offerings of any of your friends. No longer do interested people need to keep checking for changes in someone's status or postings—they can be alerted when these changes occur. The implications for hazards communication are obvious. An entity such as HVO could have relatively static content available for those who seek it, as well as content that is regularly updated with automatic alerts going to anyone who signs up for them. Once a user has found the site and worked through the information of interest at that time, he or she can be automatically alerted when that information changes.

For effective communication of hazards information, every available communication medium should be used—the message must get to the places where the public is listening. No longer can we expect people who may be affected by natural disasters to search for the communication method(s) we are using. We must deliver our message in every way conceivable to most effectively disseminate hazards information in a timely manner. As an agency, the USGS has been using social media to communicate with stakeholders since 2007, when the first podcast was launched; however, many of the primary social media outlets that are used today were only fully employed by the USGS in 2010. These primary resources—like Facebook, Twitter, YouTube, and Flickr—are information-sharing Web sites that people visit to learn about timely news, view imagery, watch videos, and interact with USGS social media ambassadors through comment strings. USGS also uses subscription-based data feeds to push content to individuals who have requested to receive specific updates. To communicate programmatic news and public updates, the USGS Volcano Hazards Program (VHP) uses the general USGS social media outlets. For very specific information relating to volcano hazards, however, the VHP employs data-feed services and has communicated up-to-the-minute eruption information via event-specific Twitter feeds. For example, the Volcano Notification Service is an RSS ("really simple syndication") feed, and a Twitter account was used during the 2009 eruption of Redoubt, in Alaska, when eruption updates were automatically pushed to followers of the Redoubt-2009 Twitter feed. In future volcanic crises, the VHP will again use event-specific accounts with social media Web sites and data feeds to communicate critical information to stakeholders. For everyday communication of news releases, observatory operations, and noncritical eruption updates, HVO and the VHP will continue to use the more broad USGS umbrella social media outlets (http://www.usgs.gov/socialmedia/).

Continuing Integration into National-Scale Volcano-Monitoring Efforts

The Hawaiian Volcano Observatory predates by 70 years the establishment of the second USGS volcano observatory—the Cascades Volcano Observatory (CVO), which was formally established in 1982 after the 1980 eruption of Mount St. Helens. The USGS's family of observatories then grew to five with the addition of the Alaska Volcano Observatory (AVO) in 1988, Long Valley Observatory (LVO) in 1999, and Yellowstone Volcano Observatory (YVO) in 2001. In a reorientation of the VHP in 2012, LVO ceased to exist formally but its functions were incorporated into the newest USGS observatory—the California Volcano Observatory (CalVO). For more information about all USGS volcano observatories, the interested reader is directed to the VHP Web site (http://volcanoes.usgs.gov/).

Expanding technical capabilities in the 21st century now allow rapid communication and sharing of data among the USGS volcano observatories, thereby promoting a much higher degree of interoperability between them. For example, the VALVE graphic-display software (Cervelli and others, 2002b, 2011), which was developed at HVO during the early 2000s, is now being upgraded and installed at all U.S. volcano observatories. A more recent development, an instrument site database that stores everything from land-access permits and instrument serial numbers to a log of site visits and instructions to find monitoring sites, was also developed at HVO and is being deployed at all USGS volcano observatories and other sites involved in volcano hazards studies. The increase in the number of observatories, together with the VHP emphasis on national focus and framework, thus mutually benefits all volcano observatories.

Many aspects of volcano monitoring can now be conducted remotely, by both ground- and space-based systems. Because of its early development, the buildings of HVO sit on the rim of Kīlauea Caldera with commanding views in all directions. Continuous visual observation was a key component of Jaggar's monitoring routine, and he needed visual line-of-sight to the volcanoes. This visual observation is now more consistently achieved with webcams and time-lapse photography, but there is still much insight to be gained by first-hand human observations of volcanic processes when opportune, practical, and safe. Former HVO Scientist-in-Charge Donald A. (Don) Swanson makes a cogent and eloquent case for the importance of on-site geological observations (Swanson, 1992). Increasing use of satellite imagery parallels and complements this trend to remote monitoring, extending the on-site observations of geologists while expanding the number of locations at which monitoring can take place.

Significantly increased interoperability and the drive toward much more remote monitoring of volcanoes is changing the way that U.S. volcanoes are monitored under the National Volcano Early Warning System (NVEWS) framework (Ewert and others, 2005), with expanding capabilities unforeseen even at the end of the 20th century. Indeed, a prime goal of NVEWS is that HVO will continue to serve as an important development and testing ground for volcano-monitoring and research efforts, not only in the United States but also in other countries with active or potentially active volcanoes. In so doing, despite its geographic insularity in the middle of the Pacific Ocean, HVO is now fully integrated into the national-scale monitoring effort of the USGS Volcano Hazards Program. If Thomas Jaggar were still living today, he doubtless would be utterly amazed, but also delighted to see how his creation a century ago has grown and thrived, using greatly increased scientific knowledge and a huge assortment of monitoring techniques and tools to observe and measure volcanoes on Earth and beyond.

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As a former Scientists-in-Charge of the Hawaiian Volcano Observatory (HVO), we (R.I.T. and J.P.K.) readily appreciate the dedication and contributions of our HVO colleagues, past and present. In writing this introductory chapter, we drew heavily from their published scientific papers and from informal discussions ("talk story") with them to learn valuable personal impressions regarding the challenges and accomplishments during their tenure at HVO. So, to them we give our heartfelt thanks for sharing with us their perspectives and insights on Hawaiian volcanism. We also wish to thank the many friends and colleagues (too numerous to mention by name) in the global volcanologic community who have shared their knowledge and expertise with us in the pursuit to better understand how volcanoes work. We would be remiss not to acknowledge the close cooperation and support we have always received from Hawai‘i Volcanoes National Park, Hawai‘i County and State Civil Defense, and the Hawai‘i Pacific Parks Association (formerly called the Hawai‘i Natural History Association).

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