**Characteristics of Hawaiian Volcanoes**
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# Chapter 10

# Natural Hazards and Risk Reduction in Hawai‘i

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## Abstract

Significant progress has been made over the past century in understanding, characterizing, and communicating the societal risks posed by volcanic, earthquake, and tsunami hazards in Hawai‘i. The work of the Hawaiian Volcano Observatory (HVO), with a century-long commitment to serving the public with credible hazards information, contributed substantially to this global progress. Thomas A. Jaggar, Jr., HVO's founder, advocated that a scientific approach to understanding these hazards would result in strategies to mitigate their damaging effects. The resultant hazard-reduction methods range from prediction of eruptions and tsunamis, thereby providing early warnings for timely evacuation (if needed), to diversion of lava flows away from high-value infrastructure, such as hospitals. In addition to long-term volcano monitoring and multifaceted studies to better understand eruptive and seismic phenomena, HVO has continually and effectively communicated—through its publications, Web site, and public education/outreach programs—hazards information to emergency-management authorities, news media, and the public.

Although HVO has been an important global player in advancing natural hazards studies during the past 100 years, it faces major challenges in the future, among which the following command special attention: (1) the preparation of an updated volcano hazards assessment and map for the Island of Hawai‘i, taking into account not only high-probability lava flow hazards, but also hazards posed by low-probability, high-risk events (for instance, pyroclastic flows, regional ashfalls, volcano flank collapse and associated megatsunamis), and (2) the continuation of timely and effective communications of hazards information to all stakeholders and the general public, using all available means (conventional print media, enhanced Web presence, public-education/outreach programs, and social-media approaches).

## Introduction

Basic studies of volcanoes and their past and present behavior provide the solid scientific foundations that underlie the mitigation strategies to reduce the risk from volcano hazards. Although scientists universally accept this paradigm today, that was not the prevailing point of view in the early 20th century. Thomas A. Jaggar, Jr., founder of the Hawaiian Volcano Observatory (HVO), was an early and staunch devotee. As emphasized earlier in this volume (Tilling and others, this volume, chap. 1), Jaggar was profoundly influenced by several natural disasters early in the 20th century (for example, the Montagne Pelée eruption in 1902 with 29,000 deaths and the Messina earthquake and tsunami in 1908 with 60,000–120,000 deaths; Tanguy and others, 1998; Risk Management Solutions, 2008). He became convinced that the only effective way to minimize the death and devastation from eruptions, earthquakes, and tsunamis was to study these potentially destructive phenomena continuously by means of permanent Earth observatories, documenting their processes and impacts before, during, and after each event. With the establishment of HVO in 1912 and throughout his entire career, Jaggar continued to advocate that "The main object of all the work should be humanitarian—earthquake prediction and methods of protecting life and property on the basis of sound scientific achievement" (Jaggar, 1909). The Hawaiian Volcano Research Association, a private business organization formed to support Jaggar and HVO, adopted for its motto: "Ne plus haustae aut obrutae urbes" ("No more shall the cities be destroyed").

Jaggar's commitment to, and approach in, using scientific data to reduce the risk from natural hazards have remained a hallmark of HVO's studies since its inception. The Island of Hawai‘i[2], with its five volcanoes (Kohala, Hualālai, Mauna

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[2] The differences in our usage of the words "Hawaii" and "Hawai‘i" in this chapter are intentional and specific: "Hawai‘i" is used to denote the eight main islands, while "State of Hawaii," "Hawaii State," or "Hawaii" refers to anything related to the State government (which includes the northwestern Hawaiian Islands, extending northwest to Kure Atoll, as well as Hawai‘i). The use of "Island of Hawai‘i" applies only to the southeasternmost island in the Hawaiian archipelago.

Kea, Mauna Loa, and Kīlauea, plus the submarine volcano Lo‘ihi off the south coast) has shown itself to be a dynamic—and at times hazardous—landscape over the past century, and this is not expected to change in the near future. Between 1912 and 2012, HVO and affiliated scientists documented 12 Mauna Loa eruptions, almost 50 Kīlauea eruptions, one Hualālai intrusion, two Lo‘ihi eruptions, 8 earthquakes of magnitude 6.0 or greater, and several tsunamis. Detailed documentation of these events has led to many important discoveries.

Jaggar intrinsically combined hazards (potentially destructive physical processes, such as lava flow, earthquake, tsunami) and risk (estimation of the potential loss, such as life, property, infrastructure, and productive capacity) in his early predictions and assessments. In subsequent decades, when HVO came under U.S. Geological Survey (USGS) administration, the emphasis was primarily on hazards and only recently began to again include risk studies (for example, Trusdell, 1995; Wood, 2011).

This chapter presents a brief history of efforts to understand and characterize volcano (fig. 1*A*) and earthquake (fig. 1*B*) hazards in Hawai‘i and efforts to minimize their adverse effects. Although not a direct part of HVO's current mission, tsunami hazards (fig. 1*C*) are also mentioned because HVO scientists have provided pivotal results that allowed forecasts of tsunami generated by distant earthquakes and documentation of locally generated tsunami. The authors feel that, for this chapter, it is more important to describe general progress in each hazard in which HVO scientists have played key roles, rather than confining the chapter's scope to what HVO has done specifically toward hazard and risk mitigation in its first century. This general approach, we believe, may be more useful to hazard specialists. The geologic processes and concepts needed for understanding the root causes of hazards in Hawai‘i are treated by Clague and Sherrod (this volume, chap. 3).

A primary aim of this chapter is to provide nontechnical background information for use by individuals and agencies responsible for developing and implementing programs to mitigate risks posed by natural hazards. Nonetheless, we believe that it should also be useful to geoscientists with an interest in the history and evolution of hazards studies in the Hawaiian Islands.

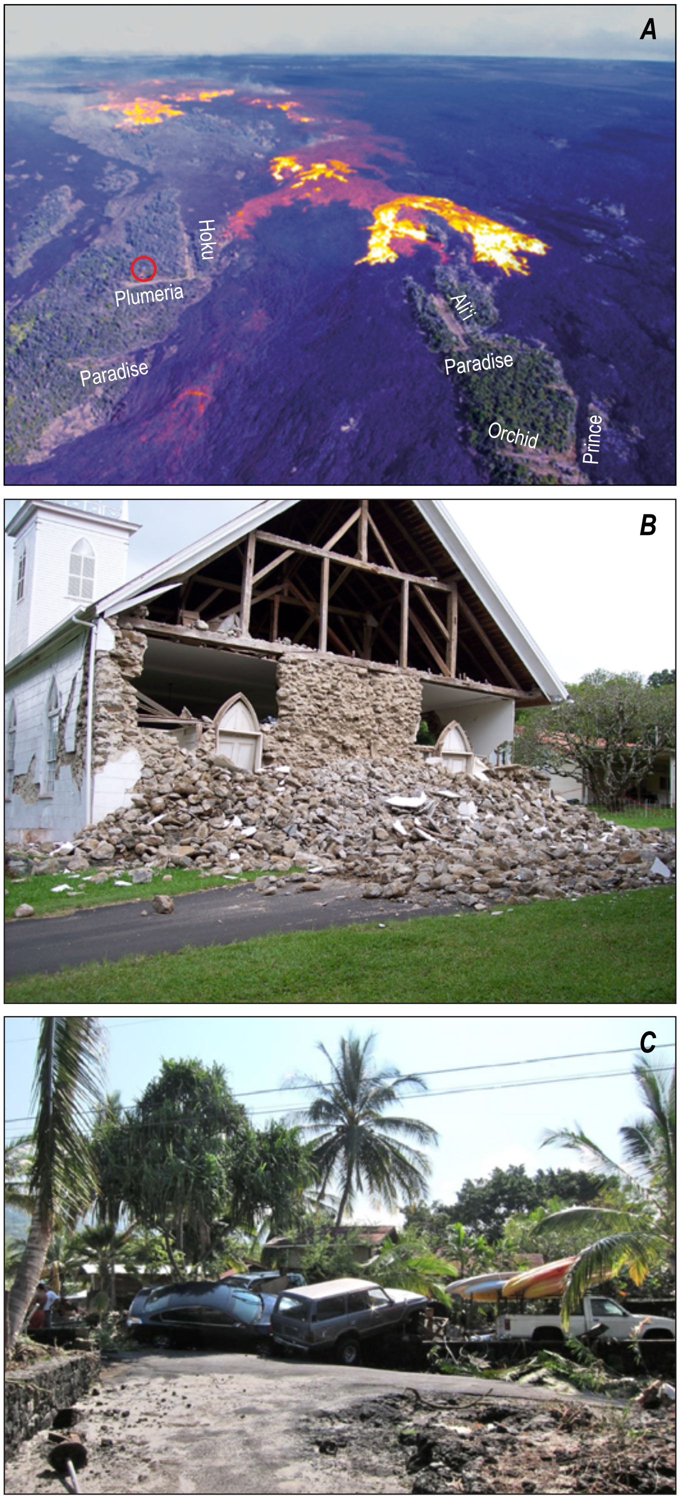

**Figure 1.** Photographs illustrating volcano-, earthquake-, and tsunami-related hazards in Hawai‘i. *A*, Thermal image overlaid upon a visual image showing active lava flows advancing through the now-abandoned Royal Gardens subdivision southeast of Pu‘u ‘Ō‘ō on February 24, 2012. The subdivision streets are named, and the last remaining house, which was destroyed about a week after this photo was taken, is circled in red (USGS image compiled by Matt Patrick). The Royal Gardens subdivision has been inundated by lava flows several times during the ongoing East Rift Zone eruption of Kīlauea Volcano. Less than 5 percent of the original property currently remains uncovered by lava (Tim Orr, written commun., 2012). *B*, View of the Kalahikiola Congregational Church showing the collapsed portions of the wall under the eave, the framing, and the wall above the doors resulting from the magnitude 6.7 Kīholo Bay and 6.0 Mahūkona earthquakes on October 15, 2006. Church is located at the northern tip of the Island of Hawai‘i (USGS photograph by T.J. Takahashi, October 20, 2006; from Takahashi and others, 2011). *C*, Photograph of piled-up vehicles at Napo‘opo‘o point near Kealakekua Bay, Island of Hawai‘i, transported by runup from the March 11, 2011, Tohoku-oki (Japan) tsunami (photograph from Trusdell and others, 2012).

# Volcano Hazards: Effusive Eruptions

Hazardous processes directly or indirectly associated with volcanic activity have posed the greatest threat to the residents of, and visitors to, the Island of Hawai‘i during the past two centuries. Although explosive eruptions have occurred at Kīlauea during the past 250 years and at other Hawaiian volcanoes in the recent geologic past, the most recent two centuries have been overwhelmingly dominated by nonexplosive (effusive) activity. Accordingly, lava flow hazards have been the most common and have caused the most damage and disruption to daily life in Hawai‘i, and, thus, will receive the most attention in the discussions to follow.

How lava flows form and move must be fully understood before the hazards they pose can be characterized. At Hawaiian volcanoes, eruptive vents are primarily located within the summit areas and along the curvilinear rift zones that extend radially away from the summits. Lava flow mechanics are relatively well understood because of the detailed studies done over the past century (see Cashman and Mangan, this volume, chap. 9), but more needs to be done. For example, internal lava flow structures, such as lava tubes or channels, are critically important to the distribution of lava during an eruption, yet only bare essentials are known about what initiates formation and failure of these structures.

A comprehensive assessment of volcanic hazards must be based, additionally, on geologic mapping of historical and prehistoric eruptive products. Lava flow hazards were first depicted as a map of zones, with each zone qualitatively defined by its proximity to vents and the rate of coverage by past lava flows. More quantitative lava flow hazards can be estimated as probabilities of coverage based solely on the recurrence interval of past lava flows within a given area. Finally, some aspects of lava flow hazards can also be investigated using computer software that simulates flowing lava (see, for example, Rowland and others, 2005). However, present computer and numerical models simplify lava flow dynamics and cannot yet fully simulate lava flow behavior, such as tube and channel development and transitions from ‘a‘ā to pāhoehoe modes (Harris, 2013), and they must be used with caution.

Efforts to mitigate risk can only be implemented after the hazards are characterized. For lava flows, some attempts have been made on the Island of Hawai‘i and in Iceland and Italy to mitigate the risk of their potential hazards by diverting or impeding lava flows using water-cooling, explosives, or construction of barriers (see, for instance, Williams and Moore, 1973; Lockwood and Torgerson, 1980; Barberi and others, 1992; Williams, 1997; Peterson and Tilling, 2000).

## Understanding Lava Flow Emplacement

“Lava” is an all-inclusive term for magma that breaches the Earth’s surface to erupt effusively or explosively. Once still-molten lava is confined to channels or tubes, its flow dynamics and emplacement are controlled primarily by viscosity, eruption rate at the vent(s), eruption duration, and topographic attributes of the terrain, such as steepness. Lava can be erupted as smooth pāhoehoe or rough ‘a‘ā flows, with a transition between the two that is defined primarily by internal shear rates (Peterson and Tilling, 1980; Soule and Cashman, 2005). ‘A‘ā lava flows generally advance faster and, therefore, pose the greater hazard. The progression of lava flow types during an eruption usually starts with ‘a‘ā flows that become channelized during the initially high effusion rates and may change to pāhoehoe flows that could eventually cover the initial ‘a‘ā flows. Pāhoehoe flows often change to ‘a‘ā as they flow over steep slopes, with gravity providing the increase in internal shear rates. It stands to reason that when an ‘a‘ā flow reaches flatter terrain, it may change back to pāhoehoe, as has been observed in the field (Hon and others, 2003). On gentle slopes, pāhoehoe flows can be emplaced endogenously (from within; see Hon and others, 1994; Walker, 1991), forming extensive inflated flow fields that include tumuli (small mounds) and lava tubes (Kauahikaua and others, 2003).

Geologic mapping has been able to define the source regions from which past lava flows were erupted, and current digital elevation models (DEMs) can be used to forecast the paths that lava flows will follow in advancing from the sources. Less well known are the factors that control the rate of advance of lava flows and the ultimate width of the flow field produced by prolonged eruptions. Our understanding of lava flow mechanics has advanced significantly over the past century (Cashman and Mangan, this volume, chap. 9), and this improved understanding has allowed us to isolate the critical parameters that we do not yet measure routinely but that are necessary to accurately estimate lava flow advance rates.

Of the parameters influencing lava flow emplacement, probably the most important is eruption rate. Several methods for computing eruption rate have been studied—differencing DEMs (for instance, Rowland and others, 1999), geophysical measurements of lava flux through tubes (for instance, Kauahikaua and others, 1998a), proxy measurements of sulfur dioxide emission rates (Sutton and others, 2003), and satellite measurements of thermal radiance from advancing active flows (for instance, Harris and others, 1998)—but, to date, none of these has provided a reliable, routine monitor of eruption rate for Hawaiian volcanoes.

The true measure of how well we understand lava flows will be our ability to model their advance. Several different approaches have been used over the past many years, and they have all necessarily involved simplifications (Harris, 2013). Each works well for a specific set of circumstances, but there is still a need to develop a more robust, generalized approach that incorporates the full physics of the emplacement process and rheology of lava. It should also be emphasized that numerical or computer simulations are critically sensitive to uncertainties in parameters, such as eruption rate, the changing rheology of molten lava as it cools, degasses, and advances away from the vent, and topography; propagation of error through the resulting modeled flow may have a significant effect on the accuracy and reliability of any prediction based on the model. While these efforts have greatly improved over the past several years, they may not yet be ready for diagnostic use during emergency situations.

## Characterizing Lava Flow Hazards

For characterization of lava flow hazards, arguably the most important consideration for any volcano is where, and how often, lava inundation has occurred in the past. The basic data for hazards determination are a detailed geologic map and comprehensive age dating of the surface lavas. In general, eruptions at shield volcanoes that are in their most vigorous stage of development, such as Kīlauea and Mauna Loa, originate within the summit and rift zone areas. On the other hand, volcanoes that may be entering into, or are already within, the less vigorous postshield or the more mature rejuvenated stage of development have had eruptive vents that are not so confined spatially. In either case, detailed geologic mapping is key in identifying the eruptive vents and pathways of past lava flows and areas of possible future lava inundation.

Mullineaux and others (1987) made the first comprehensive assessments of the volcanic hazards affecting the Hawaiian Islands. Because of the geologic mapping and dating studies made since that work, we now have improved assessments for the short-term, most frequently occurring lava flow hazards associated with the dominantly effusive eruptions of Kīlauea (mostly) and Mauna Loa during the past two-plus centuries. With additional geologic and radiometric data, we can expect to obtain even more refined assessments and precise zonation maps for earthquake, lava flow, and volcanic gas hazards.

### Lava Flow Hazard Zone Maps

The first lava flow hazards map for Hawai‘i was recently rediscovered in HVO files and may date to the 1940s or 1950s. The unknown author mapped linear zones that included the summits and rift zone vents as having the highest lava flow hazard; other zones were rated by their proximity to the highest hazard zone (vents) and by the recurrence interval of historical lava flows within the zone (estimated without any radiometric dates for the lava flows prior to 1800). The recurrence rate estimates ranged from 0 (Mauna Kea and Kohala) to 1,000 (Kīlauea summit) flows “per 10,000 years per square mile” (fig. 2). With the benefit of hindsight, it is apparent that the estimates of volcano productivity portrayed on this map were low compared to our current estimates based on more abundant and much improved knowledge.

Beginning in the 1970s, following additional mapping and dating studies, a number of USGS assessments and lava flow hazards maps were prepared, some supported in part by the Department of Housing and Urban Development (Crandell, 1975, 1983; Mullineaux and Peterson, 1974). A few of these studies also included other volcanic hazards in addition to lava flows (for instance, tephra fall, pyroclastic surges, subsidence, ground fractures); Mullineaux and others (1987) summarized and updated such work through the mid-1980s.

The first published lava flow hazards map for the Island of Hawai‘i was that of Mullineaux and Peterson (1974), which portrayed hazards zones rated according to severity from A through F, with zone F the most hazardous. This map was later modified by Mullineaux and others (1987), using additional data collected since the 1970s, and it depicted lava flow hazard in terms of nine zones. These lava flow hazard zones were qualitative and based on volcano structure and coverage rates. Hazard Zone 1, the most hazardous, was linear, because it included vents in the summits and linear rift zones of the most active volcanoes—Kīlauea and Mauna Loa. Hazard Zones 2 and 3 reflected areas downslope of vent areas on those same volcanoes. Hazard Zone 4 included all of Hualālai volcano, the third most active volcano on the island. Hazard Zones 5 and 6 were areas on Mauna Loa and Kīlauea that were protected from lava inundation by topography (for instance, caldera walls or locally high relief). Hazard Zone 7 included the most recently active vents on Mauna Kea (eruptions between 5,400 and 4,600 years before present; Wolfe and others, 1997), Zone 8 included the rest of Mauna Kea, and Zone 9 included Kohala Volcano, which has had no active volcanism in the past 10,000 years.

Additional dating and review of the 1974 and 1987 maps for Hawai‘i resulted in an updated, slightly modified version of the map (fig. 3), published by Wright and others (1992), that is still in use today. Although the 1992 map (fig. 3), which included coauthors from the County of Hawai‘i, was intended to guide development planning within the county, it has yet to be used for that purpose. It has, however, been used by property insurance and mortgage companies to set increased rates in hazard zones 1 and 2.

Qualitative hazard zonation, the basis for the existing lava flow hazard maps, requires prioritization of frequency and magnitude of the hazard. For example, the map of Wright and others (1992) emphasizes the rate of lava flow coverage, which probably best reflects the combination of these two factors (frequency and magnitude) and is appropriate because the range of intensities for effusive eruptions is limited. Small-volume effusive eruptions, which are most common, have a more restricted spatial impact than the high-volume, but more infrequent, effusive activity, such as during the ‘Ailā‘au eruption of Kīlauea about 600–550 years ago (Clague and others, 1999; Swanson and others, 2012a). Areas near vents are inundated by more lava flows than areas that are more distant, reachable only by eruptions of the longest duration sustaining far-traveling tube-fed flows.

The Island of Hawai‘i is not the only one for which lava flow hazards have been mapped. Crandell (1983) constructed a lava flow hazards map for Haleakalā volcano (Maui), based on ages of recent flows and vent distribution, using only five zones;

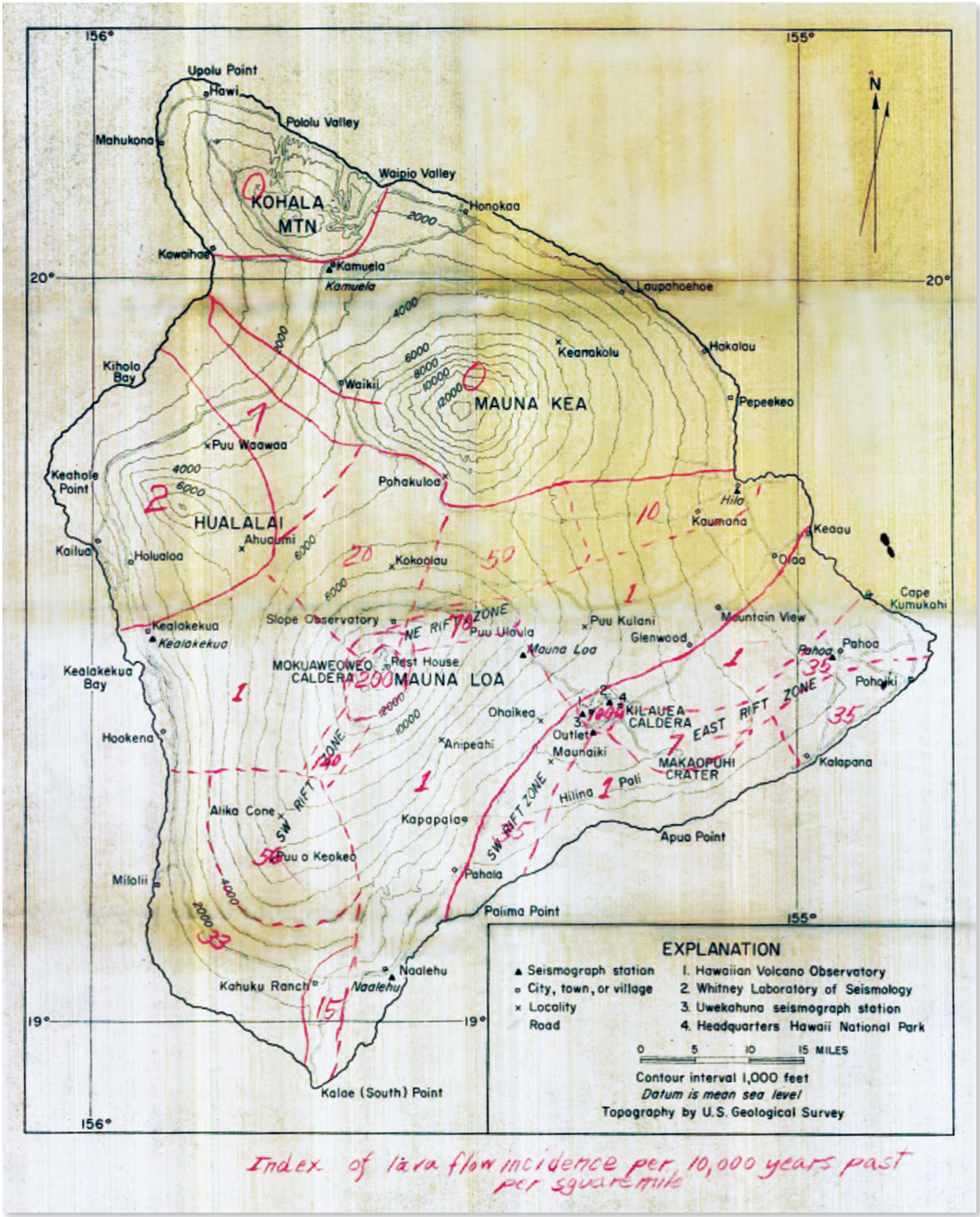

**Figure 2.** Scan of unpublished Hawaiian Volcano Observatory map (drafted in the 1940s or 1950s) that estimated lava flow incidence per unit area per 10,000 years, before dating of precontact (before 1778) lava flows became possible.

this map was later revised by Mullineaux and others (1987, fig. 22.14), with zone 1 being the most hazardous of the five zones but with slightly different criteria than those defining the zones for the Island of Hawaiʻi. In considering the differences, Mullineaux and others (1987, table 22.1) equated Maui zone 1 with Hawaiʻi zone 3, Maui zone 2 with Hawaiʻi zone 4, and Maui zone 3 with Hawaiʻi zone 6. Sherrod and others (2006) revised the lava flow hazard zones for Haleakalā using new mapping and dating but did not address the equivalency of the new zones with those of the Island of Hawaiʻi.

To reconcile the different schemes used, to date, we sought to redefine lava flow hazard zones for Maui and the other, older volcanoes to produce a lava hazards map for the entire State of Hawaii. Based on the newest mapping, Mullineaux's equivalency may overestimate the lava flow hazards on Maui (D.R. Sherrod, written commun., 2010). Despite the minor differences between the various existing lava flow hazards maps, they are all based on the general premise that the summit and rift zone vents pose the greatest potential hazards and that the hazard decreases with distance from the vents. Because known eruptive vents of lava flows on the older Hawaiian Islands do not fall neatly into the spatial pattern for Haleakalā and the volcanoes on the Island of Hawaiʻi, no lava flow hazards maps have been published for volcanoes northwest of Haleakalā along the Hawaiian volcanic chain. After considering the data now available and redefining the lowest hazard category (zone 9) to include all areas not inundated by lava in more than 10,000 years, we have compiled a preliminary lava flow hazard map for the eight main islands in the State of Hawaii (fig. 4).

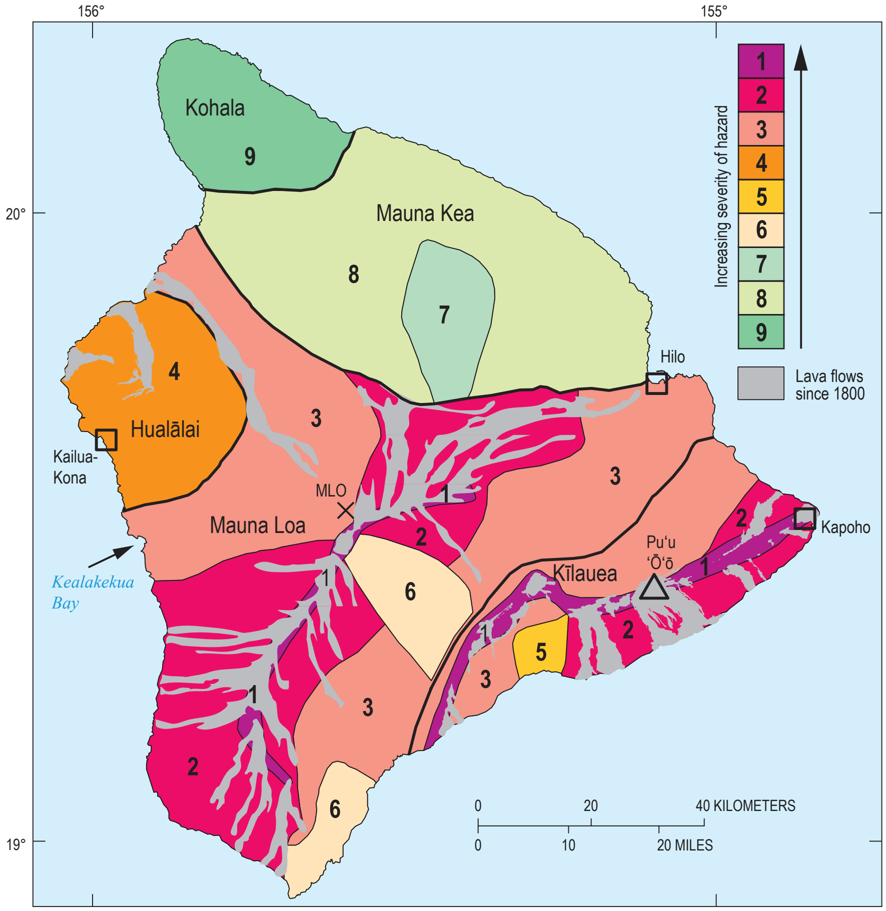

**Figure 3.** Generalized version of the most recent lava flow hazards map of the Island of Hawaiʻi, updated and revised by Wright and others (1992). The severity of the hazard increases with decreasing zone number. Thick black lines separate the five individual volcanoes on the island. Boxes denote communities discussed in the text. Triangle shows location of Puʻu ʻŌʻō eruptive vent. "X" gives location of the National Oceanic and Atmospheric Administration's Mauna Loa Observatory (MLO).

## Probabilistic Estimation

Probability estimation can provide a solid numerical basis for comparing lava flow hazards to, for example, tsunami or hurricane hazards and can be used directly to estimate risk. Like the lava flow hazard maps, probabilities are based on a geologic map, complete with lava flow ages.

The first effort to estimate probabilities of lava inundation for Hilo, the second largest city in the State, was based on the historical frequency and volume of lava flows mapped within the Hilo city limits (U.S. Army Corps of Engineers, 1980). This study also estimated the potential socioeconomic impact of lava flow inundation in Hilo, in part to ascertain whether the construction of permanent lava flow barriers upslope of Hilo (discussed later) was warranted. This study found the logarithmic values of the probability of occurrence (lava flow inundation) to be linearly related to the logarithmic values of the areal coverage of lava—in other words, the larger the target, the more likely a future lava flow will enter the target area.

Interest in geothermal energy in the 1980s and 1990s prompted an HVO assessment of the volcanic hazards in areas around likely geothermal resources along Kīlauea's East Rift Zone (Moore and Kauahikaua, 1993; Moore and others, 1993; Kauahikaua and others, 1994). Estimated probabilities of lava inundation in these areas ranged as high as 60 percent over a 50-year period.

A later study estimated lava inundation probabilities for several specific sites on Mauna Loa's Northeast Rift Zone, where a new prison facility was planned (Kauahikaua and others, 1998b). This study was, in part, prompted by a concern during the 1984 eruption of Mauna Loa that the existing Kulani Prison might be overrun by lava, and the authorities worried about possible evacuation of the prisoners (Stapleton, 1984). Probabilities of lava inundation, 12 percent or less over a 50-year period, were again determined to be proportional to the area of interest. In that assessment, steepest descent lines and lavasheds (calculated as watersheds) were determined from the best available DEMs and plotted to forecast lava paths and maximum warning times after the start of a threatening eruption (no more than 72 hours).

## Flow-Path Forecasting

Qualitative and probabilistic lava flow hazard maps both provide a long-term perspective of the threat posed by lava flows, although the probabilities may be expressed over different time frames. These long-term hazard assessments are useful for planning on a time scale of decades to centuries but not very useful for shorter time frames. For the estimation of more immediate lava flow threats, it would be more helpful to have the ability to simulate, and therefore predict, the path and advance rate of lava flows while they are active during an ongoing eruption.

Although lava flow simulation software may not yet be accurate enough to use in all situations, even a simple forecast of their paths based only on digital topography can be valuable. In this regard, it is noteworthy that, in 1912, Jaggar convinced Governor Frear of the Territory of Hawai‘i that a topographic map of the Island of Hawai‘i was necessary for the purpose of forecasting where lava flows might go once they were erupted.

> “It will have to be done anyway, some day,” said the governor yesterday, and we quite agree with Professor Jaggar that it is better to do it now, for a flow may occur at any time. The new survey will indicate what directions the flows will take, and for this reason the work cannot help but be of intense interest to all our people. The householders and others on the slopes are, of course, more immediately interested than any others.
>
> —*Pacific Commercial Advertiser* (1912)

There is no evidence, however, that Jaggar ever used topographic maps to forecast lava flow paths.

During the past two decades, improved maps and DEMs have allowed quantitative forecasting of lava flow paths. Trusdell and others (2002) defined lava-inundation zones for Mauna Loa, based on the paths of mapped flows modified for current topography, and Kauahikaua and others (1998a, 2003) and Kauahikaua (2007) calculated steepest descent paths and lavasheds to define future flow paths. Limitations of this approach include unknown sensitivity to DEM accuracy and relevance to only the first flows from the vent—subsequently the topography changes as a result of lava flow emplacement and the initial steepest descent forecasts become out-of-date and inapplicable.

Nonetheless, even with this simplest of approaches, the ability to assess sensitivity of the paths to DEM inaccuracies is very useful. Favalli and others (2005) developed a method to demonstrate flow-path sensitivity to possible DEM inaccuracies by rerunning the calculations with random additions to the DEM each time. A compilation of the results of several iterations of this approach make it clear which DEM elements have critical control on the direction of steepest descent. Favalli’s algorithm is now incorporated in many lava-simulation programs (for instance, FLOWGO; Harris and Rowland, 2001). Rowland and others (2005) used FLOWGO with the Favalli algorithm to forecast the eruption-rate-controlled extent of lava flows from Mauna Loa. Advantages of lava flow simulation include the ability to forecast multiple or compound lava flows; however, errors in the early forecasts will propagate to affect forecasts of later flows.

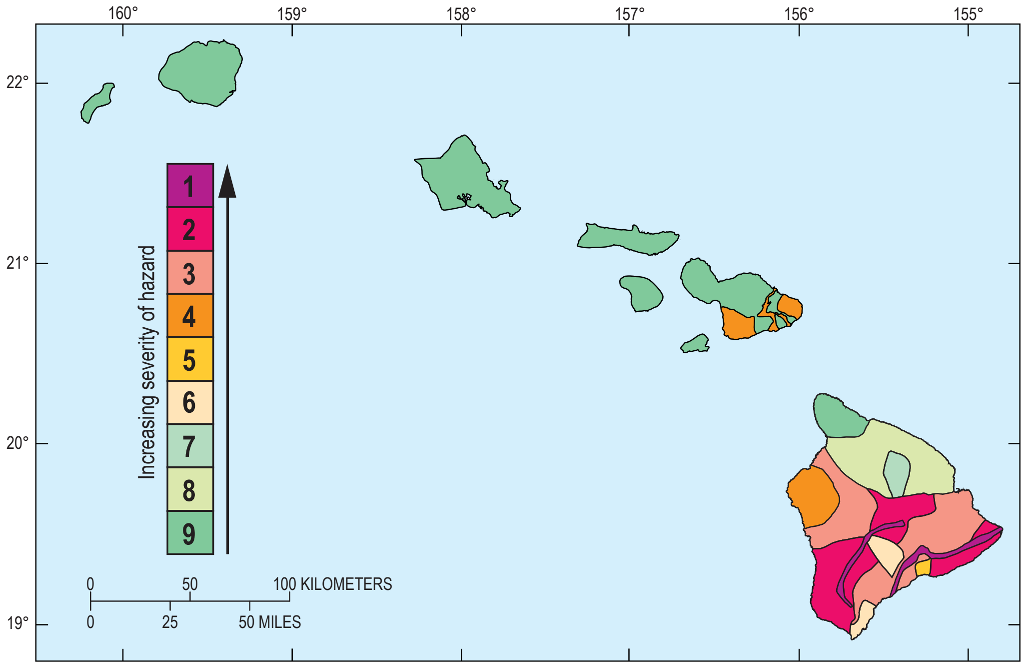

**Figure 4.** Preliminary integrated lava flow hazards map for the State of Hawaii. Zones 1 through 8 are taken from Wright and others (1992) for the Island of Hawai‘i, and zone 9 is defined as areas that have not experienced eruption or unrest in the past 10,000 years.

## Mitigation of Risk from Lava Flow Hazards

Because there is no known way to stop an eruption, the main method of mitigating the risk posed by active lava flows is to divert the flow away from populated areas or to slow its advance to allow other mitigation efforts, such as evacuation (see, for instance, Peterson and Tilling, 2000). Diverting or delaying lava flows have been attempted by the use of explosives, water, and physical barriers. Any decision to attempt to control lava flows, of course, must be made by officials charged with land-use planning and (or) emergency management.

Many forms of lava flow diversion have been tried on the Island of Hawai‘i, with varying degrees of success. The first known efforts occurred in the summer of 1881 as a broad pāhoehoe flow from Mauna Loa slowly advanced toward the town of Hilo. Low earthen and rock walls were set up, but the advancing flow stalled on its own without evidence of being rerouted (Hawaiian Gazette, 1881). It is interesting to note that explosives also were authorized by the Hawaiian Kingdom for possible diversion of this flow, but the materials arrived too late to be used.

During an intense earthquake swarm beneath Hualālai volcano in late 1929, a seemingly imminent eruption of lava prompted Lorrin A. Thurston to suggest the use of explosives again (Honolulu Advertiser, 1929a). Jaggar agreed that if the explosives were placed along a feeder tube, the blast could disrupt the flow and cause lava to run over lands that had already been covered (Honolulu Advertiser, 1929b), thereby minimizing damage. The military went so far as to assess that the effort was feasible, but the anticipated eruption never took place.

Jaggar had his first opportunity to use explosives in 1935, when a Mauna Loa lava flow threatened the water supply above Hilo. He worked with a group of Army aviators who planned and executed a bombing mission, targeting sites along the upper channels of the advancing flow. The bombing was very precise and was completed days before the eruption ended. Jaggar claimed success (for instance, Jaggar, 1945a, p. 12–16), but most other volcanologists believe that the flow stopped because the eruption shut down (Lockwood and Torgerson, 1980). In 1942, under very similar circumstances, bombs were again used on Mauna Loa to blast a spatter rampart along a fissure vent feeding a flow advancing on Hilo. The rampart was successfully breached and lava diverted, but only for a short distance before it rejoined its original channel, effectively negating the diversion attempt.

The failure of the 1942 diversion suggests that the results of future bombing efforts might be improved by taking advantage of the steepest descent path maps. If the channel had been bombed at a point where the new outflow could be directed into a steepest descent path distinct from the original one, the bulk of the lava flow might have been diverted away from the original channel. Any remaining flow in the original channel would then be greatly diminished and pose less threat to areas downchannel.

After his retirement in 1940, Jaggar published a detailed proposal to divert Mauna Loa lava flows away from Hilo (Jaggar, 1945b), but the next opportunities to erect barriers were presented on Kīlauea Volcano. During the 1955 and 1960 Kīlauea eruptions in the Puna District, several barriers were built to divert or dam lava flows (fig. 5) in attempts to protect downstream homes and farms. Neither effort was successful, although it can be argued in both cases that lava inundation may have been delayed. Gordon Macdonald, the HVO Scientist-in-Charge during the 1955 eruption and a representative of the Governor during the 1960 eruption (which occurred after he left the USGS), was an advocate for lava diversion through the use of permanent barriers to protect Hilo (see, for instance, Macdonald, 1958). Unfortunately, most of the HVO staff concluded that the plan was “expensive beyond prudent economic justification” (Wentworth and others, 1961), and a very public debate over diversion ensued in the local press in 1960. Barriers have not been used since 1960, but during the 1980s, much effort went into studying the feasibility of building permanent diversion barriers above Hilo, as both Jaggar and Macdonald had advocated (U.S. Army Corps of Engineers, 1980). That study recommended construction of an emergency barrier when needed rather than construction of a permanent barrier.

The use of water to cool and solidify the advancing lava front—causing the lava to form its own barrier—has been attempted in Hawai‘i and was later also tried on a much larger scale in Iceland (see, for instance, Williams and Moore, 1973; Williams, 1997). Water, pumped from a nearby lake, was used during the 1960 Kapoho eruption to delay consumption of houses by fire upon lava contact. In 1989, when lavas from Kīlauea’s East Rift Zone were slowly engulfing the Waha‘ula Visitor Center within Hawai‘i Volcanoes National Park, water was again used in an experiment to delay consumption of the wooden structure. Although some delay was achieved, the structures ultimately burned to the ground (fig. 6).

**Figure 5.** Photograph showing bulldozers constructing a lava flow barrier in Kapoho in January 1960. Note the advancing front of an ‘a‘ā flow between the lava fountain and the trees at left. Date of photograph and photographer unknown.

**Figure 6.** Photographs of the National Park Service Waha‘ula Visitor Center near the coast on Kīlauea Volcano in 1989 and of efforts to protect it from approaching lava. *A*, Fire hose delivers water to cool approaching pāhoehoe flows (June 22, 1989). *B*, Visitor Center engulfed in flames later that day after being ignited by hot lava. *C*, Steel girders, twisted by inflating lava flows and later buried, are all that remain of the Visitor Center after it burned (October 12, 1989). U.S. Geological Survey photographs by Jim Griggs.

The current State Lava Flow Hazard Mitigation Plan, written by a committee that included HVO and University of Hawai‘i scientists, found that lava diversion barriers were not appropriate in most situations; however, some critical facilities may be situated in areas where barriers could be a reasonable option (Hawaii State Civil Defense, 2002). For example, lava diversion barriers (5–7 m high, 700 m long, as designed by HVO scientists) were completed in 1986 (Moore, 1982; Mims, 2011) to protect the National Oceanic and Atmospheric Administration's (NOAA) Mauna Loa Observatory, which is located on the north flank of Mauna Loa volcano (fig. 3). The facility is a premier atmospheric research facility that maintains the continuous record of atmospheric change since the 1950s and is the site of the measurements forming the well-known Keeling curve of $CO_2$ concentrations in the atmosphere.

The 2002 State plan discussed above considered, but was not based on, cultural objections, but concerns have been raised about some diversion strategies. Gregg and others (2008) mined interview data obtained from Kapoho residents shortly after their town was destroyed by a Kīlauea eruption in 1960 and found that ethnic Hawaiians favored the construction of earthen barriers but did not support the use of bombs for the diversion of lava flows. This finding echoes sentiments expressed by the Hawaiian community in response to the bombing of Mauna Loa lava flows in 1935 (Jaggar, 1936), as well as later interviews for the Hilo barrier feasibility study (U.S. Army Corps of Engineers, 1980). Only earthen barriers or dams were built to impede the advance of flows during the inundation of Puna in 1955 and Kapoho in 1960. Bombing was discussed but dismissed when it was clear that such measures would be of no use (Wilhelm, 1960).

## Current Status

Potential lava flow sources and paths have been mapped, and general lava flow advance rates were estimated, as a function of effusion rates, from historical data (for instance, Kauahikaua and others, 2003). Methods for estimating the probabilities of lava flow inundation using geographic information system (GIS) software on an islandwide basis are in development (Trusdell, 2010). Although the diversion of lava flows around critical facilities may be technically feasible, it is clearly a social and political issue whose solution is beyond the scope of this review. For the present, we are able to characterize the potential paths of lava flows once their eruptive sources are identified; however, only broad guidelines can be provided for their rates of advance until accurate and reliable lava flow simulators are developed.

# Volcano Hazards: Explosive Eruptions

Although lava flows constitute the most frequent (and, therefore, most probable) volcanic threat for the islands of Maui and Hawai‘i, the less frequent occurrences of explosive eruptive activity can pose significant, more widespread hazards. Indeed, the explosive blast and gases produced during the 1790 eruption at Kīlauea's summit (discussed below) resulted in the most lethal volcanic disaster in recorded U.S. history, and there is growing evidence of even stronger Hawaiian explosive eruptions in the geologic record.

In contrast to explosive composite volcanoes related to subduction zones (for example, Mount St. Helens, United States; Mount Fuji, Japan; Pinatubo, Philippines), intraplate shield volcanoes, such as those of Hawai‘i, are thought to typically erupt nonexplosively. Deposits of tephra (ash fall) and other pyroclastic debris in Hawai‘i, however, attest to the occurrences of powerful explosive eruptions of Hawaiian volcanoes in the geologic past. Recent studies show that the frequency of explosive eruptions at Kīlauea is about the same as that for Mount St. Helens—several explosive periods every millennium (Swanson and others, 2011). Two important differences, however, should be noted: (1) Kīlauea explosive eruptions are much smaller in volume and in area affected than those at Mount St. Helens and (2) during the intervals between explosive periods, Mount St. Helens is mostly inactive, whereas effusive eruptions occur frequently, sometimes essentially nonstop (as since 1983), at Kīlauea. Not surprisingly, therefore, the Hawaiian eruptive style is usually considered to be gentle or benign; the term "Hawaiian" is used to describe any nonexplosive or weakly explosive eruption in the world with a Volcanic Explosivity Index (VEI) of <1 (for instance, Siebert and others, 2011). Because of their infrequency, relative to current effusive activity, explosive Hawaiian eruptions and their associated hazards have been less studied until recently.

## Understanding Basaltic Explosive Eruptions and Their Products

> Kilauea has not always been a quiet volcano, as it is today. . . .
>
> —*Sidney Powers* (1916, p. 227)

Kīlauea has long been recognized by Hawaiians as a volcano with a dual personality. In Hawaiian mythology, Pele, the goddess of Hawaiian volcanoes, whose home is in Halema‘uma‘u Crater within Kīlauea Caldera, is always described with two personas: a young, beautiful woman and an old, cruel hag. Hawaiian traditions and oral histories also support that Kīlauea has erupted explosively since the island was settled (see, for example, Swanson, 2008; Kanahele, 2011).

There have been three historical (postcontact) explosive eruptions of Kīlauea Volcano. In November 1790, in the most energetic of these three, an estimated 80 warriors, and as many as 400 people in all, were reported to have been killed near the volcano's summit (Ellis, 1825; Dibble, 1843; Kamakau, 1992). The cause of these deaths has been variously attributed to directed blasts of ash and hot gases (Swanson and others, 2012b), but the explosive eruption mechanism remains unknown.

In May 1924, weeks of explosive activity enlarged the diameter of Halema‘uma‘u Crater, spread sizeable debris a few kilometers from the crater, and killed one person (Hilo Tribune-Herald, 1924). While much less energetic than the 1790 eruption, this activity ejected ballistic blocks—some more than 1.5 m in average diameter—to distances greater than 1 km. The 1924 explosive activity was thought to be the result of groundwater entering the magma conduit weeks after the draining of a lava lake in the summit (Dvorak, 1992), resulting in phreatic explosions.

Most recently, in March 2008, a small crater opened explosively along the east wall of Halema‘uma‘u Crater, spreading sizeable (~0.25–1 m in diameter) debris within a few hundred meters of the vent. The explosion was hypothesized to be the result of high gas pressure blasting out rock debris that had blocked a previously open gas vent (Houghton and others, 2011). This eruption at Halema‘uma‘u persists as of September 2014, but mostly as a continuously active lava lake that also emits gas and small amounts of glassy and lithic tephra (Wooten and others, 2009).

Powerful explosive eruptions have played a large part in the evolution of Kīlauea's summit caldera. The general history of Kīlauea's summit was told by native Hawaiians to the first westerner to record his visit (Ellis, 1825, p. 137–138):

> From their account, and that of others with whom we conversed, we learned that it had been burning from time immemorial, or, to use their own words, "*mai ka po mai*," (from chaos till now,) and had inundated some part of the country during the reign of every king that had governed Hawaii. That, in earlier ages, it used to boil up, overflow its banks, and inundate the adjacent country; but that, for many king's reigns past, it had kept below the level of the surrounding plain, continually extending its surface, and increasing its depth, and occassionally throwing up, with violent explosion, huge rocks, or red hot stones. These eruptions, they said, were always accompanied by dreadful earthquakes, loud claps of thunder, vivid and quick-succeeding lightning.

Perret (1913) correctly interpreted the Hawaiians' remarks and combined them with his geologic observations to propose the following sequence of events in the geological history of Kīlauea:

- formation of a shield by overflows from a central vent,
- subsidence forming a great pit or caldera,
- explosive eruptions producing the observed ash,
- lateral subterranean outflows of lava to the sea.

More recently, HVO scientists and colleagues have filled in the previous gaps with new work, including extensive mapping and assignment of dates to many of the key events, resulting in a more detailed interpretation of the evolution of Kīlauea's summit caldera:

- More than 500 years ago, Kīlauea existed as a shield with a central vent that produced repeated overflows (Clague and others, 1999).
- Caldera formed by collapse about 500 years ago, followed by several centuries of explosive eruptions ending in 1790 (Swanson and others, 2011; Swanson and others, 2012a).
- The 1790 fatalities were a result of a base surge (Swanson and Christiansen, 1973).
- Kīlauea has alternated between periods of dominantly explosive eruptions and periods of effusive eruptions (Swanson and others, 2011).

Older explosive eruptions produced more widespread deposits of volcanic ash that were recognized by a number of studies completed in the late 19th and early 20th century. Bishop (1887) traced a yellow ash layer around the South Point of the Island of Hawai‘i and deduced that it

> . . . was formed by an explosive eruption of yellow cinder, which covered at least 100 square miles . . . with yellow ashes several feet in thickness. It must have belonged to the larger class of explosive eruptions. I hereby file my *caveat* for this discovery, in case no one has recorded a patent of prior date.

Emerson (1902), Powers (1916), and Stone (1926) described the Pāhala Ash, which is widely distributed across the southeastern part of the island and may have been Bishop's "yellow ash." A very useful compilation and detailed description of ash deposits on the Island of Hawai‘i was published by Wentworth (1938), who identified 10 mappable ash units on the island (fig. 7). Although some work has been done on the ash deposits since Wentworth's compilation, reliable ages on the pre-1790 deposits are still few. The Pāhala Ash was inferred by Decker and Christiansen (1984) to represent the cumulative deposits of many explosive eruptions from about 25,000 to 10,000 years ago. More recent work suggests that the youngest unit in the Pāhala Ash is about 13,000 years old (F.A. Trusdell, oral commun., 2012).

Ash layers have also been discovered below the surface in archaeological excavations and water-well drill holes. While excavating archaeological sites along a highway track through Kailua-Kona, Schilt (1984, p. 275) encountered a shallow ash layer that was dated by the carbon-14 method at 1260–1485 C.E. and was probably from Hualālai volcano. Water wells south of Kona have been drilled through ash layers that may have originated from Mauna Kea eruptions (Bauer, 2003). Drilling also penetrated ash layers at shallow depths at locations in Volcano Village, near Kīlauea's summit, and in the area between the town of Mountain View (halfway between Hilo and Kīlauea's summit) and Mauna Loa's Northeast Rift Zone (Stearns and Macdonald, 1946), expanding the known fallout area for past explosive deposits. The Hawaii Scientific Drilling Project (HSDP) in Hilo also found multiple ash layers deposited by explosive eruptions from Kīlauea and Mauna Kea; most were thin, with only two major explosive eruptions depositing thick ash at the drill site in the past 400,000 years (Beeson and others, 1996).

## Characterizing Tephra and Other Hazards of Explosive Eruptions

The occurrence of widespread ash deposits (fig. 7) is clear evidence that powerful explosive eruptions have occurred in Hawai‘i's geologic past, albeit infrequently, compared to effusive eruptions. Moreover, the studies of the lethal 1790 eruption at Kīlauea suggest that the deaths in that event resulted from the combined hazards of ash fall (tephra) and ground-hugging, high-velocity pyroclastic surges (see, for instance, Swanson and Christiansen, 1973), and possibly lethal gases. These hazards and their significance were evident to Jaggar (1918, p. 16), who emphasized that "Hawaii has had **Class 1, explosion and volcanic blast**

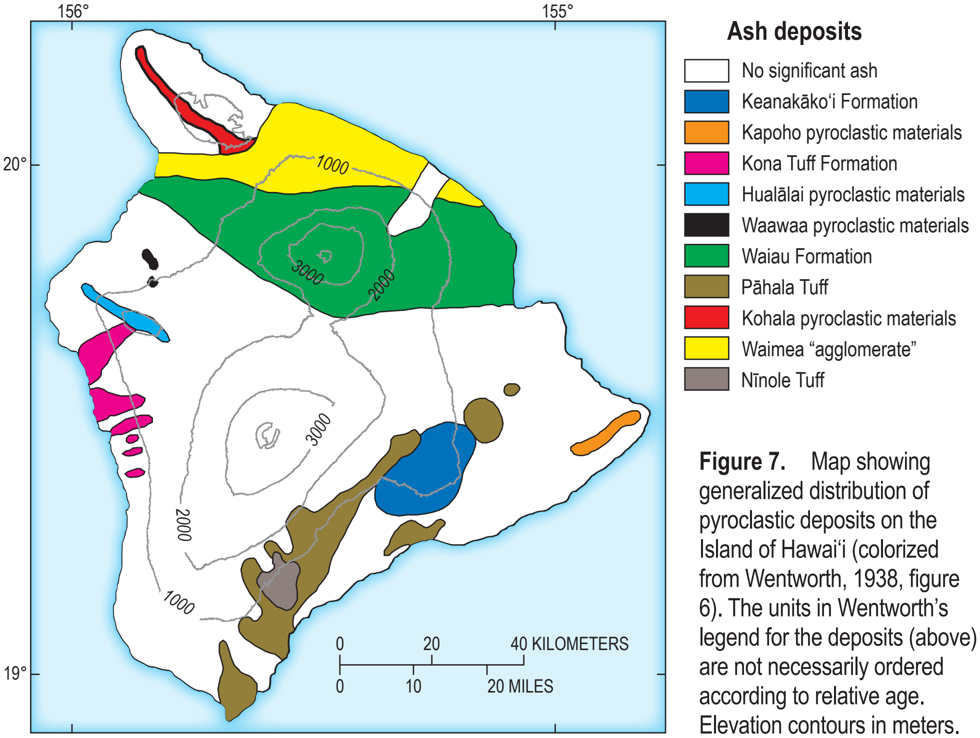

**Figure 7.** Map showing generalized distribution of pyroclastic deposits on the Island of Hawai‘i (colorized from Wentworth, 1938, figure 6). The units in Wentworth's legend for the deposits (above) are not necessarily ordered according to relative age. Elevation contours in meters.

[bold in original], in 1790, from Kilauea crater. . . .” He states further that “A repetition of that event would probably wreck [everything] for a radius approximately six miles from Halemaumau in all directions.” Jaggar also emphasized that, with strong trade winds, “heavy ash falls would be in the [downwind] Kau direction [to the southwest from Kīlauea’s summit].” The Hawaiian Volcano Observatory, at its current location atop Uēkahuna Bluff, would be destroyed.

Using only the record of the past 250 years of volcanic activity, Mullineaux and others (1987) applied the criteria of proximity to summit and rift-zone vents, eruption frequency, and wind direction to produce a tephra hazards map (fig. 8). Separately, they noted that the potential for pyroclastic surges existed only near Kīlauea’s summit (within 10 km of the center of the caldera—virtually identical to Jaggar’s Class 1 hazard).

A comprehensive modern assessment of tephra hazards for Hawai‘i would require full consideration of the older tephra deposits throughout the island, together with a long-term record of dominant wind trajectories for Hawai‘i. Though highly approximate and dated, Wentworth’s (1938) map (fig. 7) nonetheless suggests that the significant tephra deposits from larger, much less frequent, explosive events can be distributed much farther than the tephra hazard zone 1 boundaries (fig. 8) or the Kīlauea pyroclastic surge zone of Mullineaux and others (1987), and that the most voluminous deposition will occur downwind along dominant wind trajectories. For airborne ejecta from Kīlauea eruptive vents, which are all at elevations below the thermal inversion layer that starts at ~2 km above sea level, direction of deposition would generally be controlled by the northeasterly trade winds.

Above the thermal inversion layer, however, the dominant wind patterns are different. Swanson and others (2011) attributed tephra distribution southeast of Kīlauea Volcano to explosions ejecting tephra above the thermal inversion and into the more westerly jet stream wind currents. Any future comprehensive long-term assessment of tephra hazards and other pyroclastic hazards will require the incorporation of new mapping and radiometric age data on regional ash deposits acquired since the early 1990s (for instance, Buchanan-Banks, 1993; Beeson and others, 1996; Wolfe and Morris, 1996; Sherrod and others, 2007).

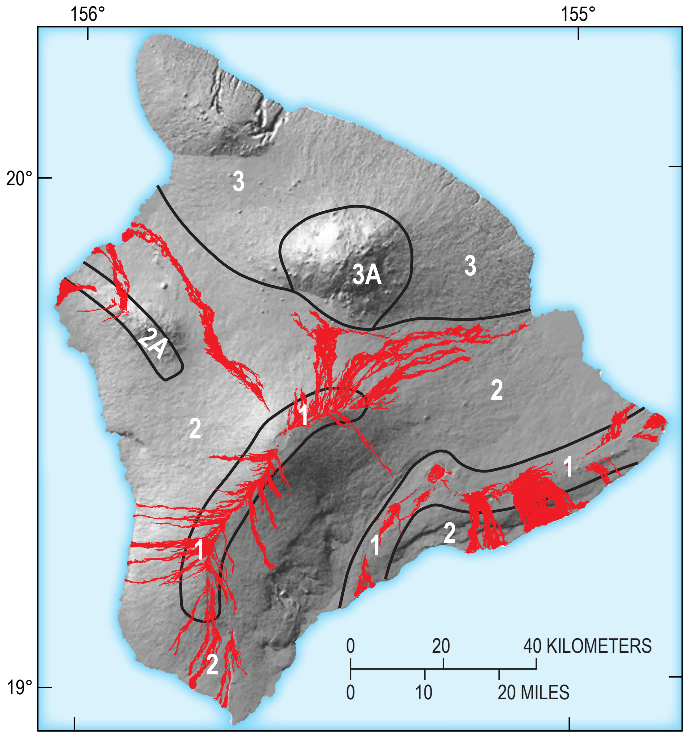

**Figure 8.** Shaded relief map showing tephra hazard zones on the Island of Hawai‘i (after Mullineaux and others, 1987, figure 22.11); red areas represent historical lava flows. Zone 1 includes areas of highest eruption frequency (the summit and rift zones of Kīlauea and Mauna Loa). Zone 2 includes areas where tephra falls from lava fountains should be frequent but thin, with subzone 2A depicting locally thick tephra falls due to infrequent eruptions of Hualālai. Zone 3 covers areas where very thin tephra falls may occur from eruptions on Kīlauea, Mauna Loa, and Hualālai under unusual northerly wind conditions; subzone 3A may be subject to very infrequent, but possibly severe, eruptions from Mauna Kea.

## Current Status

The details of Kīlauea and Mauna Loa’s explosive past are beginning to emerge, and hazards assessments must include the possibility of a large, damaging explosive eruption as a maximum credible event, along with more frequent effusive eruptions, which represent a more probable next event.

Arguably, the biggest scientific and monitoring challenge associated with hazards due to explosive eruptions is the recognition of precursory signs of explosive activity. Would such precursory indicators differ diagnostically from those that precede effusive eruptions or magma intrusions? With just three historical examples, only the smallest of which (in March 2008 at Halema‘uma‘u) was well documented geophysically, HVO must be constantly aware of the possibility—however remote—of explosive activity. To date, no mitigation measures or plans have been established for hazardous explosive processes.

## Volcano Hazards: Gas Emissions

The past century of frequent Kīlauea and Mauna Loa eruptions has made Hawai‘i one of the premier world laboratories for studying volcanic gases (Sutton and Elias, this volume, chap. 7). Long-term datasets on gas emissions are used to assess the global contribution of volcanoes to climate change (for instance, Gerlach, 2011), and also provide insights into volcanic behavior that can lead to more accurate forecasts of eruptive activity. Over the past decades, however, gas studies have taken on a new urgency as the island and State are affected by volcanic smog (vog) produced by Kīlauea’s persistent eruptions. Vog poses a health hazard by aggravating preexisting respiratory ailments, and acid rain resulting from vog damages crops and can leach lead from metal roofs into household water supplies (Sutton and others, 2000).

HVO was a pioneer in studies of volcanic gas and, since the late 1970s, has systematically monitored gas emissions at both Kīlauea and, more recently, Mauna Loa. Comprehensive discussions of the results of volcanic-gas studies in Hawai‘i and their bearing on eruptive processes are given elsewhere (for instance, Gerlach and Graeber, 1985; Greenland, 1987a, 1987b; Sutton and Elias, 1993, this volume, chap. 7). Here, we briefly summarize the hazards to humans, animals, and vegetation that are posed by exposure to volcanic gases from frequent and sustained eruptive activity in Hawai‘i. The International Volcanic Health Hazard Network (http://www.ivhhn.org/), a Commission of the International Association of Volcanology and Chemistry of the Earth, is a useful clearinghouse for information about health issues related to volcanic gases.

## Volcanic Gas Composition, Emission-Rate Variations, and Dispersion

Volcanic gas emissions precede and accompany eruptions and are composed mainly of $H_2O$ (typically 70–90 percent), $CO_2$, and $SO_2$, but they also contain varying trace amounts of other gaseous compounds (for example, HCl, $H_2S$, $H_2SO_4$, CO, Ar, HF, F). Typical gas-emission rates measured for Kīlauea range from 100s to more than 10,000 (metric) tons per day of $SO_2$ and 8,000 to more than 20,000 tons per day of $CO_2$ (Gerlach and others, 2002; Poland and others, 2012). Even though fluorine (F) is a minor component, it still can have significant harmful impacts to crops and farm animals in small amounts; HF emissions have been estimated to be 7–12 tons per day for Kīlauea (Sutton and Elias, 1993).

Gas emissions vary in composition, depending on whether a vent is at the summit or within the rift zone of a volcano. Carbon dioxide is one of the first gases to exsolve from ascending magma and, therefore, dominates nonwater emissions at the summits of Hawaiian volcanoes, which are generally thought to overlie the deeper magma conduits and storage chambers. Sulfur dioxide is one of the last gases to exsolve and is associated with shallow magma storage and eruptions, both at summits and along rift zones (Gerlach and Graeber, 1985). As an example, the opening of a vent at the summit of Kīlauea Volcano in 2008 dramatically increased the summit emissions of $SO_2$ (Wilson and others, 2008; Sutton and Elias, this volume, chap. 7).

Once a volcanic plume rises into the atmosphere, it drifts and becomes widely dispersed, depending on wind patterns and other atmospheric conditions (for instance, Sutton and others, 2000). Trade winds (from the northeast) are dominant during summer months and weaken during the winter. As noted earlier, the thermal inversion that forms at an altitude of ~2 km during trade-wind conditions often separates wind directions that can be substantially different above and below (see, for example, Schroeder, 1993). Gas and ash from plumes rising above 2 km (or from vents at altitudes above 2 km) will generally be dispersed to the east or northeast by the jet stream, whereas gas and ash from plumes or vents lower than 2 km altitude will usually be dispersed to the southwest by the trade winds (Swanson and others, 2011). All of Kīlauea's vents are below 2 km, but most of Mauna Loa's are above this elevation.

## Volcanic Gas Hazard

Vog (volcanic smog) and acid rain are the most common hazards related to volcanic gases in Hawai‘i. These are produced when volcanic gases (primarily $SO_2$) and sulfate aerosols (tiny particles and droplets) react with atmospheric moisture, oxygen, and sunlight (Sutton and others, 1997). Close to vents, the emissions are mostly $SO_2$ gas; farther from the vents, the emissions become dominantly aerosols with particulate matter that is less than 2.5 µm in diameter (referred to in air-quality discussions as PM2.5). Vog can pose a health hazard by aggravating preexisting respiratory ailments, and acid rain can damage crops and leach lead from metal roofs into household rain-catchment water supplies.

The word "vog" was coined in the middle to late 20th century (Watanabe, 2011), reflecting the relatively recent recognition of volcanic gas from Hawaiian volcanoes as a hazard. Before the start of the ongoing East Rift Zone eruption of Kīlauea in 1983, written observations of volcanic smoke, haze, or vog were uncommon, and public complaints were rare. Through the many notes of travelers passing the summit of Kīlauea since 1823, we know that the volcano was obviously emitting gases; however, reports of volcanic-gas effects away from Kīlauea were infrequent. Reports of gases during Mauna Loa activity, however, were common across the entire island chain, possibly because of the great volumes of gas that were released over short periods of time by discrete Mauna Loa eruptions from vents above the inversion layer. Gas emitted from such high vents may be blown to the northeast until falling below the inversion layer and being blown back to the islands by the trade winds.

### Early Descriptions

Many visitors to the active lava lake at Kīlauea's summit throughout the 1800s and until 1924 described the choking, suffocating effects of the volcanic gas immediately downwind of the lava lakes, but there were very few mentions of gas beyond the summit area until the mid-20th century. In the early 1800s, missionary John Whitman commented on what may be the earliest mention of vog from Kīlauea Volcano (Holt, 1979): ". . . on the N.W. part [of the island] a thin blue smoke may be observed coming from a volcano which is described by the natives as a lake of burning lava . . ."; this may be the earliest mention of vog from Kīlauea Volcano (Holt, 1979). On O‘ahu, more than 300 km northwest of the Island of Hawai‘i, southerly, or "kona," winds were commonly described as "volcano weather," bringing rain and, sometimes, hazy conditions (Lyons, 1899).

Mauna Loa apparently produced large amounts of gas during the weeks-to-months-long eruptions in the 19th and 20th centuries, and the emissions travelled far from their sources. *The Hawaiian Gazette* (1868) reported that O‘ahu was “wrapped in smoke” after the Mauna Loa 1868 eruption. Lyons (1899) reported that a haze covered the entire island group after the 1877 Mauna Loa eruption, and a newspaper account (Hawaiian Gazette, 1899) described sulphurous smells and minor amounts of ash enveloping the city of Honolulu as a result of the 1899 Mauna Loa eruption. The 1950 eruption of Mauna Loa produced a visible haze that extended more than 3,000 km to Midway Islands atoll (Free Lance-Star, 1950). Initially, the source of the haze was not known, but its significant sulfate content and particulate content, 600 times the normal amount, pointed to a volcanic origin. In each of these cases, the eruptions occurred at high-elevation vents, and the emissions were dispersed away from Hawai‘i by high-altitude winds; when those winds were to the northeast, the emissions would eventually descend into the troposphere and return to Hawai‘i with the trade winds. Kīlauea eruptions produce significant volcanic emissions from vents at lower tropospheric elevations than those from Mauna Loa. During the Kapoho eruption (from Kīlauea’s East Rift Zone; fig. 3) in 1960, $SO_2$ concentrations were so high in Hilo, 35 km to the northwest, that the Governor of Hawaii briefly considered evacuating the city (Hilo Tribune-Herald, 1960).

The increase in public concern about vog over the past 30 years is puzzling in light of the relative absence of concern during earlier years of sustained activity at Kīlauea. The lava lake at Kīlauea’s summit, which was active nearly continuously from its first documented visit in 1823 through 1924, must have produced copious amounts of volcanic gas, as does the current summit lava lake. The south and west (Kona) coast should therefore have been just as impacted by vog as they currently are, due to eruptions at both Halema‘uma‘u and Pu‘u ‘Ō‘ō; however, this may not have been the case. The Kona coast in the early 1900s reputedly had a very clean and dry atmosphere, such that Kona was often mentioned as a place of refuge for those with tuberculosis and other respiratory problems (Goodhue, 1908). The Kona air at that time was described as free from fog, dust, and mud and was so clear that it provided unlimited views to the north and south. The Kona Hospital was established in 1909 near Kealakekua, in part because of the excellent air quality. These conditions are in marked contrast to those during the present ongoing eruptions of Kīlauea Volcano. Perhaps a careful study of the climatological and sociological records of the Kona region might yield some clues as to the source of this discrepancy.

## Gas Hazard Maps

The earliest known published assessment of gas hazards on the Island of Hawai‘i was that of Mullineaux and others (1987). In their analysis, they commented that, during the frequent, nearly continuous eruptive activity from 1967 to 1974, “trade winds carried gases from Kilauea’s summit and east rift zone southwestward into the Kau District, reportedly causing a decline in sugar yields. Fumes then drifted around to the Kona District on the west coast and were blamed for the decline of other crops” (Mullineaux and others, 1987, p. 611). They also noted that, during the 1977 East Rift Zone eruption, drifting volcanic gases killed vegetation as far as 30 km from the eruptive vent.

Mullineaux and others (1987) stated that a gas hazard map would be essentially identical to their tephra hazard map (see fig. 8), rationalizing that the severity of gas hazards would similarly decrease with increasing distance from the expected vents and be commensurate with the short-term frequency of expected eruptions. $SO_2$ and $CO_2$ emissions can reach fatal levels within their gas hazard zone 1 during eruptions, judging from the gas-monitoring data for the long-lived current eruption(s) at Kīlauea.

Nonfatal, but damaging, effects have been demonstrated at even greater distances downwind from eruptive vents. The continuing persistence of vog from the ongoing Pu‘u ‘Ō‘ō eruption—reducing visibility and, sometimes, affecting people with respiratory conditions—has been a chronic complaint at many locations on the Island of Hawai‘i during both Kona (southerly) and trade-wind (northeasterly) conditions. During Kona wind conditions, neighboring islands are also affected. Although vog was already a health and agriculture nuisance during the first 25 years of the Pu‘u ‘Ō‘ō eruption, the volcanic-gas problem worsened when the summit vent opened in early 2008 and began emitting larger amounts of gases. The total emissions from the volcano were augmented for several months before the emission rate settled down to a fairly steady-state rate that is still as much as three times higher than the total pre-2008 emissions from Kīlauea.

A map of nonfatal, but potentially damaging, longer-term exposure to volcanic gas can be estimated by determining the distribution of gas constituents within lichen around the island (Notcutt and Davies, 1993). Lichens are an ideal medium, because their fluoride uptake is from the atmosphere and not from the substrate. Typical life span of the sampled plants was estimated to exceed 30 years, thereby providing good long-term averages. The pattern of fluoride abundances clearly shows the general dispersion pattern of gases from Pu‘u ‘Ō‘ō; as expected, the highest concentrations are found within Kīlauea’s summit region (fig. 9). Air-quality summaries based on monitoring by the Hawaii State Department of Health’s Air Quality Branch tell a similar story about $SO_2$ dispersion, but also include data on particulate matter (PM2.5) concentrations (Fuddy, 2011). Environmental Protection Agency (EPA) $SO_2$ standards were exceeded most frequently in the towns of Pāhala, directly southwest of Halema‘uma‘u, and Mountain View, to the north of Pu‘u ‘Ō‘ō (both locations are within 30 km of active vents), whereas EPA PM2.5 exceedances are most frequent in Kona, the most distant monitoring site from Kīlauea on the Island of Hawai‘i. The U.S. Department of Agriculture issued a Secretarial Disaster Designation for vog damage to agriculture (plants, animals, and infrastructure) on the Island of Hawai‘i in July 2008 (Sur, 2012), but it was discontinued in 2012 because of lack of public interest. Damage from the gas emissions has ranged from acid burns on commercial flower crops to possible fluorosis in cattle and goats, as well as accelerated degradation of metal fences and gates.

## Mitigation of Risks from Exposure to Volcanic Gases

Based on the gas-emission studies pioneered by HVO scientists, monitoring of volcanic-gas dispersion is now done by several agencies in Hawai‘i. HVO continues to monitor $SO_2$ and $CO_2$ emission rates at the sources (for instance, Elias and others, 1998; Elias and Sutton, 2002, 2007, 2012; Sutton and Elias, this volume, chap. 7). The Hawaii State Department of Health and the National Park Service monitor air quality in the State and Hawai‘i Volcanoes National Park, respectively. The air-quality data support mitigation decisions, such as evacuation of areas of high gas concentration until the threat diminishes. Finally, satellites on daily passes quantify the mass of $SO_2$ in the air around Hawai‘i. Although the results are not available to use for timely mitigation, the satellite data are important for documenting the $SO_2$ mass distribution throughout the State for providing context for ground-based measurements (Carn and others, 2012).

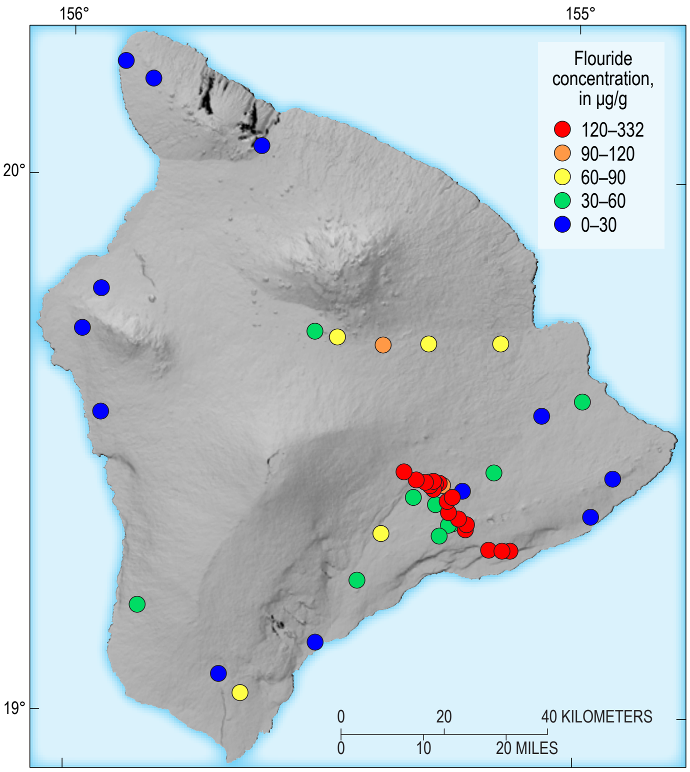

**Figure 9.** Shaded relief map showing fluoride concentrations measured in lichen sampled around the Island of Hawai‘i expressed in micrograms per gram (from Notcutt and Davies, 1993, based on their figure 2).

Using all available data, the next step is to forecast vog conditions. To this end, a feasibility study was funded by HVO at the University of Hawai‘i at Mānoa Meteorology Department, using the computer model HYSPLIT (http://weather.hawaii.edu/vmap/) with a dense wind-field model and the current $SO_2$ emission rate data measured by HVO. The results, to date, are promising and popular with the public, but the cost to implement such forecasting on a regular basis may be prohibitive. Most people are aware of either Kona or trade-wind conditions and expect $SO_2$ concentrations to be high or low during one or both situations, depending on their location. For television media in Hawai‘i, vog forecasts have increasingly become part of the weather forecasts, especially if the conditions are expected to be severe.

Public education plays a critical role in providing information sufficient for people to make individual decisions for coping with vog. The health effects of long-term, chronic exposure to volcanic gases are not known. It is known, however, that short-term exposure to vog does not cause respiratory illness, although it can exacerbate existing problems like asthma. The best health advice has been titled “shelter in place,” meaning that, during high $SO_2$ concentrations, people should stay indoors in a closed or air-conditioned room, if possible (for example, http://hawaii.gov/health/environmental/air/cab/cab_precautions.html). Following that policy, Hawai‘i County and the State of Hawaii have made efforts to provide each school and many other public facilities with one clean-air room in which those with respiratory conditions can find refuge on bad vog days.

## Earthquake and Tsunami Hazards

The frequent volcanic eruptions and earthquakes were Jaggar’s main reasons for locating a volcano observatory in Hawai‘i, and the Kīlauea Volcano site afforded abundant opportunity to study both (Tilling and others, this volume, chap. 1). The first geophysical instruments installed at HVO by Jaggar in 1912 were seismometers to record both local and distant earthquakes (Okubo and others, this volume, chap. 2). HVO staff quickly got a sense that local earthquakes occurred frequently and were often related to volcanic activity.

Jaggar wanted to understand earthquakes better but concluded early on that the key to minimizing earthquake damage lay in the construction of stronger, earthquake-resistant buildings (see, for instance, Jaggar, 1913), in addition to understanding the mechanics of earthquakes. A major scientific challenge therefore was then—and remains today—quantifying the ranges of expected shaking forces on which to base design standards for safe building construction. Throughout its history, HVO has characterized earthquake occurrences and rates with constantly improving technology and, in more recent times, has also participated in mitigation planning, zoning, and education efforts with the Hawaii State Civil Defense agency and the USGS Earthquake Hazards Program.

## Hawaiʻi Earthquake Patterns and Frequencies

Hawaiʻi, Alaska, California, and Nevada are the four most seismically active U.S. states in terms of $M>3.5$ earthquakes (Anderson and Miyata, 2006, table 1). The County of Hawaiʻi has the third highest annual earthquake losses of any county in the United States (Chock and Sgambelluri, 2005). If only seismicity related to magma accumulation, transport, and eruption is considered (mostly $M<3.5$), Hawaiʻi almost certainly would rank as the first or second most seismically active state in the U.S.

Earthquakes in Hawaiʻi do not occur randomly in space, but rather, are concentrated along pathways of the volcanic plumbing system (see Tilling and others, this volume, chap. 1; fig. 10), fault structures, and also deep within the mantle (Klein and others, 1987). Most of the earthquakes in Hawaiʻi are small ($M<3$) and are directly related to eruptions or magma intrusions, generally causing minimal damage. Relatively infrequent large ($M>6$) earthquakes (fig. 10), which can be highly destructive, are typically produced by island-scale tectonic processes (Heliker, 1997; Okubo and Nakata, 2011).

Hawaiʻi residents observed long ago that earthquake activity was closely associated with volcanic eruptions. Jaggar and HVO seismologists elaborated on this relation and, with only a few seismometers, were able to detect the start of increased seismicity before earthquakes were large enough to feel. They also were able to determine crude locations of earthquakes by estimating their distance and azimuth, based on seismic traces recorded at HVO, and so be alerted to likely sites of impending eruptions. It was not until the 1960s that the HVO seismic network had enough instruments to allow triangulation of the locations and depths of local earthquake hypocenters.

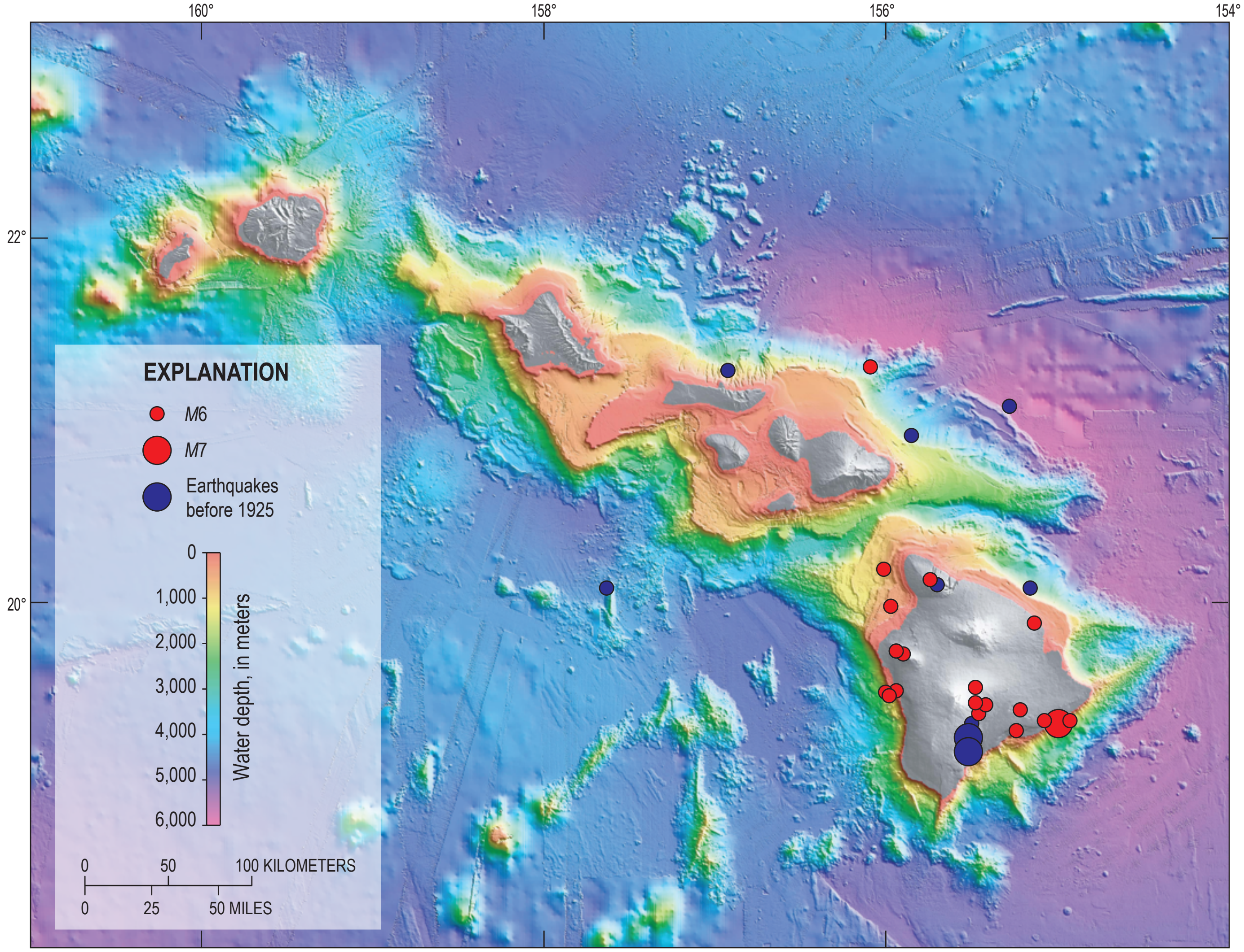

**Figure 10.** Map showing locations of *M*6 or stronger earthquakes in the Hawaiian Islands and adjacent ocean areas from 1823 to 2012 (from Okubo and Nakata, 2011); color-coded bathymetry is from Eakins and others (2003). The locations of hypocenters for earthquakes that occurred before 1925 are not well constrained.

**Table 1.** Conditional Poisson probability estimates for earthquakes in the Hawaiian archipelago and (in parentheses) in the southern part of the Island of Hawai‘i for 10-, 20-, and 50-year time periods starting in 1990.

[From Wyss and Koyanagi, 1992, table 9; *M*, magnitude; I, intensity (Modified Mercalli scale); these probabilities can be used for any 10-, 20-, and 50-year periods]

| | 1990–2000 | 1990–2010 | 1990–2040 |
|---|---|---|---|
| $M\geq6$ | 0.84 (0.71) | 0.97 (0.92) | 0.999 (0.998) |
| $M\geq6.5$ | 0.50 (0.39) | 0.75 (0.63) | 0.97 (0.92) |
| $M\geq7$ | 0.17 (0.17) | 0.31 (0.31) | 0.61 (0.61) |
| $\mathrm{I}_{max}\geq$VII | 0.67 (0.63) | 0.89 (0.86) | 0.997 (0.99) |
| $\mathrm{I}_{max}\geq$VIII | 0.50 (0.39) | 0.75 (0.63) | 0.97 (0.92) |

## Earthquake Hazards

Destruction during earthquakes is caused by energetic shaking of the ground as seismic waves pass through the Earth. To understand the impact of future earthquakes, we need to know how past earthquakes have affected the Hawaiian Islands. Wyss and Koyanagi (1992) produced the first comprehensive compilation of shaking effects from large Hawaiian earthquakes dating back to 1823. Their map shows maximum Modified Mercalli intensities from eyewitness accounts and is an excellent first cut at a seismic hazard map (fig. 11). They also estimated the probabilities of future damaging earthquakes and of maximum Mercalli intensities (table 1). Although published specifically for 10-, 20-, and 50-year intervals starting in 1990, these probabilities are valid for any time intervals of similar length.

Klein and others (2000, 2001) used these data and measurements of ground-shaking forces provided by strong-motion instruments (a type of seismometer that measures acceleration rather than velocity) to prepare probabilistic seismic hazard maps for Hawai‘i. Figure 12 estimates the peak horizontal ground acceleration (in percent g, the acceleration of gravity) that could be exceeded with a probability of 10 percent within a 50-year interval. The maximum force on a building due to earthquake shaking can be estimated as the product of the peak ground acceleration times the building mass.

The 2001 seismic hazard maps were based on a single Earth model response for strong motion (Klein and others, 2001); it was assumed that the Earth responds to earthquake waves in the same way everywhere on the island. Recently, the shear-wave velocity structure beneath each strong-motion sensor on the Island of Hawai‘i was quantified to depths of 30 m or more (Wong and others, 2011), but these new data have not yet been incorporated into improved hazard maps.

## Mitigation of Seismic Risk: Building Codes and Public Education

The effects of damaging earthquakes can be mitigated by requiring all new buildings to be designed to withstand expected shaking forces. The State of Hawaii has been proactive in passing laws unifying county building codes and requiring regular updates. The State adopted the 2006 edition of the International Building Code, which categorizes areas as zones 1 through 4, with the strongest shaking expected in zone 4 (including all of Hawai‘i County).

In addition to conducting long-term studies of earthquakes in Hawai‘i, HVO has worked with County

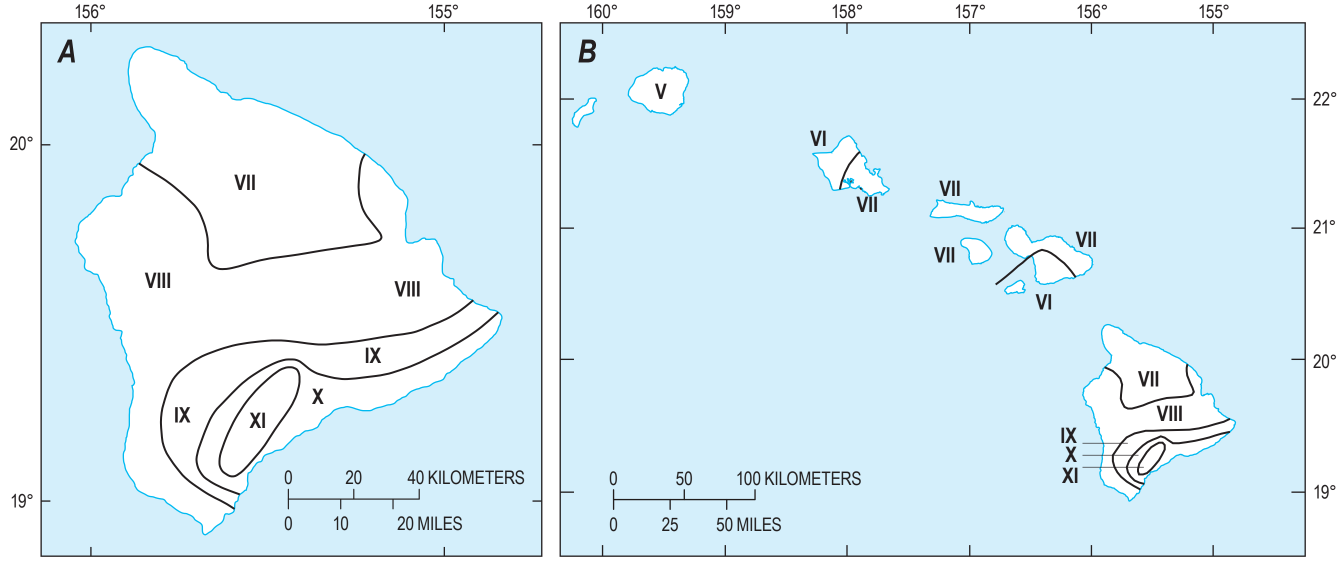

**Figure 11.** Maps showing maximum Mercalli intensities recorded for all earthquakes in the Hawaiian Islands since 1823 (from Wyss and Koyanagi, 1992). *A*, Island of Hawai‘i, where the highest intensities reflect large earthquakes of 1868, 1929, 1973, and 1975. *B*, All of the Hawaiian Islands, where the highest intensities outside the Island of Hawai‘i relate to the earthquakes of 1871 and 1938.

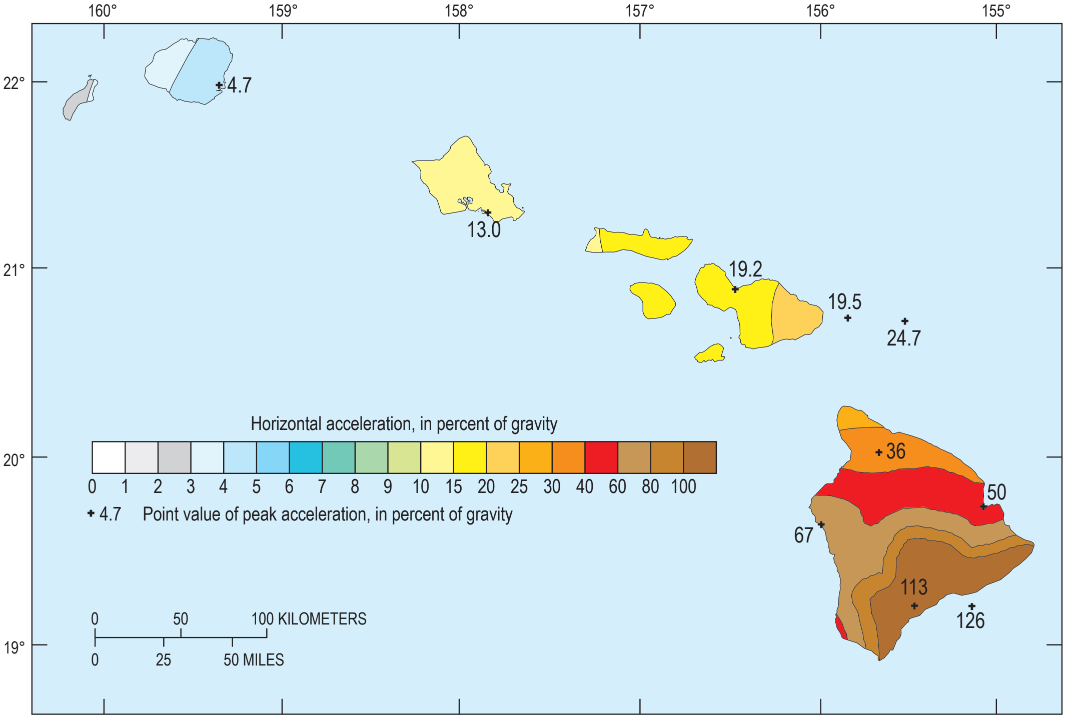

**Figure 12.** Map of the eight main Hawaiian Islands, showing probability of future earthquake ground shaking. Values are peak horizontal ground acceleration (proportional to force) that has a 10-percent probability of being exceeded in 50 years, expressed as a percentage of g, the acceleration due to gravity (from Okubo and Nakata, 2011, after Klein and others, 2000). This map can be accessed at the interactive USGS Web site http://gldims.cr.usgs.gov/hishmp/viewer.htm.

and State agencies in an advisory capacity with regard to adopting appropriate building codes and other measures to minimize seismic risk. HVO also works to increase public awareness of seismic hazards by presenting public lectures and meeting with school and civic groups (see Tilling and others, this volume, chap. 1). Finally, the articles in Volcano Watch—a column written by HVO staff and published in Hawai‘i newspapers and on HVO’s Web site—offer information about seismic hazards and risks (see, for example, Hawaiian Volcano Observatory Staff, 2006).

HVO continues to monitor Hawai‘i seismicity for the USGS and provides a Web site map display of hypocenters located in the State in nearly real time (http://hvo.wr.usgs.gov/seismic/volcweb/earthquakes/), as well as inputs to the USGS Earthquake Notification Service (https://sslearthquake.usgs.gov/ens/register.php). For any Hawai‘i earthquake of *M*4.0 or greater, HVO quickly posts a press release with earthquake parameters and the seismic history of the source area.

## The Connection Between Earthquakes and Tsunamis

In 1912 many scientists understood that tsunamis were caused by large earthquakes, but transoceanic communications at that time were insufficient to warn distant communities of an advancing wave. On September 29, 1912, HVO recorded its first “teleseismic disturbance” related to an earthquake “of great power” that occurred at a distance “no less than 5000 miles from Hawaii” (Jaggar, 1947, p. 42). By 1922, HVO reports tied the recording of a teleseism at about 6 p.m. with the arrival of “a succession of pronounced tidal waves on the beach at Hilo the next morning.” Knowing that the teleseismic waves from large, distant earthquakes travelled much faster than the tsunami waves, HVO scientists came up with a way to forecast the damaging wave’s arrival: “. . . the transit time of the first preliminary [seismic] waves through the earth in minutes and seconds is very nearly equal to the transit time of the seismic sea waves in hours and minutes. . . .” (Finch, 1924, p. 148). Tsunami forecasting based on teleseismic arrivals was born.

The forecasting of tsunamis was not yet fully operational, however. An HVO forecast in 1923 was ignored, and the tsunami caused $1.5 million in damages and one death. Another HVO forecast in 1927 was well heeded, but the tsunami failed to materialize. The next HVO tsunami forecast was after a Japan earthquake in 1933. This warning was taken seriously, and official actions taken in response were successful. No lives were lost, and damage was minimal, despite a maximum trough-to-crest wave height of 5.3 m at some west-facing shores of the Island of Hawai‘i.

Yet, on Monday, April 1, 1946, a devastating tsunami hit Hilo Bay just before 7 a.m., killing 96 people. A total of 159 people died throughout the State in the greatest tsunami disaster Hawai‘i has known, to date. Why was no warning given in 1946? The answer is surprisingly simple. The distant earthquake that heralded the April 1 tsunami was recorded at 2:06 a.m. Hawai‘i time but was not noticed until 7:30 a.m., when HVO staff reported for work—a half hour after the first waves hit Hilo (Hawaiian Volcano Observatory Staff, 2007).

In direct response to the 1946 tsunami disaster, Congress funded the creation and operation of a new agency within the U.S. Coast and Geodetic Survey called the Seismic Sea

Wave Warning System (SSWWS), now called the Richard H. Hagemeyer Pacific Tsunami Warning Center (PTWC), located on O‘ahu. HVO continued to provide tsunami warnings for Hawai‘i until SSWWS became fully operational in 1949 and also reported the arrival parameters of distant earthquakes well into the 1960s. After the 1946 disaster, HVO technicians solved the problem of how to provide round-the-clock monitoring with limited staff. In December 1946, they installed a buzzer that went off at the Observatory and in two staff residences whenever seismometers detected a distant earthquake large enough to generate a tsunami; thus, even in the middle of the night, the buzzer system would roust some HVO staff member out of bed when a large, distant earthquake occurred.

The sensor networks now available to the PTWC are more spatially extensive than HVO’s and include tide gauges, deep-ocean tsunami-detection buoys, and the combined seismic instruments of the Global Seismic Network and the USGS National Earthquake Information Center. The PTWC area of responsibility includes the Pacific Basin. HVO supplied earthquake arrival determinations to PTWC during the early years, and starting in 1999, selected channels of real-time HVO seismic data have been supplied directly to PTWC to aid with tsunami forecasting. Since 2011, all real-time seismic data acquired by HVO are supplied to PTWC, and vice versa, via Internet connections. Efforts are underway to form a single entity—the Hawai‘i Integrated Seismic Network—composed of HVO, PTWC, University of Hawai‘i at Mānoa, and State Civil Defense for the purpose of identifying and monitoring earthquake and associated tsunami hazards. HVO and the USGS will still be responsible for earthquake monitoring, while PTWC will be responsible for tsunami warnings.

Other important contributions made by HVO to tsunami science includes the rapid documentation and mapping of wave effects on Hawai‘i’s shores. Areas vulnerable to tsunami hazards are largely defined by the runup maps from previous tsunamis and, more recently, by modeling potential tsunamis. These hazards are largest along shallow-sloping coastlines directly exposed to the open ocean. HVO and affiliated scientists published runup data for the 1960 tsunami (Eaton and others, 1961), the locally generated tsunami in 1975 (Loomis, 1975; Tilling and others, 1976), and the 2011 tsunami generated by the Tohoku, Japan, earthquake (Trusdell and others, 2012).

# Indirect Volcano Hazards

Eruptive activity in Hawai‘i is preceded and (or) accompanied by earthquakes and ground deformation. In general, such phenomena are detectable only instrumentally but are sometimes sufficiently energetic to produce effects readily discernible by humans (for example, shaking, ground subsidence, and opening or widening of ground fractures). Mullineaux and others (1987) termed such eruption-related processes “indirect volcano hazards,” which are less severe and rarely damaging compared to the “direct” or “primary” volcano hazards, such as lava flows, tephra fall, pyroclastic surges, and volcanic gases. In this section, we discuss these indirect processes, as well as the low-probability, high-impact hazard of flank collapse.

## Ground Subsidence and Fractures

Ground subsidence poses an indirect hazard on active Hawaiian volcanoes in two structural settings: (1) summit regions and rift zones, which actively expand and contract as a result of subsurface magmatic activity, and (2) volcano flanks, which can slip along the contact surface between the volcano and the underlying oceanic crust (the décollement fault). Such ground motion has occurred frequently on the Island of Hawai‘i during the past two centuries. Moreover, the gradual subsidence of the entire Island of Hawai‘i from volcanic loading has been documented to be on the order of several millimeters per year (Moore, 1987).

While gradual subsidence is documented primarily by geodetic measurements, geological and archaeological evidence also exists. For example, in the Kapoho area, where rapid subsidence associated with earthquake and eruptive activity was reported in 1868, 1924 (Finch, 1925), and 1960 along a rift zone graben structure, evidence for long-term subsidence can be seen at a popular coastal swimming and snorkeling spot named Wai ‘Opae. Here, snorkelers can see a subaerially erupted pāhoehoe flow that is now submerged by several meters, with only the tops of tumuli remaining above sea level at high tide. In addition, snorkelers within Kapoho Bay can observe ancient Hawaiian fishpond walls that are now totally submerged.

Gradual subsidence related to magmatic activity is sometimes, but not always, expressed by formation of new ground fractures or widening of existing fractures. Such fractures commonly ring depressions and craters; the system of ring fractures around Kīlauea Caldera, for example, is well expressed in the map by de Saint Ours (1982). Subsidence associated with magmatic activity can also be abrupt. For example, graben-like structures developed (fig. 13), and then rapidly subsided, in the Kapoho area a few weeks before the 1960 eruption. Likewise, increases in the rate of gradual widening of fractures rimming Kīlauea pit craters (for example, Halema‘uma‘u Crater and Mauna Ulu’s summit crater) are well correlated with piecemeal collapse of their walls to trigger rock falls (see, for instance, Jaggar, 1930a,b; Tilling, 1976).

Kauahikaua and others (1994) estimated the impact of known hazards to proposed geothermal development in the lower East Rift Zone and found that subsidence at a rate between 1.2 and 1.9 cm/yr could be expected. Delaney and others (1998) further quantified the net subsidence over the 14-year period 1976–89 at 60–180 cm within the summit area and ~20 cm along the rift zones—a rate for the East Rift Zone that is about the same as that of Kauahikaua and others (1994; fig. 14).

Not only can subsidence be an engineering problem for structures built within active volcanic structures, it can be additionally damaging in areas where rift zones run across the coastline. Where the land surface slopes into the ocean, subsidence produces an inland incursion of the sea and possible submergence of developed areas along the coast. The Kapoho coastal area is the only developed location on the Island of Hawaiʻi where these problems currently exist due to rift-zone subsidence. Brooks and others (2007) found subsidence rates of 0.8 to 1.7 cm/yr for this region.

**Figure 13.** Photograph showing earthquake offset of Old Railroad Bed Road along the Koaʻe Fault north of the village of Kapoho, prior to a Kīlauea eruption. The road is vertically offset about 1.5 m. The Koaʻe and nearby Kapoho Faults are old structures, reactivated in April 1924 during major collapse of the Kapoho graben and again in 1960. These faults still exist and will doubtless move again (USGS photograph taken January 13, 1960, by J.P. Eaton).

## Faulting and Displacement of Volcano Flanks

Between the December 1965 East Rift Zone eruption and the 1975 Kalapana earthquake, Swanson and others (1976) documented slow, continuous, seaward movement of the whole of Kīlauea's south flank. This work, using then-modern geodetic methods, quantified earlier, less precise measurements that suggested such movement of the mobile flank. Swanson and others (1976) suggested that this continuous movement could result in large, damaging earthquakes by abrupt slippage along the décollement fault. In fact, the 1975 Kalapana earthquake (Tilling and others, 1976) occurred while the Swanson and others (1976) report was in press; a subsequent strong décollement earthquake occurred in 1989 (Árnadóttir and others, 1991). The large earthquakes in 1823 and 1868 also almost certainly involved décollement displacements (see, for instance, Wyss, 1988). Reoccupation of the trilateration network after the 1975 earthquake showed substantial horizontal displacements of Kīlauea's south flank, in places as large as 8 m, and several meters of subsidence along the coastline (Lipman and others, 1985).

## Volcano Flank Collapse

Mobility of volcano flanks can have cataclysmic consequences. Since the 1960s, studies have found abundant evidence of huge deposits of debris scattered on the seafloor surrounding the Hawaiian Islands. The occurrences of such massive submarine slumps, landslides, and distal turbidity-current flows in the geologic past provide evidence that the flanks of Hawaiian volcanoes occasionally become unstable

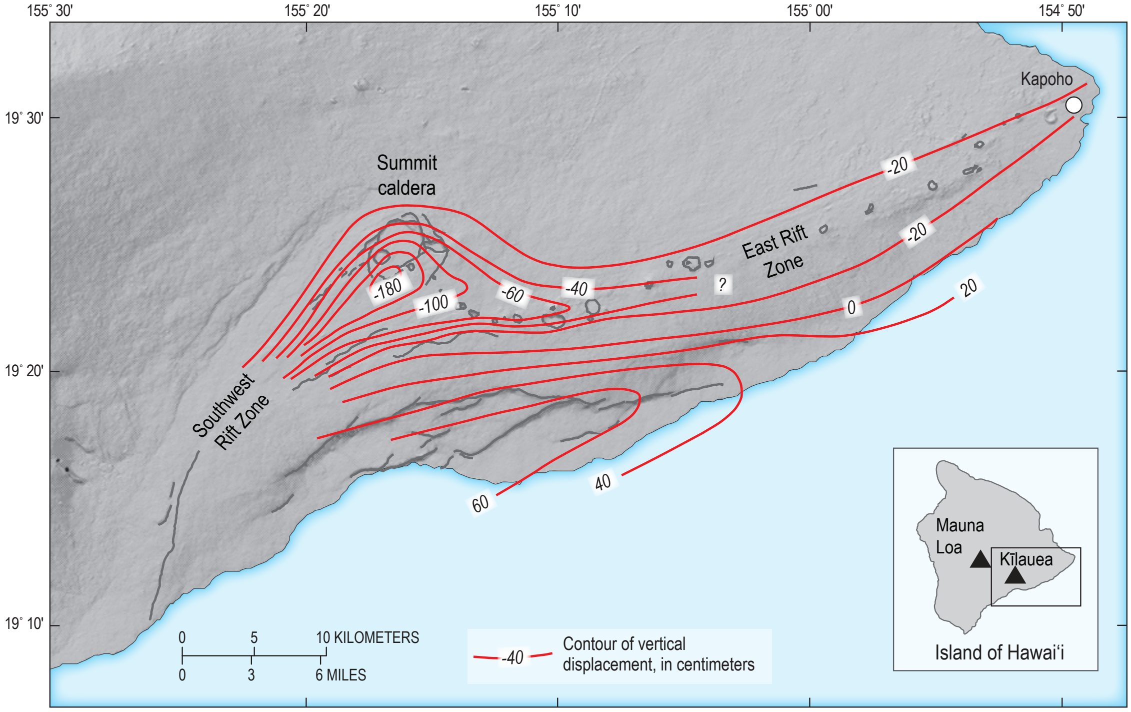

**Figure 14.** Map showing contours of vertical displacement on Kīlauea Volcano from 1976 to 1989 based on data from leveling, as well as from a tide gauge, water wells, and surface tilt measurements (from Delaney and others, 1998, fig. 3*C*). Positive numbers mean uplift, negative numbers subsidence.

and fail catastrophically (for instance, Lipman and others, 1988; Moore and Moore, 1988; Moore and others, 1989; Holcomb and Robinson, 2004). The most recent of these flank collapses has been dated at about 100,000 years ago off the west coast of the Island of Hawai‘i. Present-day deposits of broken coral, rock, and other sediment near sea level—an elevation that would have been several hundred meters higher at the time of the most recent collapse—suggest that the collapse generated a “megatsunami” (McMurtry and others, 2004). Such powerful tsunami from collapse of Hawiian volcano flanks have been hypothesized to deposit rocks and sediments as high as several hundreds of meters above sea level in other locations in the Hawaiian Island chain and even in Australia (see, for instance, Moore and Moore, 1984; Young and Bryant, 1992).

## Characterizing the Hazard

The hazard zones for ground subsidence and volcano-flank faulting were combined in a single map (fig. 15) by Mullineaux and others (1987, fig. 22.12). This map serves only to depict the areas of the most common, and relatively small-scale, short-term hazards posed by displacements associated with frequent effusive eruptions and intrusions. While acknowledging that abrupt “large-scale” subsidence and faulting would pose more serious hazards, such as those accompanying major tectonic earthquakes and volcano-flank collapse, Mullineaux and others (1987) made no attempt to assess them because of their very low frequency. Volcano flank collapse and associated tsunami are an example of the classic high-impact, low-probability hazard.

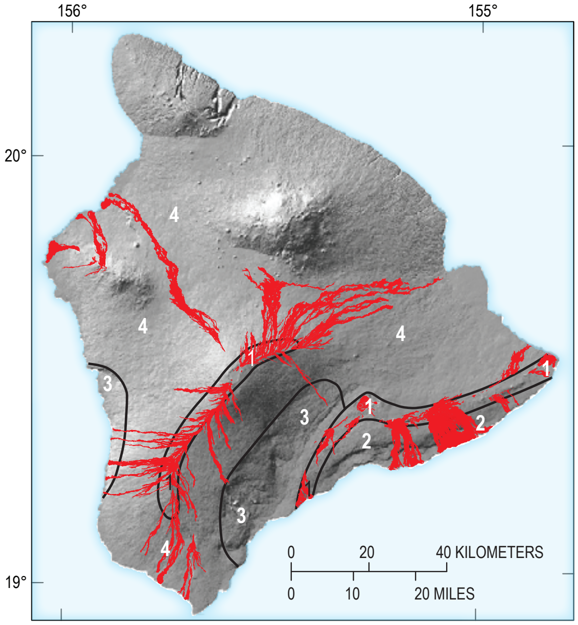

**Figure 15.** Map depicting the numbered hazard zones 1 to 4 for ground fractures and “small-scale” subsidence for the Island of Hawai‘i (from Mullineaux and others, 1987, figure 22.12). Also shown are historical lava flows (red areas). Subsidence and fracturing events are frequent in zone 1, which covers the summit and rift zones of Kīlauea and Mauna Loa, but are somewhat less frequent in zone 2, on the south flank of Kīlauea. Zone 3 includes areas around the Kealakekua and Ka‘ōiki Fault Systems on Mauna Loa. Zone 4 includes the remainder of the island.

## Mitigative Measures

The only effective mitigation strategies available for relatively small-scale indirect hazards are to avoid using the areas susceptible to such hazards for high-density development or critical facilities through land-use zoning and public education. There are no practical mitigative measures for large-scale, truly catastrophic hazards associated with volcano flank collapse; such hazards would impact areas far beyond the maximum hazard zone in figure 15. We anticipate, however, that the close, continuous volcano monitoring conducted by HVO—particularly of Kīlauea’s mobile south flank—should be able to detect any unusual acceleration in ground displacements that might suggest departure from “normal” volcano behavior. Armed with such information, we can provide early warning to emergency-management authorities that the flank is becoming highly unstable and that immediate work should begin on contingency plans.

# Future Challenges in Reducing Risk

HVO founder Thomas Jaggar, Jr., advocated using the best possible scientific information to reduce risks posed by natural hazards—effectively using good science to enhance public safety. During the past century, HVO, through its long-term monitoring studies and topical research, has adhered to Jaggar’s guiding principle in responding effectively to hazards that most frequently affect Hawai‘i. While much has been accomplished, much also remains to be done. In future decades, HVO and the USGS not only must continue to deal with Hawai‘i’s most common hazards (lava flows, volcanic gases, earthquakes, and tsunami), but will have an additional, perhaps more demanding, task in addressing low-frequency, high-impact hazards that are known to have occurred in the geologic past: (1) voluminous explosive eruptions capable of producing tephra deposits on a regional scale (fig. 10) and (2) collapses of volcano flanks to produce huge submarine landslides and attendant local megatsunami. Below we highlight some major challenges that HVO, its partners, and collaborating scientists will face in augmenting and improving the scientific basis to reduce risk from natural hazards in Hawai‘i.

## Improved Characterization and Understanding of the Hazards

In perhaps the first-ever, albeit qualitative, publication to assess or rank natural hazards in Hawai‘i, Jaggar (1918, p. 16–17) considered four broad categories under what he called “The Index of Danger from Volcanoes”: “. . . **Class 1, explosion and volcanic blast**, . . . **Class 2, lava flow**, . . . **Class 3, earthquakes**, . . . [and]

**Class 4, tidal waves**. . . .” As previously discussed, Wentworth (1938) compiled the distribution of regional ash deposits from large explosive eruptions and an unknown HVO staff scientist produced the first, though unpublished, lava flow hazards map for the Island of Hawai‘i, possibly in the 1940s or 1950s. Hazards studies then languished until the comprehensive work of Donal Mullineaux and his associates (Mullineaux and Peterson, 1974; Mullineaux and others, 1987), who used all data available through the 1970s to characterize hazards across the Island of Hawai‘i. With much geologic (including mapping), geochemical, and geophysical data acquired during the past quarter century, we now have improved assessments for lava flow, volcanic gas, and earthquake hazards (see earlier discussion). The basic procedures for identifying and forecasting lava flow paths, long-term gas dispersion, and earthquake- and tsunami-prone areas are also now well understood and are becoming more quantitative. These are based both on documented past occurrences (historical and precontact) and on computer models that simulate the hazard mechanisms and impacts.

With continued data collection and scientific/technological advances in the next 100 years, we can expect to obtain refined assessments and precise zonation for Hawai‘i’s most frequently occurring volcano hazards (lava flows, gas emissions, and earthquakes) within short-to-intermediate time scales. At present, however, we lack the necessary data to significantly improve the assessments of hazards associated with volcano flank collapses or powerful explosive eruptions that produce voluminous tephra, as have occurred in the geologic past. Essential first steps to refine our understanding of both these low-probability but high-impact hazards are detailed mapping and dating studies on land and offshore. Such studies are necessarily long-term and will require considerable commitment of scientific and economic resources. For regional tephra falls, dating of the deposits, as currently delimited by the Island of Hawai‘i geologic map (Wolfe and Morris, 1996), is inherently difficult, because the ash deposits are generally highly altered and (or) reworked. For potential volcano flank collapses, detailed studies, including denser geodetic monitoring networks, should focus on the likely breakaway zones.

In the future, methods to characterize and assess both hazards and risks will improve, affording greater precision and accuracy or, at the least, a better understanding of the forecast uncertainty. It is clear that increasing use will be made of probabilistic hazard and risk assessments for long-term effects and of event (or logic or decision) trees for active responses (see, for example, Newhall and Hoblitt, 2002; Martí and others, 2008). Seismic hazard maps are already probabilistic (for instance, Hanks and Cornell, 1994; http://redirect.conservation.ca.gov/cgs/rghm/pshamap/), with lava flow hazard maps not far behind. An added advantage of probabilistic hazard estimates is that one can compare across all hazards and determine whether a specific area is more threatened by, for example, floods, hurricanes, earthquakes, or tsunamis compared to lava flows. Probabilistic methodologies have already become a useful cross-hazards language but, to date, have limited use in education or emergency-management efforts (Nathan Wood, written commun., 2012). Moreover, in the broad discipline of risk assessment, there is considerable debate among specialists over the merits and disadvantages of probabilistic versus possibilistic assessments. For purposes of assessment of natural hazards and risk, probabilistic estimates generally refer to the most likely events during a given time interval, whereas possibilistic estimates apply to worst-case scenarios. Both should probably be considered, suggesting that more studies are required of worst-case events with high impact but low probability (Clark, 2006; Brunsma and Picou, 2008).

We know what the worst-case scenarios are for Hawai‘i. The largest lava flows (for instance, the Pana‘ewa flow south of Hilo erupted from Mauna Loa) are now mapped and dated but not sufficiently studied to understand their eruption dynamics (were they rapidly emplaced at a high eruption rate or were they the result of prolonged activity at a lower eruption rate?). Widespread deposits from explosive eruptions are also mapped but are difficult to date or to identify with a source volcano. Earthquakes as strong as $M8$ are possible within the south flank of Mauna Loa (Chock and Sgambelluri, 2005), and such earthquakes will almost certainly generate local, destructive tsunamis. Much more work needs to be done, however, to add to our knowledge of the worst possible outcomes of Hawaiian volcano and earthquake activity.

We are well aware that a fundamental, and probably unavoidable, deterrent to assigning high priorities to studies of low-probability but high-impact hazardous processes involves basic human nature. Human beings, including decisionmakers and even scientists, quite naturally tend to pay much more attention to the most immediate threats posed by natural hazards (in other words, those likely to recur within their lifetime) rather than to those that have extremely low probability but remain possible in the remote future (in other words, those not likely to occur within hundreds or even thousands of years).

## Updated Volcano Hazards Assessment and Map for the Island of Hawai‘i

The most recent, and still used, volcano hazards assessment and map for the Island of Hawai‘i (Mullineaux and others, 1987; Wright and others, 1992) do not reflect the data and knowledge gained since the early 1980s (especially for lava flows). With present geologic and geophysical information, along with better tools to convey the hazards posed, improved zonation maps for hazards due to lava flows, volcanic-gas emissions, and ground fractures and subsidence doubtless can be produced. However, any significant advancement in the assessment and zonation maps of hazards associated with voluminous explosive eruptions (for instance, pyroclastic flows and surges, regional ashfalls) will require new data from integrated islandwide mapping and laboratory investigations. In any case, preparation in the near future of an interim updated assessment and map (based on presently available data and methodology, even without waiting for the generation of additional data) would be of use to all stakeholders, including the USGS, the State of Hawaii, and the County of Hawai‘i.

## Enhancements in Communication of Hazard and Risk Information

Traditionally, available hazards information has been compiled into a map on which the highest hazard zones reflect where the hazard is most frequent, most intense, or both, while the lowest hazard zones are the least affected. With improvements in computer technology, it is now technically easier to update hazards assessments and zonation maps of various time scales (long-, intermediate-, and short-range). Although it lacks the quantitative parameters—geologic as well as socioeconomic—needed to evaluate and compute risk, this mode of conveying hazards information remains effective and will continue to be used into the foreseeable future.

HVO currently uses a variety of means to communicate hazards information but has yet to take full advantage of modern media characteristics. The Internet has made information available at any time, and effective hazard communications can make use of that. Short Message Service (SMS) texting and e-mail already provide addressable communication methods that are available continuously between scientists and emergency managers. Social networking modes, such as YouTube, Facebook, and Twitter offer many new options once any potential security threats have been cleared by the USGS Information Technology security policy. Such established social media forums could significantly augment the audience to which HVO hazard messages are sent. Also, the wide availability of Google Maps and Google Earth provide an almost ideal medium by which to distribute spatial information. For example, the lava flow hazard map for the Island of Hawai‘i and information on HVO-located earthquakes are now available in Google Earth format.

However, it should be emphasized that in any effective hazard communication, there is also a need for better ways to communicate the uncertainties of hazard forecasts and assessments. This is a problem across studies of all hazards, whether natural or manmade, and much effort in recent decades has gone into improving the messages and warnings regarding hazards to explicitly incorporate information on uncertainties.

Over the past 20 years, HVO has developed and actively used a Web site to disseminate up-to-date information, maps, photographs, and videos of volcanic activity, as well as publications to deliver more in-depth studies and hazards assessments. In addition, HVO submits a weekly article on volcanoes and hazards to local newspapers in Hawaii; we have now compiled more than 1,000 of these articles, which are available to the public on the HVO Web site. HVO scientists have published and kept up-to-date several USGS Fact Sheets on timely issues like vog, earthquakes, and lava flow hazards. We have become even more proactive in the past decade, establishing Volcano Awareness Month in 2009, in which HVO scientists give public talks on current volcano and earthquake hazard issues at locations around the Island of Hawai‘i. Starting in 2012, HVO now participates in the local Disaster Preparedness Fairs in both Maui and Hawai‘i Counties to distribute information about volcano and earthquake hazards. The USGS Volcano Science Center also distributes regular hazard assessments using the e-mail Volcano Notification Service (VNS), making it possible for anyone to keep up with one or all U.S. volcanoes, even using just a smart phone.

## Concluding Remarks

Volcanoes are always big news in Hawai‘i, and their activities and impacts are followed avidly by island residents, government officials, and visitors. Because of the frequent—and sometimes continuous (as from 1983 to present)—eruptive activity, HVO scientists are in constant communication with National Park Service and Civil Defense officials with regard to ongoing or potential hazards. Effective communication is thus conducted on a regular basis via the well-established channels described by Tilling and others (this volume, chap. 1). Of course, there is sometimes also a need for special or urgent communications under crisis conditions, as is the case at volcanoes elsewhere in the world that erupt infrequently or unexpectedly.

In its first century monitoring Hawaiian volcanoes, HVO has communicated hazards information by making it accessible in an efficient and timely manner, using the best available methods and technology. There is every reason to believe that this century-long legacy will carry into the next 100 years, with new methods focused on pushing hazards information to individuals as simply yet comprehensively as possible.

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