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How and Why Hawaiian Volcanism Has Become Pivotal to Our Understanding of Volcanoes from Their Source to the Surface

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ABSTRACT

Hawai'i is a superb venue for volcanological research because of the high frequency and easy access to eruptions and its unique geological setting in the central Pacific far from plate boundaries or continents. Studies of Hawaiian volcanoes and their deep roots have helped shape our understanding of Earth processes from the deep mantle to the atmosphere. Since the creation of the Hawaiian Volcano Observatory in 1912, research on Hawaiian volcanoes has led to many fundamental discoveries. A few of these discoveries spanning the range of topics discussed in this volume are reviewed here: the role of Hawaiian geology in understanding mantle-derived magmas; the importance of helium isotopes in determining the nature and structure of the mantle; the physical controls on lava flow type, emplacement, and how far they will travel; and Hawaiian submarine geology, including the newest volcano (Lō'ihi) and the giant Nu'uanu landslide. A critical knowledge level has been achieved about Hawaiian volcanoes allowing scientists to test hypotheses that address essential issues about the way Earth works. Working on Hawaiian volcanoes is a humbling experience not only due to their grandeur but also because with new knowledge we realize how much is still not well understood.

1.1. INTRODUCTION

This volume, *Hawaiian Volcanoes: From Source to Surface,* is the third American Geophysical Union monograph devoted to Hawaiian volcanism. The other two are: monograph 92, *Mauna Loa Revealed: Structure, Composition, History and Hazard*s [*Rhodes and Lockwood*, 1995], and monograph 128, *Hawaiian Volcanoes: Deep Water Perspectives* [*Takahashi et al.*, 2002]. This is a remarkable testament to the importance and interest of Hawaiian volcanism to the geosciences community. Why has research on Hawaiian volcanism warranted this attention?

In this chapter, a personal perspective is given on the influences that may have led to the focus of many early 20th century studies on Hawaiian volcanoes. A review is presented of four broad areas of discovery that have been made about fundamental magmatic and other geological processes based on studies of Hawaiian volcanoes. These discoveries have led to Hawai'i becoming the "type example" for many magmatic and volcanic phenomena. Studies of Hawaiian volcanoes and their deep roots have and are continuing to shape our understanding of Earth processes from the deep mantle to the atmosphere (source to surface).

Three questions will be addressed below: (1) What attracted early 20th century geoscientists to Hawai'i and made it a preferred site for studying volcanism? (2) Why has research on Hawaiian volcanism been so important to our overall understanding of magma generation, evolution, and eruption? (3) What are some of the noteworthy but perhaps not-so-obvious discoveries that have come from studying Hawaiian volcanoes since the founding of the Hawaiian Volcano Observatory (HVO) in 1912? These discoveries include the origin of magma series and the melting history of Hawaiian volcanoes, primitive noble gases (helium), the undersea volcano Lō'ihi, the giant submarine Nu'uanu landslide, and lava flow dynamics and emplacement. Many other exciting topics related

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to research on Hawaiian volcanoes are not included in this review, although some are discussed in this volume.

1.2. WHAT HAS ATTRACTED VOLCANOLOGISTS TO HAWAI'I?

The allure of active volcanism has long beckoned scientists to the Hawaiian Islands. What they found has brought them back and, in some cases (G. A. Macdonald), led them to stay. Many factors have contributed to Hawaiʻi becoming a premier venue for studying volcanic processes: (1) Eruptions are frequent, mostly quiescent and easily accessible [e.g., *Dana*, 1890; *Macdonald et al.*, 1983]. (2) The tropical setting allows year-round observations. (3) Excellent publicity about Hawaiian volcanoes by newspaper and book writers (e.g., Mark Twain and Isabella Bird), artists who painted majestic scenes of the volcanoes (Figure 1.1), and national lobbying efforts by citizens of Hawaiʻi who were interested in volcanology. (4) Hawaiʻi is in the United States (since its annexation in 1898 [*Daws*, 1968]) and has for several decades had frequent, direct air service from many major Pacific and North American cities. (5) Hawaiians and other local residents have great *aloha* for visitors.

The Hawaiian Islands have been called "the loveliest fleet of islands that lies anchored in any ocean" [Mark Twain, in *Frear*, 1947]. Thus, despite the considerable distance of the islands from any continent (e.g., ~3800 km from California), Hawaiʻi has drawn volcanologists and geologists for more than 170 years. The first geologist to visit Hawaiʻi was James D. Dana, who became one of the giants of American geology and its first volcanologist [*Appleman*, 1987]. He arrived with the U.S. Exploring Expedition in 1840 after a long sea voyage from Fiji and just following a spectacular eruption on Kīlauea's East Rift Zone [*Appleman*, 1987]. The chief naturalist on this expedition was the noted American entomologist and artist Titian Peale, who produced many sketches and beautiful paintings of Kīlauea Volcano. His work is part of what has become known as the "Volcano School," a group of artists who painted dramatic nocturnal scenes of Kīlauea and Mauna Loa volcanoes. The French painter Jules Tavernier (1844–1889)] was arguably the most important member of the Volcano School. His painting of a fiery night at Kīlauea in the 1880s stirs the souls of geologists and other volcanophiles (Figure 1.1). The school included an international array of artists: Ernst Christmas (Australia, 1863–1918), Constance Cumming (Scotland, 1837–1924), Charles Furneaux (America, 1835–1913), D. Howard Hitchcock (America, 1861–1943), and Ogura Itoh (Japan, 1870–1940). Their paintings brought the beauty and excitement of active Hawaiian volcanoes to the attention of many across the United States and around the world.

Before his first visit to Hawaiʻi, Dana visited other volcanic areas, including the frequently active Italian volcanoes (Stromboli and Vesuvius), which were both erupting during his visit [*Dana*, 1835]. He also explored

Figure 1.1 Painting of Kīlauea Volcano entitled "Volcano at Night," on canvas by Jules Tavernier, circa 1885–1889. Used by permission from the Honolulu Museum of Art.

other oceanic Islands, including the Cape Verdes, Tahiti, Fiji and, Samoa, prior to arriving in Hawai'i. Dana made a second visit to Hawai'i and Italy in preparation for his insightful and well-illustrated book *Characteristics of Volcanoes with Contributions of Facts and Principles from the Hawaiian Islands* [*Dana*, 1890]. In this book, he compared and contrasted the features and activity of Hawaiian volcanoes with those of Vesuvius and Etna. Although the Italian volcanoes were better known in the 19th century, Dana felt that Italy and Hawai'i should share equally in the attention of scientific investigators. *Dana* [1890] promoted visiting the Hawaiian Islands by noting that only a two-week voyage was required from New York (three weeks from Europe) to visit the "great, open, free-working craters of Hawai'i." He also noted the usually quiet way Hawaiian volcanoes send forth lava streams 30–50 km long, creating a "peculiarly instructive field for the student of volcanic science, as well as attractive to the lover of the marvelous."

The early missionaries also played an important role in making the presence of Hawai'i's active volcanoes known and exciting to the western world. Reverends A. Bishop, C. S. Stewart, W. Ellis, J. Goodrich, and T. Coan published books and/or articles on their observations of eruptions of Kīlauea and Mauna Loa volcanoes. Most notable was Reverend Coan, who was an avid eruption watcher and good friend of James Dana. The two corresponded regularly. Dana, who was an editor for the *American Journal of Science*, published "with comments" several of Coan's reports on eruptions of Kīlauea and Mauna Loa in the journal [e.g., *Dana*, 1850]. Coan made many fundamental observations about volcanic processes, including the importance of lava tubes (which he called "pyroducts") for transporting lava ~20 km from its vent during Mauna Loa's 1843 eruption. He observed this eruption after hiking for four days through the jungle. Dana disagreed with this report and published his opinion in the same article, arguing the eruption must have been fed by a long fissure [*Dana*, 1850]. The eyewitness (Coan) was correct about the importance of lava tubes in transporting fluid lava 10 km or more from its primary vent. Several other reports by *Coan* [1856, 1869, 1880] were also published in the *American Journal of Science* (without comment) after notable eruptions of Kīlauea or Mauna Loa.

The books and articles by Dana, missionaries and others, and the paintings of the Volcano School artists undoubtedly inspired many other pioneering volcanologists and geologists to visit and report on Hawai'i's active volcanoes and their lavas, including *Daly* [1911], *Hitchcock* [1911], *Jaggar* [1912], *Perret* [1913], *Cross* [1915], and *Powers* [1915]. These early studies laid the foundation and were a motivation for subsequent work, including the diverse studies that are presented in this monograph. One insightful comment in the preface to *Dana*'s [1890] book is still true today: "But much remains to be learned from the further study of the Hawaiian volcanoes." The chapters in this monograph do much to increase our knowledge of how volcanoes work, although they also raise many questions for future research.

The establishment of the HVO in 1912 was a critical milestone in the eventual emergence of Hawaiian volcanism as a classic example for many volcanic processes. After the catastrophic eruptions of Mt. Pelée (Lesser Antilles) in 1902 and Krakatau (Indonesia) in 1883, where tens of thousands of people were killed, there was a heightened awareness that a volcano observatory was needed to monitor and learn more about volcanoes. In 1909, Thomas Jaggar and Reginald Daly, both professors at the Massachusetts Institute of Technology, visited Hawai'i and developed the idea of establishing a permanent site for a volcano observatory on Kīlauea [*Wright et al.*, 1992]. In 1911, Jaggar recruited Frank Perret, an entrepreneur and inventor (he worked for Edison as a teenager and received a patent for his electric fan) and a self-taught volcanologist, to begin the work of establishing an observatory. The new observatory was permanently established during the following year and involved the help of many other scientists, including Fusakichi Omori, the Japanese pioneer in seismology whom Jaggar visited after his 1909 trip to Kīlauea [*Apple*, 1987], and gas sampling and analysis experts E. Shepard and A. Day, from the Carnegie Institution [e.g., *Shepard*, 1925]. For more information about HVO, see the new compilation by *Tilling et al.* [2014] as well as the pictorial history of Hawaiian volcanism by *Wright et al.* [1992].

The creation of Hawai'i National Park in 1916 (the name was changed to Hawai'i Volcanoes National Park in 1961) was another notable event that brought attention to the active volcanoes in Hawai'i. Jaggar was a vocal proponent in the creation of the new park. He gave guided tours of Kīlauea to visiting U.S. Congress members, spoke to many groups about the need for the park, and even went to Washington, D.C., to testify. In his testimony, *Jaggar* [1916] emphasized that "There is no place on the globe more favorable for the systematic study of volcanology and the relations of local earthquakes to volcanoes as in Hawai'i, and for this reason alone, if for no other, it would be appropriate to set aside a national park in this wonderland of volcanic activity, where the earth's primitive processes are at work, making new land and adding new gases to the atmosphere." Within eight months of his testimony, President Wilson signed the bill creating Hawai'i National Park, the 12th national park in the United States [*Wright et al.*, 1992].

Several key additional factors were critical for the emergence of Hawai'i as a premier venue for studying magmatic processes. Hawai'i's distant location from any continent or plate boundary has led to its selection as a site for testing many hypotheses, including the anatomy of hotspot volcanoes via deep scientific drilling to 3.5 km [*Garcia et al.*, 2007; *Stolper et al.*, 2009] and whether mantle plumes extend into the deep mantle [*Wolfe et al.*, 2009; *Weis et al.*, 2011]. In comparison to other mantle plumes, the Hawaiian mantle plume is considered the hottest [*Sleep*, 1990]. The high temperature of the plume is

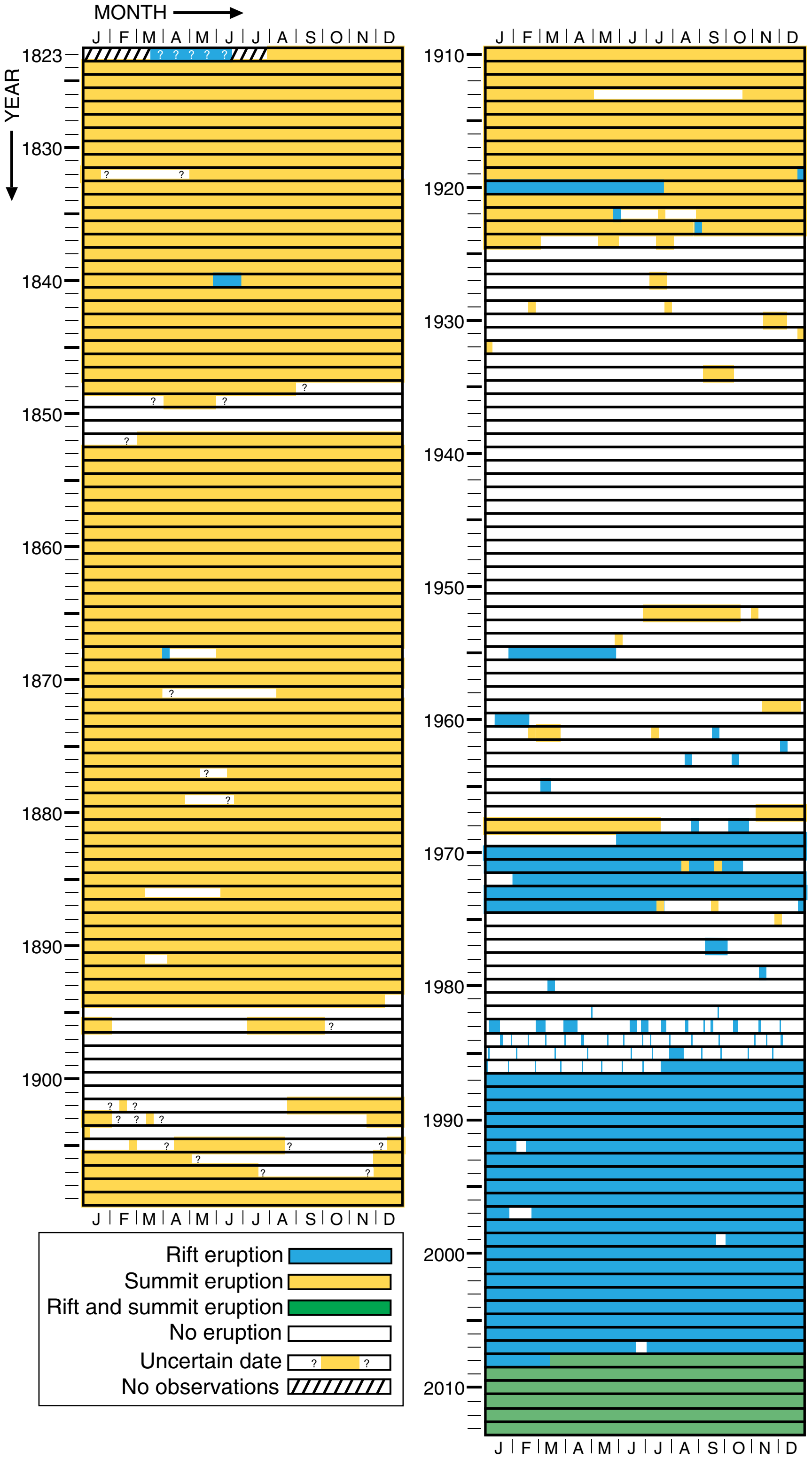

Figure 1.2 Graphic summary of the historical eruptive activity at Kīlauea Volcano from the first written observations in August 1823 to December 2013. Activity is subdivided by location (summit shown in gold and rift zones in blue). Eruptive activity since March 2008 (shown in green) has been nearly continuous both at the summit in Halemaʻumaʻu Crater and in and around the Puʻu ʻŌʻō vent along the East Rift Zone. Modified from *Macdonald and Eaton* (1964) and *Garcia et al.* [2003], based on descriptions by *Dana* [1890], *Brigham* [1909], *Fiske et al.* [1987], *Bevens et al.* [1988], *Macdonald et al.* [1983], *Heliker and Mattox* [2003], and T. Orr (2013, personal communication).

undoubtedly responsible for Hawai‘i’s frequent eruptions. Since westerners arrived in Hawai‘i and began recording eruptive activities ~190 years ago, Kīlauea has been prolific (Figure 1.2), which has promoted volcanological research on and tourism to the Hawaiian Islands.

1.3. HOW HAVE STUDIES OF HAWAIIAN VOLCANOES INFLUENCED OUR KNOWLEDGE OF MAGMATIC AND VOLCANIC PROCESSES?

Many discoveries have been made about fundamental Earth processes as a result of research on Hawaiian volcanoes. Rather than provide a list of these discoveries, four examples are discussed below to give a flavor of their diversity and impact on our understanding of geological phenomena. Obvious examples that are well documented elsewhere are not included (e.g., mantle plumes and volcano monitoring; see Chapter 24). For some of these examples given below, I have participated in the research (melting history and marine geology), whereas others I have observed with interest (noble gases and lava flows).

1.3.1. Origin of Magma Series and Melting History of Hawaiian Volcanoes

One fundamental geological controversy in which studies of Hawaiian lavas played an early and pivotal role had to do with the origin of magma series. This story is superbly told by *McBirney* [1993] and is summarized here. Field work on the Eocene Scottish volcanic centers in the 19th century led to the realization that alkalic basaltic rocks are the dominant rock type, whereas tholeiitic rocks are minor in abundance and mostly differentiated [*Bailey et al.*, 1924]. This observation led to the hypothesis that alkaline magmas were primary and mantle-derived, and the later tholeiitic lavas were formed as a result of contamination of alkaline magmas by continental crust (siliceous metamorphic rocks and granites [*McBirney*, 1993]). Debate on this issue raged until *Lacroix* [1928] reported that the huge shield volcanoes in Hawai‘i are made of tholeiitic lavas with only minor alkalic lavas, and no continental crust is available for contamination to form tholeiitic lavas. This story was refined by *Macdonald* [1963] based on extensive field studies and collaboration with T. Katsura for geochemical work [e.g., *Macdonald and Katsura*, 1964]. They showed that on the subaerial Hawaiian shield volcanoes, alkalic lavas were found only as late-stage caps, typically comprising ~1 vol% of the volcano, with the bulk of the volcano being tholeiitic [*Macdonald and Abbott*, 1977]. Laboratory work that used observations from Hawai‘i showed that both types of magma can be primary and that depth and extent of melting are the determining variables in controlling whether alkalic (deep and low degree of melting) or tholeiitic magma (shallower and higher degree of melting) is produced [e.g., *Green and Ringwood*, 1967].

The Hawaiian magma evolution story changed dramatically with the discovery of an active volcano south of the Island of Hawai‘i (Lō‘ihi; Figure 1.3), which is told in more detail below (Section 1.3.3.1). Lō‘ihi was found to have both tholeiitic and alkalic lavas [*Moore et al.*, 1982]. Detailed sampling via submersible led to the recognition that the tholeiites form only a thin veneer overlying a base of weakly to strongly alkalic lavas (see summary by *Garcia et al.* [2006a] and references cited therein). This critical observation led to a petrogenetic melting model for Hawaiian volcanoes [*Frey et al.*, 1990]. This model, revised with new ages and volumes (Figure 1.4), is consistent with numerical modeling studies of Hawaiian volcanoes [e.g., *Ribe and Christensen*, 1999]. It provides a context for explaining the observed variations in rock type during the growth of Hawaiian volcanoes. The model is simplistic and does not account for large, short-term variations in magma supply rate (e.g., an order of magnitude for historical Kīlauea [*Pietruszka and Garcia*, 1999]). Low magma supply and infrequent eruption at the initial and end stages of growth of Hawaiian volcanoes are correlated with low degrees of melting and eruption of alkaline lavas. Higher magma supply and more frequent eruptions occur when the volcano is centered over the hotspot and tholeiitic lavas are erupted, producing >90% of the volcano (Figure 1.4). This model was refined for the postshield stage using a combination of field work, theoretical petrology, and geochemistry by Fred Frey (with colleagues and students). They developed a conceptual model that related the reduced magma supply during the waning stages of volcanism to the eruption of nearly aphyric, differentiated lavas (hawaiite-trachyte). They hypothesized that the conduit supplying magma to the shallow reservoir system of the volcano solidified, leading to ponding of alkalic basaltic magma at or near the MOHO where it underwent crystal fractionation to produce lower density (buoyant) magma [*Frey et al.*, 1991]. The Hawaiian evolutionary growth model (Figure 1.4) has been used to explain magma-type variations on other oceanic islands, including the Canaries [*Hoernle and Schmincke*, 1993], Easter Island [*Haase et al.*, 1997], and Réunion [*Albarede et al.*, 1997], as well as continental basalt sequences around the world [e.g., *Xing et al.*, 2011; *Lease et al.*, 2008].

1.3.2. Noble Gases–Helium Isotopes

The study of noble gases has greatly enhanced our understanding of the chemical heterogeneity and structure of Earth’s mantle and the origin of Earth’s atmosphere [e.g., *Graham*, 2002; *Moreira*, 2013]. Noble gases have been inert to biological and chemical reactions during Earth’s history, making them superb tracers of mantle processes [e.g., *Moreira and Kurz*, 2013]. Ocean island basalts have played a key role in noble gas research because their lavas avoid the contaminating effects of continental crust, allowing them to serve as excellent windows into the mantle. The preferred sites for trapping

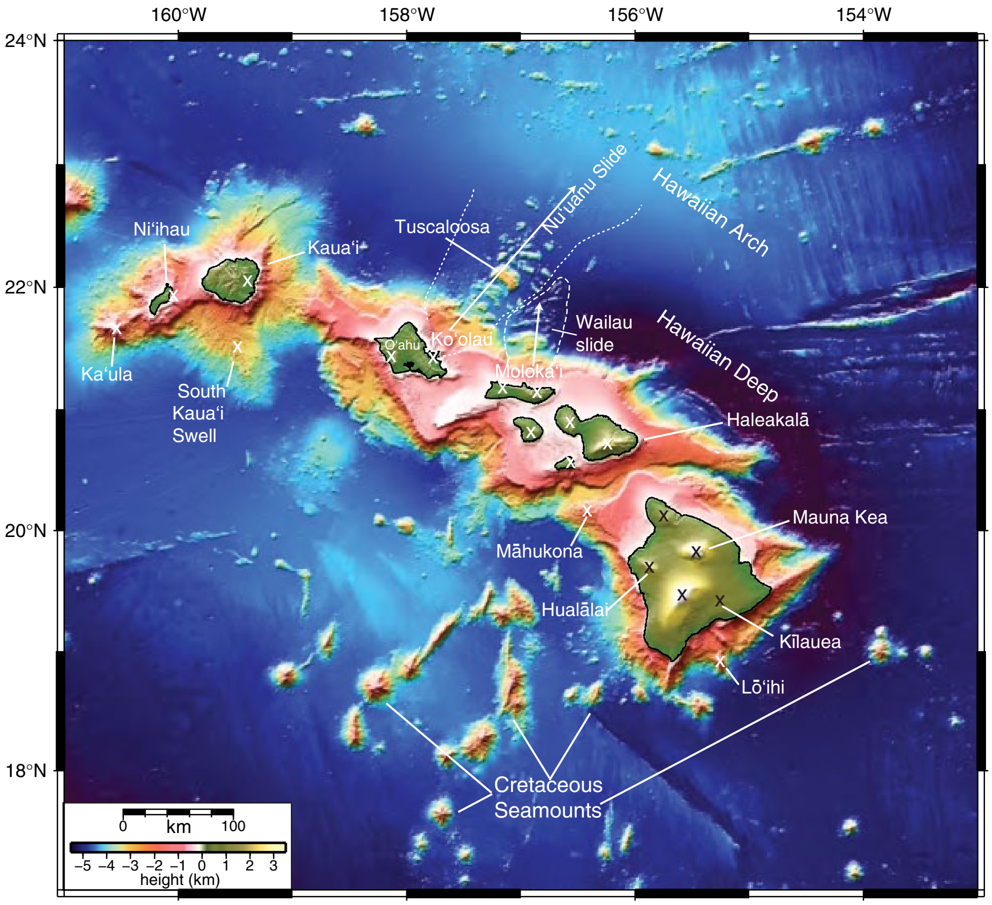

Figure 1.3 Bathymetric map of the Hawaiian Islands region with features discussed in the text labeled. Summits or centers of volcanoes are labeled with an "x." The Hawaiian Deep is the dark blue area surrounding the islands. The Hawaiian Swell is the light blue area to the north of the Deep. The base map was created by Garrett Ito and used by permission.

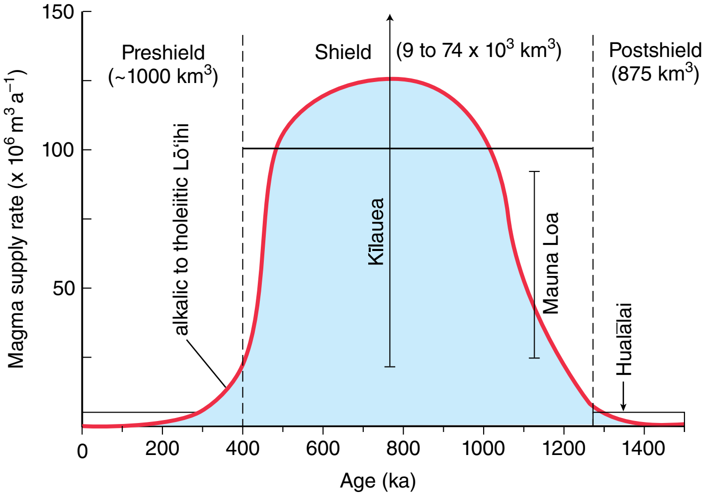

Figure 1.4 Growth history model for a Hawaiian shield volcano. This composite model is based on volume and age estimates for the preshield stage [*Garcia et al.*, 1995; *Guillou et al.*, 1997], shield [*Robinson and Eakins*, 2006; *Frey et al.*, 1990], and postshield [*Frey et al.*, 1990]. Magma supply rate estimates (vertical bars) are from *Pietruszka and Garcia* [1999] and *Poland et al.* [2012] for Kīlauea, *Wanless et al.* [2006] for Mauna Loa, and *Moore et al.*, [1987] for Hualalai.

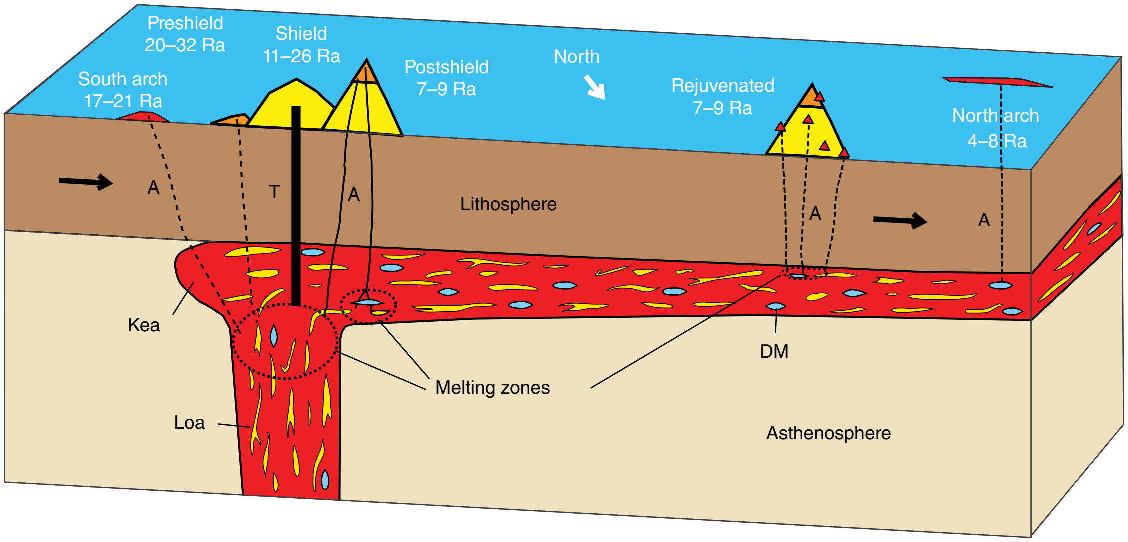

Figure 1.5 Schematic cross section of the Hawaiian mantle plume drawn through the Kea side of the Hawaiian Islands. The plume contains at least three distinct components: the plume matrix is considered the Kea component. The other two dominant components are the Loa (yellow blobs) and depleted mantle (DM, blue blobs). Overlying the schematic are He isotope values (^{3}He/^{4}He) given in Ra (atmospheric ratio). Arrows show direction of movement of the lithosphere. The South Arch alkaline lavas have relatively high ^{3}He/^{4}He values. Lōʻihi lavas have the highest ^{3}He/^{4}He values. Downstream from Lōʻihi, ^{3}He/^{4}He values decrease, becoming identical to those of mid-ocean ridge basalt (MORB) for the postshield and rejuvenated stages and the North Arch (A, alkalic, T, tholeiite). Schematic after *Garcia et al.* [2010].

noble gases within basalts are the glassy rinds of submarine lavas or melt inclusions in olivine and pyroxene phenocrysts [e.g., *Lupton*, 1983]. Among the noble gases, helium isotopes have received the most attention in the study of mantle heterogeneity because excess ^{3}He is an indicator of primitive mantle reservoirs and is ubiquitously present in oceanic lavas [*Graham*, 2002]. The other isotope of helium, ^{4}He, is mostly radiogenic in origin, produced primarily from the decay of U and Th. Helium has a short atmospheric residence time (~1 Myr) and is thought to be lost from the slab prior to subduction [*Lupton*, 1983]. Thus, its concentration is lowered but the ^{3}He/^{4}He ratio of the mantle is not substantially changed by subduction [*Gonnermann and Mukhopadhyay*, 2009].

A wealth of He isotope data has been collected over the last 35 years from ocean island basalts since the discovery of elevated ^{3}He/^{4}He ratios in midocean ridge and back-arc basin basalts (9–12 times the atmospheric ratio, Ra [*Krylov et al.*, 1974; *Lupton and Craig*, 1975]). The first indication that Hawaiian magmas have higher ^{3}He/^{4}He ratios than midocean ridge basalt came from analysis of fumarole gas from Kīlauea, which yielded a ^{3}He/^{4}He ratio of 15 Ra [*Craig and Lupton*, 1976]. The early noble gas studies on Hawaiian rocks examined phenocrysts in lavas from Kīlauea and Haleakalā volcanoes and mantle xenoliths from Salt Lake Crater on Oʻahu and Hualālai volcano [e.g., *Kaneoka and Takaoka*, 1978; 1980; *Kyser and Rison*, 1982]. They found elevated ^{3}He/^{4}He ratios in the lavas, which implies a primitive source for Hawaiian magmas, and that the xenoliths were not genetically related to Hawaiian tholeiites.

The discovery and sampling of Lōʻihi Seamount led to a frenzy of noble gas work on Hawaiian rocks after the first reported helium measurements revealed very high ^{3}He/^{4}He ratios (up to 32 Ra [*Kurz et al.*, 1982]). Subsequent studies of Lōʻihi samples showed a wide range of ^{3}He/^{4}He ratios (20–32 Ra [*Kurz et al.*, 1983; *Kaneoka*, 1983; *Rison and Craig*, 1983]) with no apparent correlation with age (e.g., lavas from the 1996 Lōʻihi eruption yielded ^{3}He/^{4}He ratios of 26 Ra, midway in the range [*Garcia et al.*, 1998]). The wide range in ^{3}He/^{4}He ratios showed that the Lōʻihi's source is heterogeneous, which is consistent with results for other radiogenic isotopes [*Garcia et al.*, 2006a]. Studies of older Hawaiian volcanoes generally yielded lower ratios (mostly <26 Ra) and an overall trend of decreasing ^{3}He/^{4}He ratios with decreasing age during shield and continuing into postshield volcanism [e.g., *Kurz et al.*, 1987, 1995, 2004] (Figure 1.5). The postshield transitional lavas from Māhukona are an exception to this temporal trend, with their relatively high ^{3}He/^{4}He ratios (16–21 Ra) and Lōʻihi-like Pb isotope ratios. These ^{3}He/^{4}He high ratios were interpreted to indicate a Lōʻihi source component for some Māhukona rocks [*Garcia et al.*, 2012].

Basalts from many other oceanic islands also show elevated ^{3}He/^{4}He ratios (>15 Ra; Samoa, Galápagos, Juan Fernandez, Pitcairn, Society Islands, Azores [see references in *Hofmann et al.*, 2011]). These results indicate that the mantle source regions for these hotspot-related lavas are deeper, more isolated, and less degassed and have lower time-integrated (U + Th)/^{3}He ratios than the source for midocean ridge basalts [*Graham*, 2002]. Globally, the highest and most primitive ^{3}He/^{4}He ratios (>30 Ra) are found only in Lō'ihi and Icelandic plume-derived basalts [*Kurz et al.*, 1982; *Stuart et al.*, 2003]. The helium isotope results for Hawaiian basalts led to the two-layer mantle hypothesis [*Allègre*, 1987], which, with some modifications, is still widely accepted among geoscientists. This hypothesis advocates that the source for Hawaiian and other mantle-plume-related basalts arises from the base of a layered lower mantle, perhaps near the core/mantle boundary or from the 670 km discontinuity [e.g., *Kurz et al.*, 1982; *Kaneoka*, 1983; *Allegre and Moreira*, 2004]. The helium isotope results, which advocated a deep mantle source for Hawaiian basalts, spurred seismologists to look for and find seismic evidence of a deep plume under Hawai'i [e.g., *Wolfe et al.*, 2009].

Another surprising discovery was the presence of relatively high ^{3}He/^{4}He ratios (17 and 21 Ra) in alkali lavas from the South Arch volcanic field upstream from the Hawaiian plume [*Hanyu et al.*, 2005]. In contrast, alkalic lavas from the postshield and rejuvenation stages of Hawaiian volcanism have values typical of MORB (7–9 Ra; Figure 1.5). These results and the previous work on shield tholeiitic lavas led to the realization that there is a strong asymmetry in the distribution of ^{3}He/^{4}He ratios in Hawaiian basalts, with lavas erupted ahead of the main shield phases of volcanism having consistently higher values (Figure 1.5). The Lō'ihi and South Arch samples also have high volatile contents (especially CO_2), which prompted the hypothesis that metasomatic fluids play an important role in carrying high ^{3}He/^{4}He fluids to the upstream side of the Hawaiian plume [*Dixon and Clague*, 2001; *Hanyu et al.*, 2005; *Hofmann et al.*, 2011]. These fluids are thought to form during incipient melting in the plume.

Science sometimes leaps forward from serendipitous events. The study of helium isotopes in Haleakalā lava and minerals is a fascinating example that ties in with Hawaiian mythology. Haleakalā is the Hawaiian "house of the sun." Early Hawaiians applied the name to the summit area of this volcano, where the demigod Maui snared the sun and forced it to slow its journey across the sky [*Westervelt*, 1910; *Pukui et al.*, 1974]. It is in this area where basalts yielded the highest ^{3}He/^{4}He values ever reported in Hawai'i (34–37 Ra). These values were assumed to be a primordial signature [*Kaneoka and Takaoka*, 1978]. Subsequent work on a suite of lavas drilled into outcrops at the summit of the volcano showed that the ^{3}He/^{4}He decreased with depth in the cores and that the heated olivine had higher ratios (especially at lower temperatures) than olivine crushed in vacuo (>60 vs. 8 Ra [*Kurz*, 1986; *Kurz et al.*, 1987]). These results were interpreted to indicate a cosmogenic rather than a primordial origin for the high ^{3}He/^{4}He ratios. Cosmic radiation effects are interpreted to have caused spallation reactions (on the major elements in the minerals) to form ^{3}He over hundreds of thousands of years [*Kurz*, 1986] in the cold arid climate (polar tundra zone) at the house of the sun, ~3050 m above sea level. Haleakalā was the first reported terrestrial occurrence of in situ cosmogenic helium and helped open the door to a new research field in rock exposure age dating [e.g., *Granger et al.*, 2013]. Being a stable nuclide with a high production rate in olivine and pyroxene [*Goehring et al.*, 2010], ^{3}He is the most commonly measured cosmogenic nuclide and has the potential to yield age information for surfaces up to millions of years old, provided erosion has not modified the surface [*Granger et al.*, 2013].

1.3.3. Marine Studies of Hawai'i

One of Earth's last frontiers is beneath its oceans, as witnessed by the discoveries that are continuing to be made during expeditions to the flanks and seafloor around the Hawaiian Islands (Figure 1.3). Thomas Jaggar was a visionary in advocating for marine research. Part of his rationale for construction of a new observatory in Hawai'i was its unique position in the central Pacific, making it favorable for the study of the deep-sea floor [*Jaggar*, 1913]. Jaggar was greatly influenced by the work of *Dana* [1890], which included one of the first bathymetric maps of the Pacific. Although based on very limited soundings by the U.S. Hydrographic Office, *Dana* [1890] showed the Hawaiian chain extended to Kure Island at ~29°N and that a depression surrounds and is within 65 km of the Hawaiian Islands (highlighted by the 3000 fathom contour on his map). Unlike other depressions in the North Pacific off Japan and the Aleutian Islands, the Hawaiian depression was interpreted by *Dana* [1890] as a possible consequence of gravitational pressure related to the nearby volcanoes with the amount of subsidence related to volcano size. Given the limited bathymetric data and geological knowledge at the time, it is amazing that Dana was able to define this feature, albeit crudely, and to offer a reasonable explanation for its origin. This depression is now called the Hawaiian Deep and it is paired with an arch. Both features are thought to be related to lithospheric flexure caused by the rapid and voluminous loading of the Pacific Plate by Hawaiian volcanism [e.g., *Jackson and Wright*, 1970; *Bianco et al.*, 2005]. The Hawaiian Arch is superimposed on the broader uplift (swell) related to the Hawaiian plume (Figure 1.3). The Hawaiian Islands are one of foremost locations to study the structure and dynamics of mantle plumes using features related to the swell. For example, ~200 km downstream from the vertical axis of the Hawaiian plume, swell topography was used to estimate the plume's excess temperature (400 K), radius

(50–70 km), and upper mantle viscosity (10^{20} and 3×10^{20} Pa s [*Zhong and Watts*, 2002]). The Hawaiian Swell has also been interpreted to be a result of crustal underplating by intrusion of Hawaiian magma, suggesting that the swell is partially supported by shallow chemical buoyancy [*Leahy et al.*, 2010].

Following the development of the echo sounding method in the 1920s and its use by the U.S. Navy to survey the oceans, a bathymetric map of the North Pacific basin was published illustrating the basic features of the Hawaiian chain [*U.S. Navy*, 1939]. A more detailed version of this map that focused on the flanks of the Hawaiian Islands was presented by *Stearns* [1946]. It included many interesting features that were not discussed, including the dramatic rift zones of Haleakalā, Kīlauea, and West Moloka‘i volcanoes and the submarine volcanoes Lō‘ihi and Māhukona on the south and northwest flanks of the Island of Hawai‘i. These features are evident on a current bathymetric map of the Hawaiian Islands (Figure 1.3). Lō‘ihi and Māhukona were “rediscovered” in the 1980s. For more on the history of marine expeditions in Hawaiian waters prior to 2000 (including the Gloria surveys that provided acoustic backscatter maps of the U.S. Exclusive Economic Zone 370 km offshore from Hawai‘i), see *Moore and Clague* [2002].

Many discoveries have been made on the flanks and seafloor surrounding the Hawaiian Islands. Two of these discoveries warrant special attention and are highlighted here: Lō‘ihi Seamount and the Nu‘uanu landslide (Figure 1.3). Lō‘ihi Seamount is thought to represent the youngest volcano in the Hawaiian chain (*Moore et al.*, 1982), whereas the Nu‘uanu landslide was a catastrophic debris avalanche that originated on the submarine flanks of Ko‘olau Volcano [*Moore*, 1964]. J. G. Moore was the lead author on both studies. He is a pioneer and the foremost expert on the marine geology of Hawaiian waters. Although his work started with and continued mapping granites in the Sierra Nevada Mountains of California [*Moore*, 2000], he has done more during the last 50 years to illuminate the marine geology of Hawai‘i than anyone else. His tenure at HVO as scientist-in-charge in 1962–1964 may have served as a springboard for his later marine studies.

1.3.3.1. Lō‘ihi Seamount

Located ~35 km south of the Island of Hawai‘i (Figure 1.3), Lō‘ihi first became a known bathymetric feature in 1940 on a U.S. Coast and Geodetic chart (no. 4115). No attention was drawn to the seamount until a large earthquake swarm occurred south of the Island of Hawai‘i in 1952. The initial thought was the swarm might be an active submarine volcano [*Macdonald*, 1952]. No tremor was recorded and the epicenter locations were aligned in an east-west band ~10 km north of Lō‘ihi [*Klein*, 1982]. These results led *Macdonald* [1952] to conclude that the swarm was related to faulting and not an active volcano. A bathymetric survey of the seafloor southeast of the Island of Hawai‘i in 1954 revealed more details about Lō‘ihi and four other seamounts, which were all given Hawaiian names [*Emery*, 1955]. Because of its elongate shape, the name Lō‘ihi (meaning “long” [*Puki and Elbert*, 1984]) was recommended by some Hawaiian scholars. Lō‘ihi is one of many seamounts surrounding the Hawaiian Islands (Figure 1.3). Rocks from some of these other seamounts were dated by K-Ar methods yielding Cretaceous ages [*Dymond and Windom*, 1968], which led to Lō‘ihi being considered as an “older volcanic feature” [*Moore and Fiske*, 1969].

Renewed interest in Lō‘ihi followed two earthquake swarms south of the Island of Hawai‘i in 1971–1972 and 1975. The swarms were interpreted to be related to volcanic activity, and the improved HVO seismic network placed the epicenters beneath Lō‘ihi Seamount [*Klein*, 1982]. This prompted a marine expedition to the seamount in 1978 to determine if it was an active volcano. Photographs of its summit area showed young-looking lavas. Subsequent dredging of Lō‘ihi obtained fresh, glassy lavas [*Moore et al.*, 1982]. These and other rock samples were extensively analyzed geochemically [see *Garcia et al.*, 2006a, for a summary]. The source for its lavas is now considered one of the end members for the geochemical variation in Hawaiian shield volcano lava for major elements and Pb isotopes [e.g., *Weis et al.*, 2011; *Jackson et al.*, 2012].

Many bathymetric surveys were made of Lō‘ihi to better understand its formation and to make comparisons after seismic and volcanic events. The height of Lō‘ihi is estimated to be ~3.5 km above its basement [*Garcia et al.*, 1995], making it comparable in height to Etna Volcano. Thus, Lō‘ihi is a respectable-sized volcano (by continental standards), although it is dwarfed by its larger neighbor Mauna Loa (~13 km tall). Two ~300 m deep pit craters were discovered at the summit of Lō‘ihi during early swath mapping surveys [*Malahoff et al.*, 1982; *Fornari et al.*, 1988]. The Alvin and Pisces V submersibles were used to collect samples in stratigraphic order from these pit craters and from the dissected east flank of Lō‘ihi, revealing that the volcano is dominantly alkalic with a thin veneer of tholeiitic lavas [*Garcia et al.*, 1995]. The alkalic lavas yielded unspiked K-Ar ages up to 102 ± 13 ka [*Guillou et al.*, 1997]. Reconstruction of Lō‘ihi’s history using these ages indicates it is considerably older than expected, possibly 400 ka (Figure 1.4). Another exciting discovery was the presence of excess ^{3}He, methane, and microorganisms in the water column above Lō‘ihi, suggesting that the volcano has hydrothermal activity [*Malahoff et al.*, 1982]. This was confirmed during Alvin dives in 1987, which found warm springs (15–30°C [*Karl et al.*, 1988]).

The largest swarm of earthquakes ever observed at a Hawaiian volcano occurred at Lō‘ihi Seamount in July

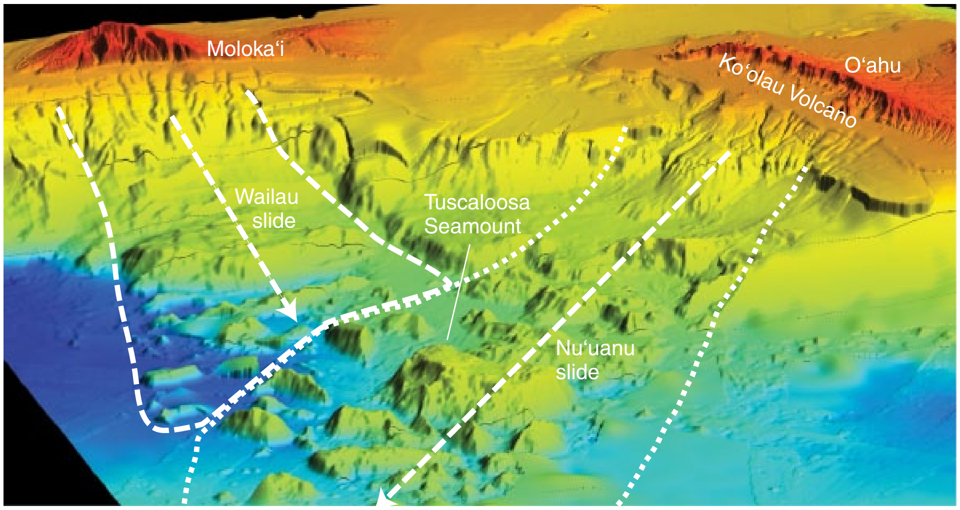

Figure 1.6 Shaded relief map showing a three-dimensional perspective view of the Nuʻuanu and Wailau landslide debris. White lines are the boundaries of the debris fields with arrows showing the direction of motion away from the flanks of shield volcanoes on Oʻahu and Molokaʻi. Map was constructed using the bathymetric data of *Smith et al.* [2002]. Figure created by Greg Moore and used by permission.

and early August 1996 [*Caplan-Auerbach and Duennebier*, 2001]. During or following the earthquake swarm, a new large summit pit crater similar in size to the two other Lōʻihi craters formed [*Lōʻihi Science Team*, 1997]. Intense hydrothermal plume activity was found in the water above the new crater [*Lōʻihi Science Team*, 1997]. Hydrothermal fluids from the vents had temperatures up to 200°C and contained polysulfide minerals (wurtzite, pyrrhotite, and chalcopyrite) signifying even higher fluid temperatures (>250°C [*Davis and Clague*, 1998]). Research is continuing on Lōʻihi to document the hydrothermal system and the associated biological communities.

Samples of shiny basalt collected after the earthquake swarm were dated using the short-lived isotope ^{210}Po (138 day half-life). Their ages indicate eruption during the first half of 1996, prior to the earthquake swarm [*Garcia et al.*, 1998]. Petrological studies of the new lavas suggest that they crystallized at moderate depths (8–9 km), which is about 1 km below the hypocenters for earthquakes from the 1996 swarm [*Garcia et al.*, 1998; *Caplan-Auerbach and Duennebier*, 2001]. Taken together, the petrological and seismic evidence imply that Lōʻihi's current magma chamber is considerably deeper (≥4 km) than the shallow magma reservoirs (2–4 km) associated with the nearby active shield volcanoes Kīlauea and Mauna Loa.

1.3.3.2. Nuʻuanu Landslide

High sea cliffs are common around the Hawaiian Islands (e.g., north coasts of Kauaʻi and East Molokaʻi). *Dana* [1890] proposed that these cliffs were the products of faulting. Others suggested that many of the cliffs were formed by marine erosion [*Hitchcock*, 1900; *Wentworth*, 1927] or the headwalls of giant landslides [*Stearns and Macdonald*, 1946]. The debate about these cliffs and the possibility they are related to landslides continued for decades. The Geological LOng-Range Incined Asdic (GLORIA) surveys (1986–89) documented the ubiquitous distribution of landslides surrounding the Hawaiian Islands [*Normark et al.*, 1993]. At least 68 major landslides (more than 20 km long) were recognized between Midway and the Island of Hawaiʻi [*Moore et al.*, 1994]). The largest is the Nuʻuanu slide off the northeast flank of Oʻahu [*Normark et al.*, 1993]. The full extent of the slide (Figure 1.6) was not appreciated until the detailed swath mapping by Japan Marine Science and Technology Center (JAMSTEC) during the cooperative Japan-U.S. program in 1998–1999. This survey covered an area of ~50,000 km^2 off the north flanks of the islands of Oʻahu and Molokaʻi [*Smith et al.*, 2002]. Both islands are sources of a major landslide (Figure 1.6). The JAMSTEC Hawaiʻi program included submersible diving to observe and collect samples from the blocks associated with the slides [*Yokose*, 2002]. The geochemistry of most samples collected from the Nuʻuanu slide debris is identical to the distinctive composition of lavas from Koʻolau volcano on the east side of Oʻahu (e.g., high SiO_2, low CaO and FeO), supporting the argument that Koʻolau was the main source of the blocks northeast of Oʻahu [*Shinozaki et al.*, 2002]. The lavas from blocks off the north coast of Molokaʻi (which are aligned parallel to the island) have compositions unlike that of Koʻolau and are thought to be part of the Wailau landslide from East Molokaʻi [*Shinozaki et al.*, 2002].

Four piston cores (each ~7 m long with one or more volcanic sand or silt layers) were taken during the JAMSTEC program with the goal of documenting the timing of the slides using paleomagnetics and paleontology. The volcanic sand layers are thought to be related to major landslides. One core was taken from the flat summit of Tuscaloosa Seamount, the largest block in the Nuʻuanu slide (30 km long, 17 km wide, and >2 km thick). The core has a >26 cm thick, black sand layer with glass compositions identical to those of East Molokaʻi lavas and unlike those of Koʻolau Volcano [*Sherman et al.*, 2002]. The sediments just above the sand yielded a fossil age of 1.77–2.0 Ma, which places a minimum age for both the older Nuʻuanu and younger Wailau slides [*Sherman et al.*, 2002]. Unfortunately, the JAMSTEC piston cores were unable to delineate the age of the Nuʻuanu slide.

Serendipity occurred during the planning for International Ocean Drilling Program (IODP) Leg 200, which was designed to develop an ocean floor observatory along a deep-sea cable between California and Hawaiʻi. Time (42 h) was allocated to drill up to 100 m into the sediments on the crest of the Hawaiian Arch (260 km from Oʻahu) to determine the depositional history, age, thickness of, and hazards associated with the Nuʻuanu slide. Unexpectedly, indurated sediments were encountered at ~13 m in the hole, slowing the drilling and resulting in only a 41 m deep hole. To our astonishment, eight distinct volcanic sand layers (the lower seven of which have glass with Koʻolau compositions) were recovered with mixed or Eocene radiolaria [*Garcia et al.*, 2006b]. Both features are common in deep-sea turbidite layers [*Garcia and Hull*, 1994]. The upper seven sand layers were probably deposited between 1.0 and 2.15 Ma based on paleomagnetics [*Garcia et al.*, 2006b]. The age of the lower sand, which is >5 m thick, is unknown. Four of the sand layers are >1.5 m thick. It is unclear which (if any) were related to the Nuʻuanu slide, given that many deeper turbidite layers were detected in seismic profiles across the arch [*Garcia et al.*, 2006b]. The identification of numerous turbidite layers in both the seismic profiles and piston cores indicates that debris from many landslides were able to travel >260 km from Oʻahu and climb up the 500 m high Hawaiian Arch to be deposited at this site. Thus, landslides from Hawaiian volcanoes are common and pose a more serious threat than previously assumed. How big is that threat?

The detailed JAMSTEC bathymetry map was used to estimate the Nuʻuanu landslide volume, to reconstruct Koʻolau volcano to its prelandslide size, and to evaluate the hazards associated with the landslide. The volume of the submarine portion of the slide is estimated at 2–3 × 10^3 km^3, making it one of the largest slides on Earth [*Satake et al.*, 2002]. The debris avalanche field is ~50 km wide and extends for ~150 km from Koʻolau (Figure 1.6). If the debris field was caused by a single landslide, modeling shows that the tsunami height it generated would have been >100 m along the north side of Oʻahu and Molokaʻi, up to 70 m along the southern California coast, where it was directed, and 10–40 m along the coasts of Oregon and Washington [*Satake et al.*, 2002]. Thus, Hawaiian landslides have the potential to be one of the largest natural disasters on Earth.

The documentation of giant landslides around the Hawaiian Islands resulted in the search for similar features around other oceanic islands. It was no surprise that large landslides were discovered around many other oceanic islands (e.g., Canary Islands, Cape Verde Islands, Réunion, Tristan da Cunha [*Holcomb and Searle*, 1991; *Masson et al.*, 2002; *Ancochea et al.*, 2010]). Large landslides around oceanic islands had been suspected for many decades where gaps were identified in the original shape of the islands [e.g., *Daly*, 1924; *Fairbridge*, 1950]. The availablilty of swath mapping to survey up to 10 km wide sections of the deep ocean floor made it possible to confirm the presence of the submarine landslides in various climates and tectonic settings [*Holcomb and Searle*, 1991]. These results indicate that many oceanic volcanoes have been substantially reduced in size by landslides and that significant risks are posed by these volcanoes. However, the frequency of such collapses on Hawaiian volcanoes seems to be low (1 per 20 ka [*Garcia et al.*, 2006b]) compared to the risks posed by other natural hazards (earthquakes, fires, and floods).

1.3.4. Dynamics and Emplacement of Lava Flows

Studies of Hawaiian volcanoes have been fundamental to our evolving understanding of the dynamics and emplacement of lavas flows. For example, the classic terms that are now universally used for describing two principal flow types are of Hawaiian origin. *Dutton* [1884] was the first to introduce to the geological community the terms “pāhoehoe” and “ʻaʻā,” which were used by Hawaiians to describe these two distinctive flow types. Although these terms were considered “barbarous” by some geologists at the time, they were quickly adopted by most geologists [*Macdonald*, 1972]. Pāhoehoe is characterized by a smooth, billowy, rolling, or ropey surface, whereas ʻaʻā has a rough, jagged, spinose, and clinkery surface. These two common flow types were studied extensively by *Macdonald* [1953, 1967], primarily using Hawaiian examples. He noted that both viscosity and the amount of internal disturbance owing to flowage were critical in determining flow type.

Macdonald’s work was extended by others using Hawaiian examples to better understand the internal mechanics of lava flows. *Peterson and Tilling* [1980] evaluated the causes for the transition of basaltic lava from pāhoehoe to ʻaʻā (e.g., volumetric flow rate, flow dimensions, slope, and momentum) as well as the internal mechanics within lava flows and how they create the observed flow features. *Peterson and Tilling* [1980] assumed that nearly all Hawaiian basaltic lava erupts as pāhoehoe. *Rowland and Walker* [1990] showed, using examples from recent Mauna Loa and Kīlauea eruptions, that the volumetric discharge rate plays a key control in determining flow type, with ʻaʻā forming when flow rates are higher than >5–10 m^3/s, whereas at lower rates pāhoehoe flows are erupted. The lavas from the ongoing eruption of Kīlauea demonstrate this effect beautifully. ʻAʻā was produced mostly during the high-fountaining, high-effusion-rate episodes at the Puʻu ʻŌʻō vent from 1983 to 1986, whereas pāhoehoe flows were prevalent from 1986 to 1992 during the low-effusion and low- to no-fountaining eruption at the Kupaianaha satellite vent [*Rowland and Walker*, 1990]. In most cases, discharge rate is primarily controlled by processes within the volcano (e.g., relaxation of a stressed, shallow magma chamber and degassing [*Rowland and Walker*, 1990]). Through extensive field work, George Walker and his students documented the varieties of pāhoehoe flow types [pipe-vesicle bearing (P type), spongy (S type) and toothpaste], the distribution of crystals within flows, and their internal and external flow structures [e.g., *Walker*, 1987, 1989; *Rowland and Walker*, 1987, 1988; *Wilmouth and Walker*, 1993]. These studies led to better understanding of the controls of viscosity on lava flow dynamics and processes of degassing.

Studies of Kīlauea lavas were pivotal in the recognition of the importance of inflation to the emplacement of pāhoehoe sheet flows. Sheet flows, which are a major crust-forming component in flood basalts, continental rifts, and along fast-spreading midocean ridges [e.g., *Ballard et al.*, 1979; *Macdonald et al.*, 1989; *Tolan et al.*, 1989], are emplaced without channels. *Macdonald* [1953] was probably the first to apply the term "inflation" to pāhoehoe flow growth for features he observed in Hawaiian lavas. The concept was more fully documented by *Walker* [1991] in describing historical lavas within Kīlauea Caldera. *Hon et al.* [1994] quantified the effects of inflation while monitoring Kīlauea's active flow field, showing that a 20 cm thick flow lobe was able to expand into a many meter thick sheet over a period of weeks. This concept of slow but relentless growth was applied to continental flood basalt provinces to radically change ideas for the method and timing of flood basalt emplacement. *Self et al.* [1996, 1998], *Thordarson and Self* [1998], and *Vye-Brown et al.* [2013] proposed that inflation of these voluminous flows [~1000 km^3] occurred over periods of decades, instead of days to weeks, as previously suggested, which reduces the potential environmental impact of flood basalt eruptions [*Self et al.*, 1998]. The inflation model has extraterrestrial applications in helping to explain emplacement of voluminous flows on Mars and Io [*Keszthelyi et al.*, 2000, 2006].

Lava flows present substantial hazards to communities around the world. Civil defense managers need to know how far a channelized lava flow can travel before it solidifies. Knowing the answer to this question is imperative for assessing the hazard during an eruption. The FLOWGO model was developed to answer this question. FLOWGO is a kinematic, self-adaptive, numerical model to describe the down-flow thermal and rheological evolution of channel-contained lava [*Harris and Rowland*, 2001]. It offers a means of analyzing lava flow thermo-rheological relationships; identifying important factors that determine how far a channel-fed flow can extend; assessing lava flow hazards; and reconstructing flow regimes for prehistoric, unobserved, or remote flows. FLOWGO considers flow velocities, widths, surface crust parameters, heat budget, cooling rate, absolute temperature, crystallinity, viscosity, and yield strength in assessing the distance a channelized lava flow will travel. The results of the model were field tested using Mauna Loa, Kīlauea, and Etna eruptions, where vent locations, eruption durations, effusion rates, and channel dimensions were known, achieving good results [*Harris and Rowland*, 2001]. The model was then applied to assessing the risk from future eruptions of Mauna Loa, a volcano that sent a flow into the city of Hilo (Figure 1.3) in 1881 and another that reached within 6 km of the city in 1984. The modeling results indicated that topography alone cannot be used to derive potential inundation distances from channel-fed flows [*Rowland et al.*, 2005]. For example, Hilo, which sits in a topographic low, is relatively safe from all but the highest effective-effusion rate channel-fed flows, especially if northeast rift eruptions continue to be produced from vents at elevations >2500 m. However, if a tube-fed eruption occurs, such as the one in 1881, the city will be threatened again. The FLOWGO model has been exported to other volcanic regions, including the Galápagos and Mt. Cameroon [*Rowland et al.*, 2003; *Wantim et al.*, 2013].

Lava from the 1984 eruption of Mauna Loa has been instrumental in understanding the effects of microphenocrysts on flow dynamics. During this eruption, the microphenocryst content of lava near the vent increased from 0.5 to 30 vol% without any concurrent change in either bulk magma composition or eruption temperature (1140 ± 3°C [*Lipman et al.*, 1985]). This change was attributed to undercooling of the magma by 20–30°C from degassing of volatiles [*Lipman et al.*, 1985]. The undercooling and crystallization increased the effective viscosity of the magma, which probably caused volumetric flow rates to decrease and led to stagnation of the flow [*Lipman et al.*, 1985]. The increase in crystallinity helped save the city of Hilo from being inundated by lava. These effects are broadly similar to those inferred to result from degassing during eruption and downslope flow of lava on Etna volcano [*Sparks and Pinkerton*, 1978]. The importance of microphenocrysts in controlling lava effective viscosity has been applied to understanding magma emplacement for a wide range of rock types in diverse settings, including Mount St. Helens dacite [*Cashman*, 1992], Inyo dome rhyolite [*Swanson et al.*, 1989], Mt. Etna basalt [*Armienti et al.*, 1994] and Mt. Fuji basalt [*Ishibashi*, 2009].

1.4. SUMMARY

Studies of Hawaiian volcanoes from their source to surface have been pivotal in our quest to better understand many Earth processes. Volcanologists from all over the world have been and are continuing to be attracted to Hawai‘i for research. The reasons for this attraction include the high frequency of eruptions, and year-round and easy access as well as Hawai‘i’s relatively uncomplicated geological setting in the center of the Pacific Plate. People are familiar with Hawai‘i because it is a favorite tourist destination. Thus, research done on Hawai‘i is of broad appeal. More importantly, a critical level of knowledge has been achieved about Hawaiian volcanoes since the founding of the HVO in 1912. Therefore, scientists are drawn to Hawai‘i to test hypotheses and to address fundamental issues about the way Earth works.

As a result of research on Hawai‘i over the last 100 years, tremendous progress has been made in our understanding of how magma is generated, what happens to it during ascent, and how it is transported on the surface as lava flows. The recognition that Hawai‘i’s giant shield volcanoes consist almost entirely (90%–95%) of tholeiitic lava reversed early notions that tholeiitic magma was formed by contamination of alkaline magma by continental crust. This recognition coupled with work on midocean ridge basalts led to a resurgence in experimental petrology that showed that the degree and depth of melting are critical for determining the composition of parental magmas (tholeiitic vs. alkaline). These results were combined with field and geochemical studies to place the evolution of Hawaiian volcanoes into a platetectonic framework. The discovery of excess ^{3}He in Hawaiian basalts unleashed an explosion of work on noble gases in oceanic basalts. Studies of noble gases in Hawaiian lavas led to the recognition of a distinct, relatively primitive, and undegassed reservoir deep within the mantle. These results prompted a revolution in models for the structure and heterogeneity of Earth’s mantle.

The underwater geology around the Hawaiian Islands has revealed many new insights into geological processes, as predicted by *Jaggar* [1913]. One example is Lō‘ihi Volcano, which was thought to be a Cretaceous seamount until two earthquake swarms in the 1970s led to marine expeditions that found fresh, glassy lavas and active hydrothermal springs. Lō‘ihi is now considered the youngest member of the Hawaiian-Emperor chain. In 1996, this infant volcano was the site of the largest earthquake swarm ever recorded on a Hawaiian volcano following a small eruption.

The enormous size, relatively steep submarine slopes, and rapid growth of Hawaiian volcanoes cause them to become gravitationally unstable and collapse. Dozens of giant landslides, some with debris extending more than 200 km from their source, have been recognized along the Hawaiian ridge and around other oceanic volcanoes. These landslides are thought to have produced colossal tsunamis. Thus, landslides from oceanic volcanoes pose a major risk to populations bordering Earth’s oceans. However, the frequency of these landslides appears to be low (at least in Hawai‘i) with a possible reoccurrence interval of every 20,000 yr.

Hawai‘i is the classic site for two characteristic lava types with Hawaiian names: ‘a‘ā and pāhoehoe. The frequent and changing styles of eruption of Mauna Loa and Kīlauea volcanoes have provided superb natural laboratories for evaluating the dynamics of lava flows and how they are emplaced. Extrusion rate is a dominant factor in determining whether ‘a‘ā or pāhoehoe flows are formed during a Hawaiian eruption. When pāhoehoe lava is erupted, the transition to ‘a‘ā is governed by volumetic flow rate, flow dimensions, slope, crystallinity, and momentum as well as the internal mechanics.

As shown by the excellent chapters on diverse topics in this monograph, much has been learned about the processes related to Hawaiian volcanism since the work of *Dana* [1890]. Nevertheless, after working on Hawaiian volcanism for the last 38 years, it has become apparent to me how little is really known about volcanoes. I have more questions now than when I started my research. Nevertheless, the next decade of study on Hawaiian volcanoes will be exciting as more interdisciplinary work is done and new techniques are developed to probe Earth’s interior leading to more discoveries. Regardless of any discoveries, we will continue to be in awe of the power and beauty of the fireworks from the Hawaiian volcano goddess Pele.

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