Characteristics of Hawaiian Volcanoes
Editors: Michael P. Poland, Taeko Jane Takahashi, and Claire M. Landowski
U.S. Geological Survey Professional Paper 1801, 2014

Chapter 3

Growth and Degradation of Hawaiian Volcanoes

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Abstract

The 19 known shield volcanoes of the main Hawaiian Islands—15 now emergent, 3 submerged, and 1 newly born and still submarine—lie at the southeast end of a long-lived hot spot chain. As the Pacific Plate of the Earth's lithosphere moves slowly northwestward over the Hawaiian hot spot, volcanoes are successively born above it, evolve as they drift away from it, and eventually die and subside beneath the ocean surface.

The massive outpouring of lava flows from Hawaiian volcanoes weighs upon the oceanic crust, depressing it by as much as 5 km along an axial Hawaiian Moat. The periphery of subsidence is marked by the surrounding Hawaiian Arch. Subsidence is ongoing throughout almost all of a volcano's life.

During its active life, an idealized Hawaiian volcano passes through four eruptive stages: preshield, shield, postshield, and rejuvenated. Though imperfectly named, these stages match our understanding of the growth history and compositional variation of the Hawaiian volcanoes; the stages reflect variations in the amount and rate of heat supplied to the lithosphere as it overrides the hot spot. Principal growth occurs in the first 1–2 million years as each volcano rises from the sea floor or submarine flank of an adjacent volcano. Volcanic extinction ensues as a volcano moves away from the hot spot.

Eruptive-stage boundaries are drawn somewhat arbitrarily because of their transitional nature. Preshield-stage lava is alkalic as a consequence of a nascent magma-transport system and less extensive melting at the periphery of the mantle plume fed by the hot spot. The shield stage is the most productive volcanically, and each Hawaiian volcano erupts an estimated 80–95 percent of its ultimate volume in tholeiitic lavas during this stage. Shield-stage volcanism marks the time when a volcano is near or above the hot spot and its magma supply system is robust. This most active stage may also be the peak time when giant landslides modify the flanks of the volcanoes, although such processes begin earlier and extend later in the life of the volcanoes.

Late-shield strata extend the silica range as alkali basalt and even hawaiite lava flows are sparsely interlayered with tholeiite at some volcanoes. Rare are more highly fractionated shield-stage lava flows, which may reach 68 weight percent SiO_2. Intervolcano compositional differences result mainly from variations in the part of the mantle plume sampled by magmatism and the distribution of magma sources within it.

Volcanism wanes gradually as Hawaiian volcanoes move away from the hot spot, passing from the shield stage into the postshield stage. Shallow magma reservoirs (1–7-km depth) of the shield-stage volcanoes cannot be sustained as magma supply lessens, but smaller reservoirs at 20–30-km depth persist. The rate of extrusion diminishes by a factor of 10 late in the shield stage, and the composition of erupted lava becomes more alkalic—albeit erratically—as the degree of melting diminishes. The variation makes this transition, from late shield to postshield, difficult to define rigorously. Of the volcanoes old enough to have seen this transition, eight have postshield strata sufficiently distinct and widespread to map separately. Only two, Koʻolau and Lānaʻi, lack rocks of postshield composition.

Five Hawaiian volcanoes have seen rejuvenated-stage volcanism following quiescent periods that ranged from 2.0 to less than 0.5 million years. The rejuvenated stage can be brief—only one or two eruptive episodes—or notably durable. That on Niʻihau lasted from 2.2 to 0.4 million years ago; on Kauaʻi, the stage has been ongoing since 3.5 million years ago. As transitions go, the rejuvenated stage may be thought of as the long tail of alkalic volcanism that begins in late-shield time and persists through the postshield (+rejuvenated-stage) era.

Because successive Hawaiian volcanoes erupt over long and overlapping spans of time, there is a wide range in the age of volcanism along the island chain, even though the age of Hawaiian shields is progressively younger to the southeast. For example, almost every island from Niʻihau to Hawaiʻi had an eruption in the time between 0.3 and 0.4 million years ago, even though only the Island of Hawaiʻi had active volcanoes in their shield stage during that time.

Once they have formed, Hawaiian volcanoes become subject to a spectrum of processes of degradation. Primary among these are subaerial erosion, landslides, and subsidence. The islands, especially those that grow high above sea level,

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experience mean annual precipitation that locally exceeds 9 m, leading to rapid erosion that can carve deep canyons in less than 1 million years.

Hawaiian volcanoes have also been modified by giant landslides. Seventeen discrete slides that formed in the past 5 m.y. have been identified around the main Hawaiian Islands, and fully 70 are known along the Hawaiian Ridge between Midway Islands and the Island of Hawai‘i. These giant landslides displace large amounts of seawater to generate catastrophic giant waves (megatsunami). The geologic evidence for megatsunami in the Hawaiian Islands includes chaotic coral and lava-clast breccia preserved as high as 155 m above sea level on Lāna‘i and Moloka‘i.

Large Hawaiian volcanoes can persist as islands through the rapid subsidence by building upward rapidly enough. But in the long run, subsidence, coupled with surface erosion, erases any volcanic remnant above sea level in about 15 m.y. One consequence of subsidence, in concert with eustatic changes in sea level, is the drowning of coral reefs that drape the submarine flanks of the actively subsiding volcanoes. At least six reefs northwest of the Island of Hawai‘i form a stairstep configuration, the oldest being deepest.

Introduction

Most volcanism on Earth is focused along the global network of tectonic plate boundaries, either at the midocean-ridge spreading axes or at volcanic arcs located above subduction zones. Other volcanism does occur in midplate locations and has been attributed to “hot spots” (Wilson, 1963) or mantle plumes (Morgan, 1972). A primary postulate

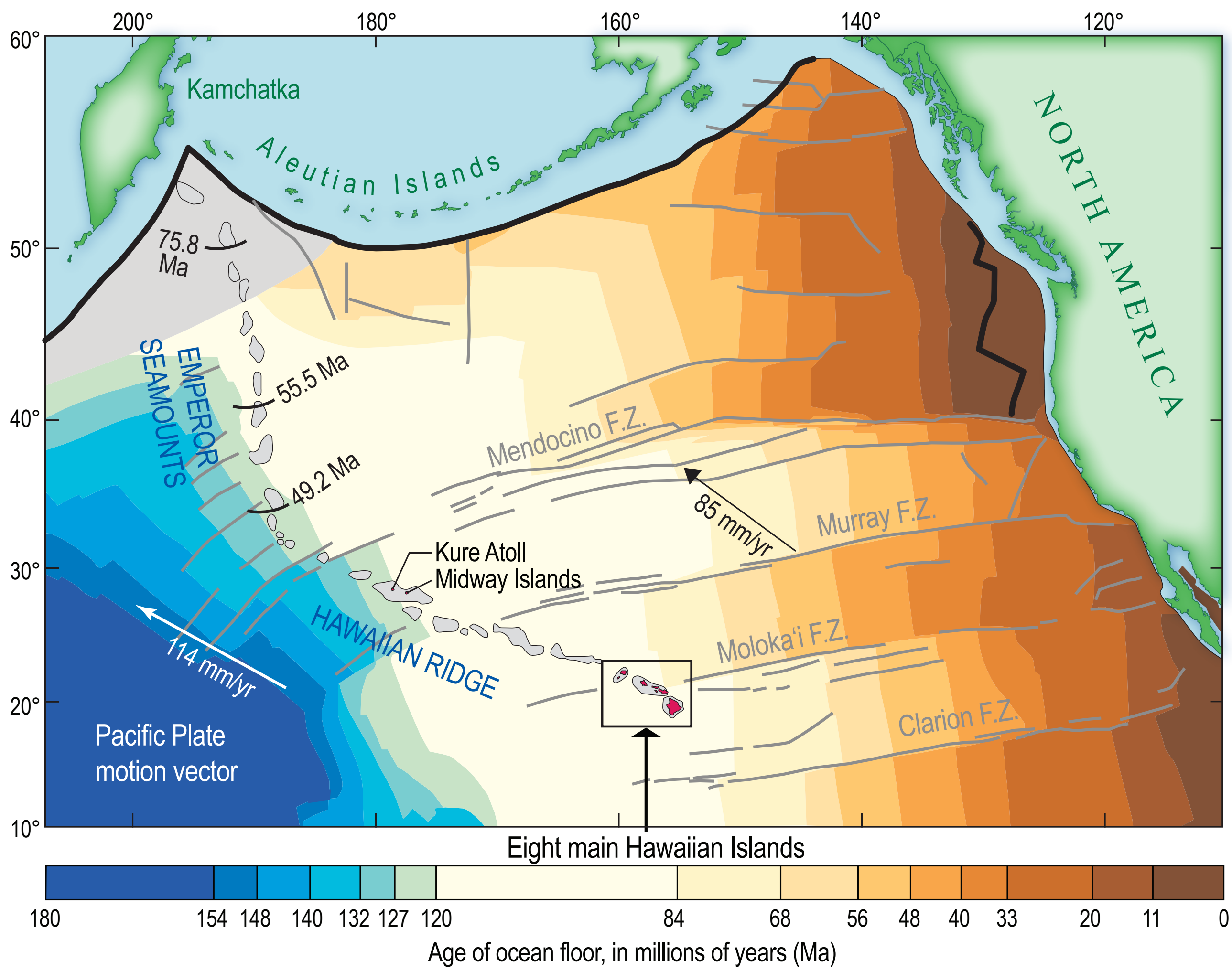


Figure 1. Map showing the Hawaiian Islands (red) and Hawaiian–Emperor volcanic chain, most of which consists of submarine seamounts, all depicted by their outlines at 2-km water depth (generalized from Clague and Dalrymple, 1987). Vectors indicate Pacific Plate motion relative to presumed fixed mantle hot spot in millimeters per year (mm/yr; from Simkin and others, 2006). Fracture zones (F.Z.) from Atwater and Severinghaus (1989). Isochrons along Emperor Seamounts chain show age of volcanism in millions of years (Ma; Duncan and Keller, 2004). Ocean floor age (Müller and others, 1997) from imagery available on EarthByte Web site (http://www.earthbyte.org/Resources/Agegrid/1997/digit_isochrons.html#anchorFTPa0). Mercator projection.

is that these commonly linear chains of midplate volcanoes form as the lithospheric plate migrates over a fixed or slowly moving magma source in the mantle. Of such chains, that which includes Hawai‘i is by far the longest lived and most voluminous example. This paper is an attempt to summarize the geologic history of these remarkable volcanoes, focused on the eight main Hawaiian Islands.

Geologic Setting

The Hawaiian Islands are formed by the youngest volcanoes in the chain comprising the Hawaiian Islands, the Hawaiian Ridge, and the Emperor Seamounts—an alignment of more than 129 volcanoes that stretches across more than 6,100 km of the North Pacific Ocean (fig. 1; Clague, 1996). This chain is the type example of an age-progressive, hot-spot-generated intraplate volcanic province (see, for example, Clague and Dalrymple, 1987; Duncan and Keller, 2004; Sharp and Clague, 2006), with the oldest volcanoes, about 81 Ma in age (Keller and others, 1995), located east of the Kamchatka Peninsula of northeastern Asia. A prominent bend in the chain, now dated as a gradual transition occurring from 55 to 45 Ma, is located more than 3,550 km west-northwest of Hawai‘i (Sharp and Clague, 2006). The Hawaiian-Emperor chain cuts obliquely across magnetic lineaments and fracture zones, for the most part without regard to preexisting structure of the oceanic crust (fig. 1; Clague and Dalrymple, 1987), although the Hawaiian Ridge is broader and higher near the chain’s intersections with the Moloka‘i and Murray Fracture Zones (Wessel, 1993).

The sizes and spacing of the volcanoes are nonuniform. Along the Hawaiian leg of the chain, the highest magma flux, as total crustal magmatism (probably including some small preexisting Cretaceous seamounts), peaked at 18 and 2 Ma (near 8 m^3/s), whereas the lowest flux (<4 m^3/s) was from about 48 to 25 Ma (Van Ark and Lin, 2004). The magma flux during formation of the entire Emperor chain was low ($<\sim4$ m^3/s), with the greatest flux at about 50 Ma. Only 24 of the entire chain’s volcanoes failed to breach sea level and become islands (as well as Lō‘ihi Seamount, which has not yet grown to sea level), but few islands were ever large or survived as high islands for more than 1–2 m.y. Only eight volcanoes northwest of the main islands grew to 1,500 m or more above sea level (Clague, 1996).

The volcanic chain represents an enormous outpouring of basaltic lava since 81 Ma. The volume of the main Hawaiian Islands, accounting for flexural depression of the crust, is nearly twice that calculated from bathymetry alone (Robinson and Eakins, 2006). Simply applying this correction to the entire chain yields a total volume of about 2×10^6 km^3, with about 25 percent erupted since 6 Ma to form the present Hawaiian Islands. This estimate roughly doubles an early estimate (Bargar and Jackson, 1974) that did not account for crustal flexure. Moreover, an average extrusion rate of 3.1 m^3/s (0.07 km^3/yr) for the 81-m.y. history of the entire Hawaiian-Emperor chain can be derived by graphically integrating the flux curve of Van Ark and Lin (2004). That rate suggests the magmatic volume of the chain is not twice, but closer to six times, that calculated from bathymetry alone.

Much of what we know about Hawaiian volcanoes is derived from studies conducted by scientists of the Hawaiian Volcano Observatory (HVO) on the active Kīlauea and Mauna Loa volcanoes. These studies, combined with early work by Harold Stearns and Gordon Macdonald at all the main Hawaiian Islands, provide the framework for understanding the growth and degradation of the older islands in the chain. The present review emphasizes results obtained during the past 25 years, the period since summaries were published on the occasion of HVO’s 75th anniversary (Decker and others, 1987).

Volcano Growth—A Brief History of Ideas on Eruptive Stages

An idealized model of Hawaiian volcano evolution involves four eruptive stages: preshield, shield, postshield, and rejuvenated stages (fig. 2; Stearns, 1946; Clague, 1987a; Clague and Dalrymple, 1987; Peterson and Moore, 1987). These stages likely reflect variation in the rate at which heat is supplied to the lithosphere as the Pacific Plate overrides the Hawaiian hot spot (see, for example, Moore and others, 1982; Wolfe and Morris, 1996a). Although five volcanoes of the main islands likely have all four stages present, none has products of all stages exposed, in part because preshield-stage lava is commonly buried but also because several of the volcanoes have not completed their eruptive development. Volcanic extinction follows as a volcano moves away from the hot spot. Dissection by large landslides may occur at any time in the growth or quiescence of a volcano, and subaerial erosion is ongoing whenever the volcano is emergent.

This synoptic view of volcano growth originated with Harold Stearns 70 years ago, long before the advent of plate tectonic theory (Stearns, 1946). Details have been added, subtracted, or rearranged as the timing of events has been better established, especially through studies of the submarine Lō‘ihi Seamount, the submarine flanks of the islands, and substantial mapping, radiometric dating, and geochemical analysis of the subaerial and submarine rocks that form the volcanoes.

For example, in Stearns’s original assessment, shield growth culminated in a caldera-forming stage, whereas now it is known that calderas can form and fill repeatedly during much of the history of the volcano. The shield stage itself was frequently subdivided to emphasize whether summit eruptions are occurring mainly in the submarine environment, at sea level, or almost entirely subaerially, owing to the tendency to discharge effusive or explosive eruptive products in the different settings (for example, Peterson and Moore, 1987). The capacity for groundwater-driven explosivity in the volcanic record is widespread until the summit grows above the main rain belt on the volcano

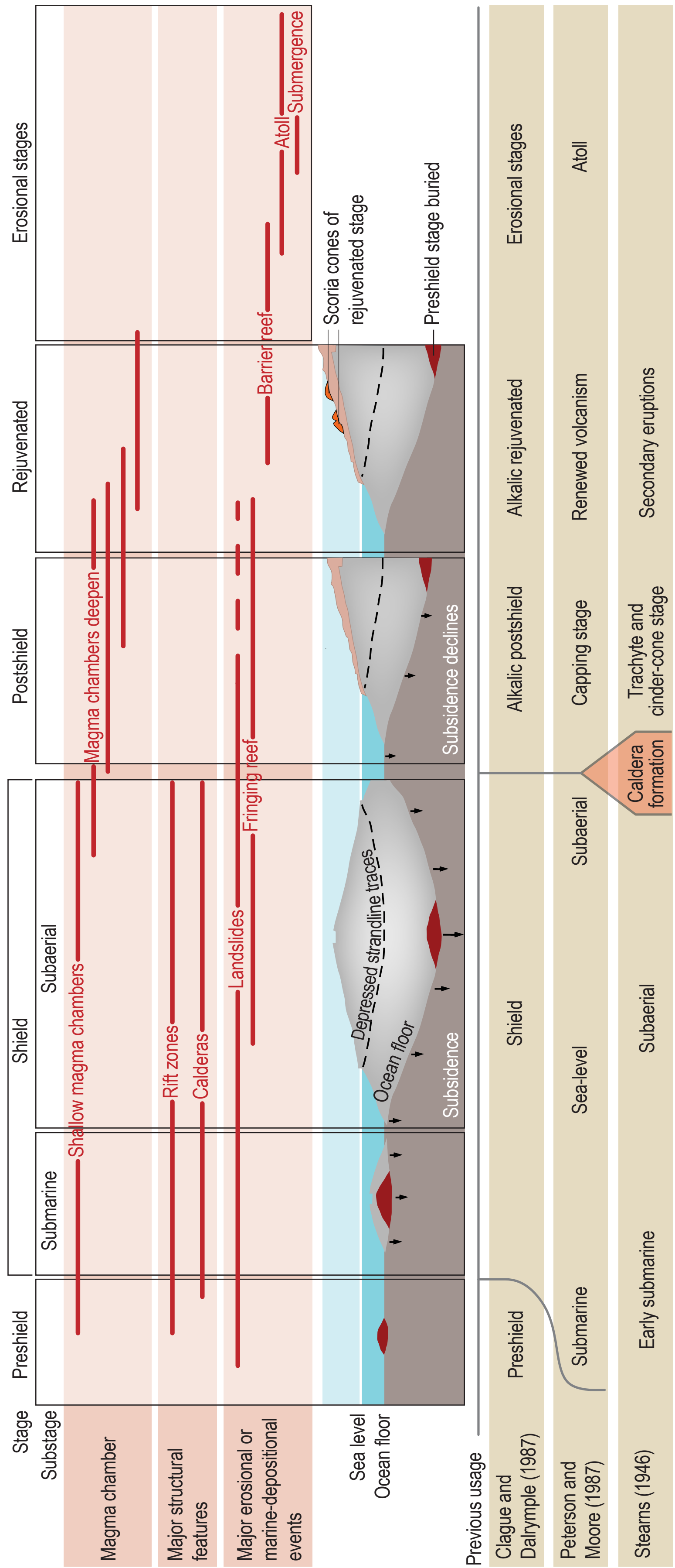


Figure 2. Diagram of the evolution of Hawaiian shield volcanoes as a sequence of generalized growth stages.

(Clague and Dixon, 2000). Such explosivity may persist regardless of a volcano's height, judging from explosion debris that mantles the northwest and southeast rims of the caldera atop 4,169-m-high Mauna Loa (Macdonald, 1971; Trusdell and Swannell, 2003). Groundwater perched in the dike swarms of the summit and upper rift zones may be the cause of these explosions.

The transitions from alkalic preshield to tholeiitic shield to alkalic postshield stage are commonly gradational if defined on the basis of chemical composition. For example, many of the Hawaiian volcanoes have interbedded alkalic and tholeiitic lava flows near the end of the shield stage, as they make the transition to the postshield stage (fig. 3). A similar chemical transition marks the earlier change from the preshield to the shield stage, at least at Lōʻihi volcano[3]. These stratigraphic complexities raise the question about how best to define the stage boundaries. Should the preshield stage end when the first tholeiitic shield lavas erupt or when the last of the preshield alkalic lavas erupt? Should the end of the shield stage be the youngest tholeiitic basalt or the oldest of the postshield alkalic lava? In this paper, we emphasize the gradational character of these stage boundaries at many volcanoes.

[3]Noncapitalized "volcano" is applied informally, whereas capitalization of "Volcano" indicates adoption of the word as part of the formal geographic name, as listed in the Geographic Names Information System, a database maintained by the U.S. Board on Geographic Names. Lōʻihi Seamount is the formal geographic name.

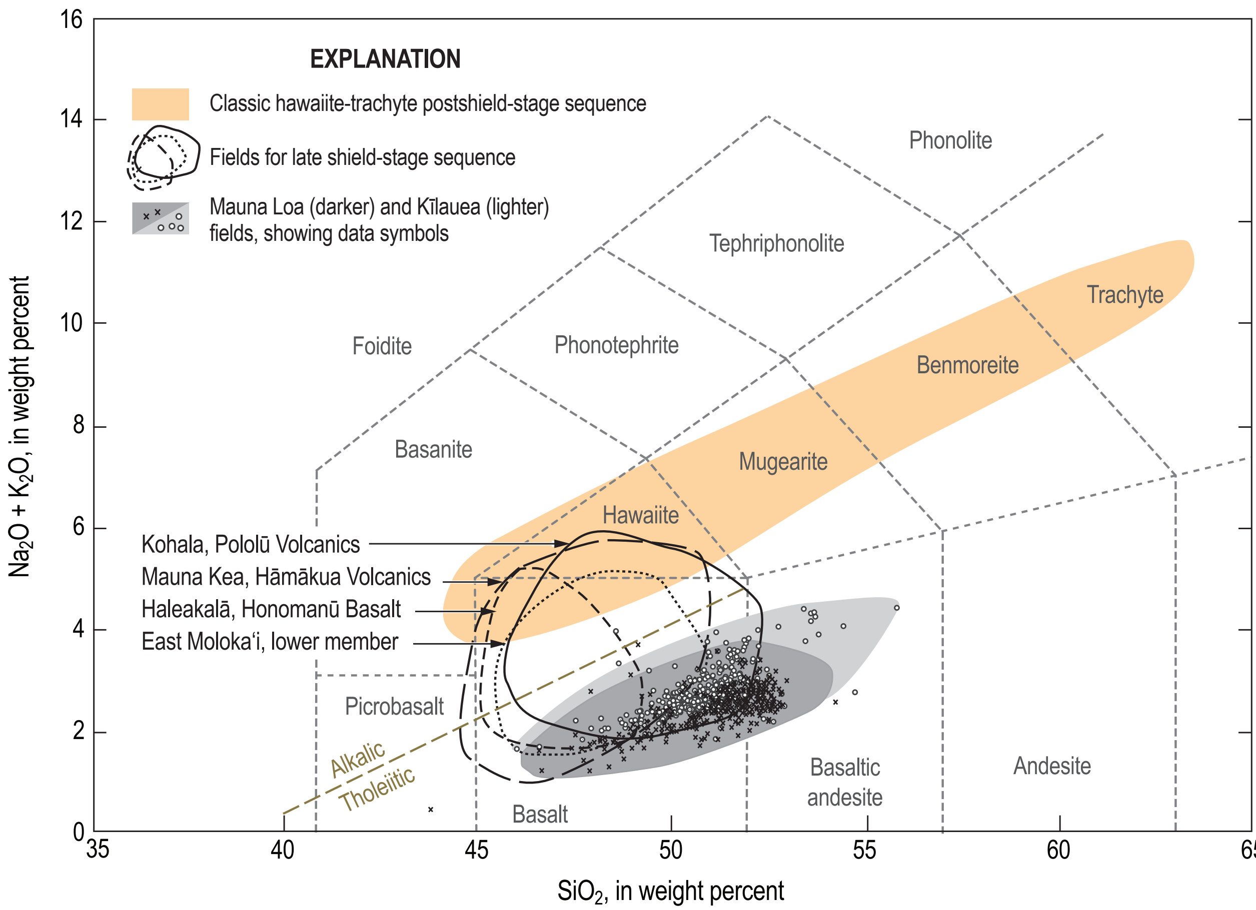


Figure 3. Alkali-silica diagram (Na_2O+K_2O versus SiO_2) composited from several Hawaiian volcanoes. Rock classification grid from Le Maitre (2002); shown dashed is boundary separating tholeiitic from alkalic basalt (Macdonald and Katsura, 1964). Data for Kīlauea and Mauna Loa from Wolfe and Morris (1996b); corresponding fields shown generalized to enclose all but a few outlying points. Bold black lines, variously solid, dashed, or dotted, indicate fields for increasingly alkalic late shield or transitional postshield basalt and minor hawaiite of Haleakalā, Mauna Kea, East Molokaʻi, and Kohala. Postshield lava is commonly even more alkalic, plotting in the field that ranges from hawaiite to trachyte, and encompasses all data from Waiʻanae (Pālehua Volcanics), Kohala (Hāwī Volcanics), and Mauna Kea (Laupāhoehoe Volcanics). The several exceptions to this fundamental pattern of increasingly alkalic composition across the late shield to postshield stages are discussed in the text. Listed in the appendix are the specific data sources for these many fields, on the basis of a published Hawaii-statewide whole-rock geochemistry GIS database (Sherrod and others, 2007).

The evolutionary stages, though rooted in geologic mapping, are an interpretation of stratigraphic sequences imposed after a geologic map is completed. In the submarine realm, the assignments necessarily rely on geomorphology and petrologic analysis of samples collected by remotely operated vehicles or manned submarines. The stage boundaries are somewhat arbitrary, because a volcano's evolution is commonly gradational. Two frequently controversial transitional periods are (1) the transition from shield to postshield stage and (2) the transition from postshield to rejuvenated stage.

Of some recent interest is the boundary between postshield- and rejuvenated-stage volcanism. An eruptive hiatus has long been inferred between the two stages, which suggests this boundary could be uniquely defined; indeed, the term "rejuvenated" arose to classify the subsequent reawakening of a volcano. Stearns (1946) referred to the rejuvenated stage as secondary volcanism, and Macdonald (1968) called it posterosional, a term that implied that substantial time was required to erode the large valleys later filled by the youngest volcanic rocks. But radiometric dating has shown that little, if any, time elapsed between emplacement of volcanic sequences once separated into postshield and rejuvenated stages at Waiʻanae (Oʻahu; Presley and others, 1997) or Haleakalā (Maui; Sherrod and others, 2003). All these alkalic lavas are now thought to be of the postshield stage. On Kauaʻi, age and chemical data (discussed in detail in the section titled "For Kauaʻi, Rejuvenated Stage is Gradational from Postshield Stage") suggest that the boundary between postshield and rejuvenated stages is gradational and that the eruptive hiatus once used to distinguish the two stages is lacking there.

We wrestled with introducing new names for the volcanic stages but decided it would only add confusion. Instead, the four stages are retained, but with emphasis on the transitional or gradational boundaries between sequential stages. As will be shown, these transitions vary from volcano to volcano. The evolutionary stage model of Hawaiian volcanoes remains a robust predictive tool for scientific exploration, but each volcano has peculiarities that temper the model's application.

Some objections persist in the choice of names. For example, the shield shape that inspired the name of the "shield" stage forms only during the subaerial phase of shield-stage growth, in contrast to steeper slopes built during the submarine phase of the shield stage. As used here, shield stage includes the entire period when voluminous tholeiitic lavas are erupted. The term "preshield" might be interpreted as encompassing volcanic growth from inception until the development of the subaerial shield shape, but we use the term to indicate only the early alkalic part of volcano growth. A similar objection might apply to the term "postshield," because postshield alkalic lavas simply veneer the shield and so maintain the volcano's shield shape. Regardless, we use postshield to describe alkalic lava that begins erupting at the end of the shield stage. The terms "rejuvenated," "post-erosional," or "secondary" all imply eruption following a time gap during which erosion took place. We now know that, at least on Kauaʻi, postshield-stage alkalic lava and strongly alkalic rejuvenated-stage lava erupted over a lengthy period that lacks major time gaps—the earliest rejuvenated-stage lava is similar in age to alkalic basalt, hawaiite, and mugearite of the postshield stage.

To be clear, the term "shield stage" (as a growth stage) should not be equated directly with the term "shield volcano," the term for any broad, typically large volcano. Hawaiian volcanoes have long been the archetypal shield volcano.

Brief geographic data for the 17 volcanoes encompassed by the main Hawaiian Islands are compiled in table 1. Fifteen of those volcanoes are emergent (above sea level), and two (Māhukona, Lōʻihi) are now fully submarine. Also included on the list are another two (or three) whose origin as discrete volcanoes remains uncertain. Latitude and longitude are taken from summit points for most of the volcanoes, although approximate caldera centers are included for Kīlauea, Mauna Loa, and Māhukona (from topographic maps).

Measuring the Growth of Hawaiian Volcanoes

The rate of growth of Hawaiian volcanoes is typically quantified in two ways. Volumetric rates (km^3/yr) have been described for volcanoes, such as Kīlauea, for which fairly precise eruptive volumes have been measured for periods of decades or centuries. Also, volumetric rates averaged over long time periods have been assigned to a few volcanoes where the bulk volume and a fairly good estimate of eruptive duration are known. Stratigraphic accumulation rates (m/k.y.) are determined by dating sequences of lava flows, either in natural exposures or from drill core, which can provide substantially thicker sections for sampling. Unlike volumetric rates, stratigraphic accumulation rates vary widely, simply because of differing geographic distances from a volcano's summit or rift zones, where volcanic accumulations are thickest.

Preshield Stage

The earliest growth stage of Hawaiian volcanoes was the latest to be discovered, because its products are deeply buried in older volcanoes, and substantial technological advances were required for sampling in deep water. The preshield stage, now known from Lōʻihi Seamount and Kīlauea, Kohala, and perhaps Hualālai volcanoes, appears to be entirely submarine and consists of tholeiitic, transitional, alkalic, and strongly alkalic lavas. Compositionally transitional volcanic rocks were once thought to represent a preshield stage at Māhukona volcano because of their high He isotopic ratios (Garcia and others, 1990), similar to that of Lōʻihi lavas, but these rocks are now known to be of postshield stage on the basis of radiometric ages of about 0.3 Ma (Clague and Calvert, 2009). Any preshield-stage strata at Māhukona are probably deeply

Table 1. Location and summit altitude of volcanoes from Niʻihau to Lōʻihi.

[Geographic coordinates referable to World Geodetic System 1984. Altitude is in meters and feet above mean sea level, as read from topographic maps; negative altitudes indicate bathymetric depth. Footnotes explain the variation between ours and other reported onland summit altitudes]

	Volcano	Longitude	Latitude	Summit	Feature name; topographic map or other reference
				Known volcanoes	
1	Niʻihau	–160.0834	21.9386	392 m; 1,286 ft[1]	Keanauhi Valley (1989, 1:24,000)[1]
2	Kauaʻi	–159.4974	22.0585	1,598 m; 5,243 ft	Kawaikini; Waiʻaleʻale (1983)
3	Waiʻanae (Oʻahu)	–158.1416	21.5072	1,227 m; 4,025 ft	Kaʻala; Haleʻiwa (1983)
4	Koʻolau (Oʻahu)	–157.7881	21.3581	960 m; 3,150 ft	North of Kōnāhuanui; Honolulu (1983)
5	West Molokaʻi	–157.1570	21.1422	421 m; 1,381 ft	Puu Nana; Molokaʻi Airport (1952, 1:24,000)
6	East Molokaʻi	–156.8684	21.1065	1,515 m; 4,970 ft[2]	Kamakou; Kamalo (1968)
7	Lānaʻi	–156.8731	20.8121	1,030 (+) m[3]; 3,379 ft	Lānaʻi South (1984, scale 1:25,000)[3]
8	Kahoʻolawe	–156.5715	20.5617	452 m; 1,483 ft	Spot elevation west of Puʻu ʻO Moaʻula Nui; Kahoʻolawe East (1991)
9	West Maui	–156.5863	20.8904	1,764 m; 5,788 ft	Puʻukukui; Lahaina (1992)[4]
10	Haleakalā	–156.2533	20.7097	3,055 m; 10,023 ft	Red Hill summit; Kilohana (1983)
11	Māhukona (submarine)	–156.1399	20.1315	–1,100 m; 3,610 ft	Clague and Moore (1991)
12	Kohala	–155.7171	20.0860	1,678 m; 5,505 ft[5]	Kaunu o Kaleihoʻohie; Waipio (1916)[5]
13	Mauna Kea	–155.4681	19.8206	4,205 m; 13,796 ft	Summit benchmark; Mauna Kea (1982)
14	Hualālai	–155.8644	19.6888	2,521 m; 8,271 ft	Summit benchmark HAINOA; Hualālai (1982)
15	Mauna Loa summit	–155.6054	19.4755	4,169 m; 13,679 ft	Benchmark TU0145; Mauna Loa (1981)
	Mauna Loa Caldera	–155.5920	19.4722		
16	Kīlauea summit	–155.2868	19.4209	1,269 m; 4,163 ft	Uēkahuna Bluff (benchmark TU2382)[6]
	Kīlauea Caldera	–155.2839	19.4064		
17	Lōʻihi	–155.2601	18.9201	–975 m; –3,199 ft	Fornari and others (1988); earlier reports cite slightly shallower summits, 969 m depth (Malahoff, 1987) and 950-m depth (Carson and Clague, 1995)
				Suspected volcanoes	
18	Southwest of Kaʻena Ridge (submarine)	–158.6490	21.7371		Eakins and others, 2003
	60 km WNW of Oʻahu; may be same location as site C1, above	–158.8526	21.6685	About –3,000 m	Eruption(?) 1956 C.E.; Macdonald (1959)
19	Penguin Bank(?) (submarine)	–157.6488	20.9722	–200 m	Carson and Clague (1995); Price and Elliott-Fisk (2004); Xu and others (2007a)

[1]Niʻihau: Highest point is at Pānīʻau benchmark (TU1870), 392 m orthometric altitude (local mean sea level). Previous version of the NGS data sheet reported 352 m, a typographical error corrected during the preparation of this table. A slightly lower altitude, 381 m, corresponds to the altitude of a spot elevation northwest of Kamahakahaka, elsewhere along the coastal bluff (State of Hawaii databook, http://hawaii.gov/dbedt/info/economic/databook/).

[2]East Molokaʻi: Summit of Kamakou on Kamalo quadrangle (1968) is marked at the junction of ahupuaʻa and appears to be highest point. A slightly lower spot elevation is located a distance of 100 m southeast on the Molokaʻi East quadrangle (1983).

[3]Lānaʻi: Summit point Lānaʻi hale has no surveyed benchmark but lies within (higher than) 1,030 m contour (Lānaʻi South, 1:25,000, 1984). Commonly cited is altitude 1,026 m (3,366 ft), a spot elevation at nearby Haʻalelepaʻakai (State of Hawaii databook).

[4]West Maui: 1992 topographic map has muddy printing of altitude annotations; the 5,788 ft-altitude of Puʻukukui resembles 6,788.

[5]Kohala, Hawaiʻi: Modern topographic maps do not show the summit altitude. A spot elevation 5,505 ft appears on Waipio topographic map (scale 1:62,500, surveyed 1911–1913 by R.B. Marshall, published 1916 and reprinted 1951). This altitude also appears in booklet "USGS index to topographic and other map coverage." No spot elevation is shown on the 1:250,000-scale island map or the 30 × 60-minute topographic map. The summit lies within (higher than) the 5,480-ft contour (40-ft contour interval; Kamuela topographic quadrangle, 1982), which is a commonly reported altitude slightly short of the summit.

[6]Kīlauea: Uēkahuna Bluff (benchmark TU2382) (Miklius and others, 1994).

buried. The transition from the preshield stage to the shield stage can be gradual with interbedded alkalic and tholeiitic lavas, as described below for Lōʻihi Seamount, or abrupt, as suggested by existing data at Kīlauea Volcano[4] (Calvert and Lanphere, 2006; Lipman and others, 2002, 2006).

Lōʻihi Preshield Stage

Lōʻihi Seamount, newest of the Hawaiian volcanoes, lies about 54 km south of Kīlauea Caldera and 975 m below sea level (fig. 4). Its summit is about 2.5 km above the adjacent sea floor. Lōʻihi has well-developed rift zones (Moore and others, 1982; Fornari and others, 1988) and a summit caldera complex (Malahoff, 1987; Clague, 2009) with three inset pit craters 0.6–1.2 km in diameter, similar in scale to Halemaʻumaʻu in Kīlauea's summit caldera. The southernmost pit crater formed in 1996 during a strong seismic swarm (Lōʻihi Science Team, 1997; Davis and Clague, 1998; Garcia and others, 1998; overview in Garcia and others, 2006). Also, the summit and flanks of Lōʻihi are scalloped by landslides (Fornari and others, 1988) that expose lava sequences on the upper east flank (Garcia and others, 1995). Thus, Lōʻihi demonstrates that the major structural features of Hawaiian volcanoes, such as calderas, rift zones, and flank failures, are well established during the preshield stage or in the transition to the shield stage.

Lōʻihi whole-rock analyses are chiefly tholeiitic and alkalic basalt with sparse picrobasalt, basanite, and hawaiite (fig. 5). Dredged submarine rocks at Lōʻihi show a compositional trend from alkalic to tholeiitic with diminishing age. It was recognized early on that the recovered alkalic lavas had thicker palagonite rinds than the tholeiitic lavas and were, therefore, likely older, on average (Moore and others, 1982). Recent work (Pauley and others, 2011) shows that alkalic glass alters more slowly than tholeiitic glass, so the alkalic glasses are even older, relative to the tholeiitic ones, than previously thought. Stratigraphic sections of lavas from two pit craters at Lōʻihi's summit (Garcia and others, 1993) and along a fault scarp on the east side of the summit (Garcia and others, 1995) show that, indeed, on average, the alkalic lavas are older than the tholeiitic lavas, albeit with considerable overlap. Interbedding of tholeiitic and alkalic glass fragments was also seen in an 11-m-thick section of volcaniclastic deposits emplaced during the last 5,900 years on the southeast part of the summit (Clague and others, 2003; Clague, 2009). Alkalic and tholeiitic lava flows exposed in the

[4]Of the large volcanoes among the Hawaiian Islands, only Kīlauea has the term "Volcano" as part of its formal geographic name and, hence, capital V (Geographic Names Information System, http://geonames.usgs.gov/).

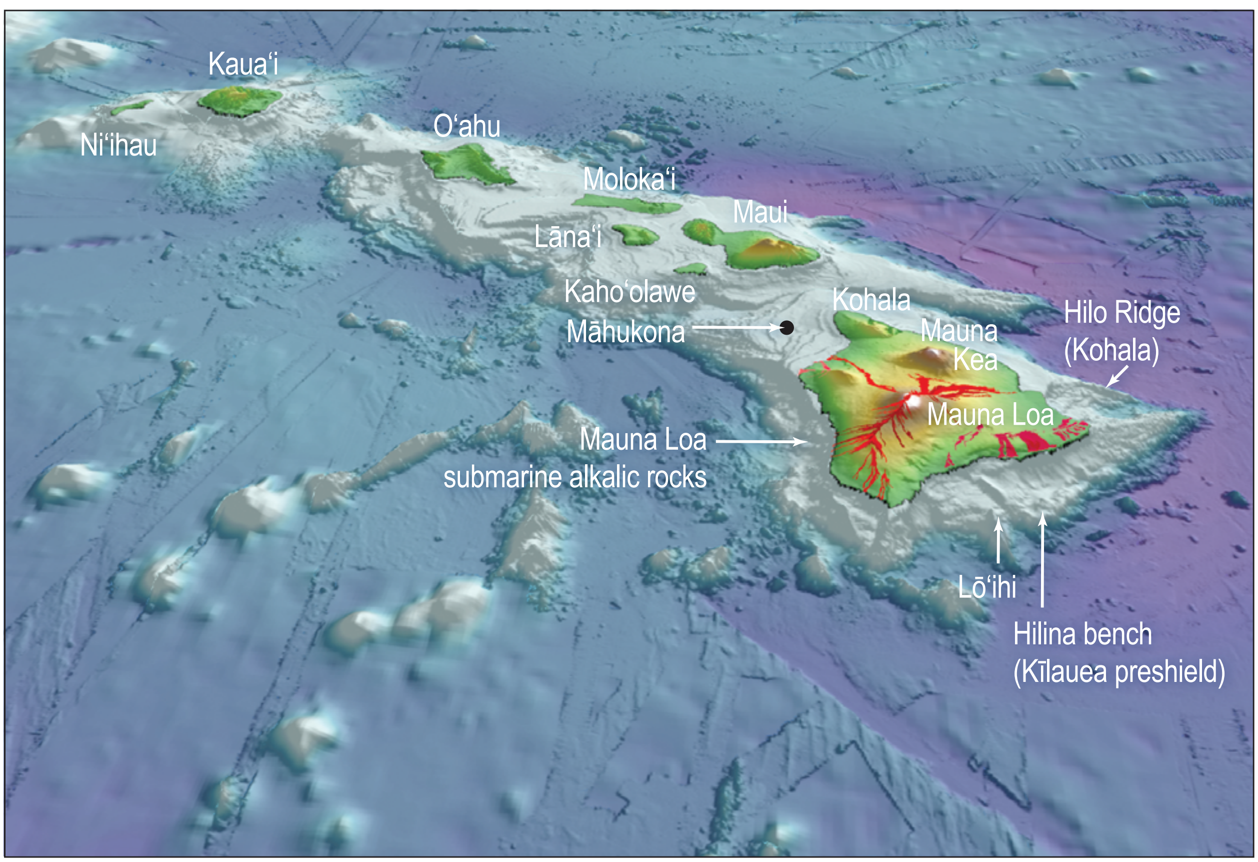


Figure 4. Diagrammatic illustration showing oblique aerial view of main Hawaiian Islands. Base illustration courtesy of J.E. Robinson.

walls of the summit pit craters are interbedded through a much thicker stratigraphic sequence, 300–370 m, and presumably represent a longer interval of time (Garcia and others, 1993). All these studies indicate that the compositional trend (older to younger) is alkalic to tholeiitic as the volcano evolves from the preshield to the shield stage.

Eruptions at Lō‘ihi's present summit (at 975-m water depth), and deeper along the volcano's upper rift zones have been both effusive (Moore and others, 1982; Malahoff, 1987; Umino and others, 2002) and explosive (Clague and others, 2003; Clague, 2009; Schipper and others, 2010a,b), suggesting that the early stage may include an early deep (chiefly?) effusive substage and a later explosive and effusive substage. The explosive alkalic eruptions, due to the high magmatic volatile content of the alkalic magmas, appear to be mainly from fountains (called poseidic eruptions by Schipper and others, 2010a, to distinguish the quenching of volcanic fragments in water from that in air) or from Strombolian activity (Clague and others, 2003).

Growth rates for Lō‘ihi can be estimated from a 500-m-thick section of lava flows on the volcano's east flank. Unspiked K-Ar dating yielded ages ranging from about 100 ka at the base to 5 ka at the top (Guillou and others, 1997a), suggesting an average lava accumulation rate for the preshield stage of about 5 m/k.y. (By way of contrast, shield stage rates are 6–16 m/k.y., discussed later.) The K-Ar data are vexing, however, because ages from two of the five dated samples are inconsistent with their stratigraphic position, so we view this accumulation rate cautiously. Radiocarbon dating from a foraminifera-bearing volcaniclastic section 11 m thick produced growth rates as high as 3.7 m/k.y. during a few millennia (Clague, 2009). Thus, available evidence suggests volcanic growth during the preshield stage and the earliest shield stage lags somewhat behind the robust upward growth during most of the shield stage. Lō‘ihi's volume now is roughly 1,700 km^3 (Robinson and Eakins, 2006), and most of it apparently formed during the preshield stage.

When will Lō‘ihi breach sea level? This question of simple curiosity can be answered only speculatively. The volcano may form an island in as little as 50,000 years from now (DePaolo and Stolper, 1996). However, with its summit 975 m below sea level and growth rate of 5 m/k.y., the island's birth year may lie as much as 200,000 years in the future.

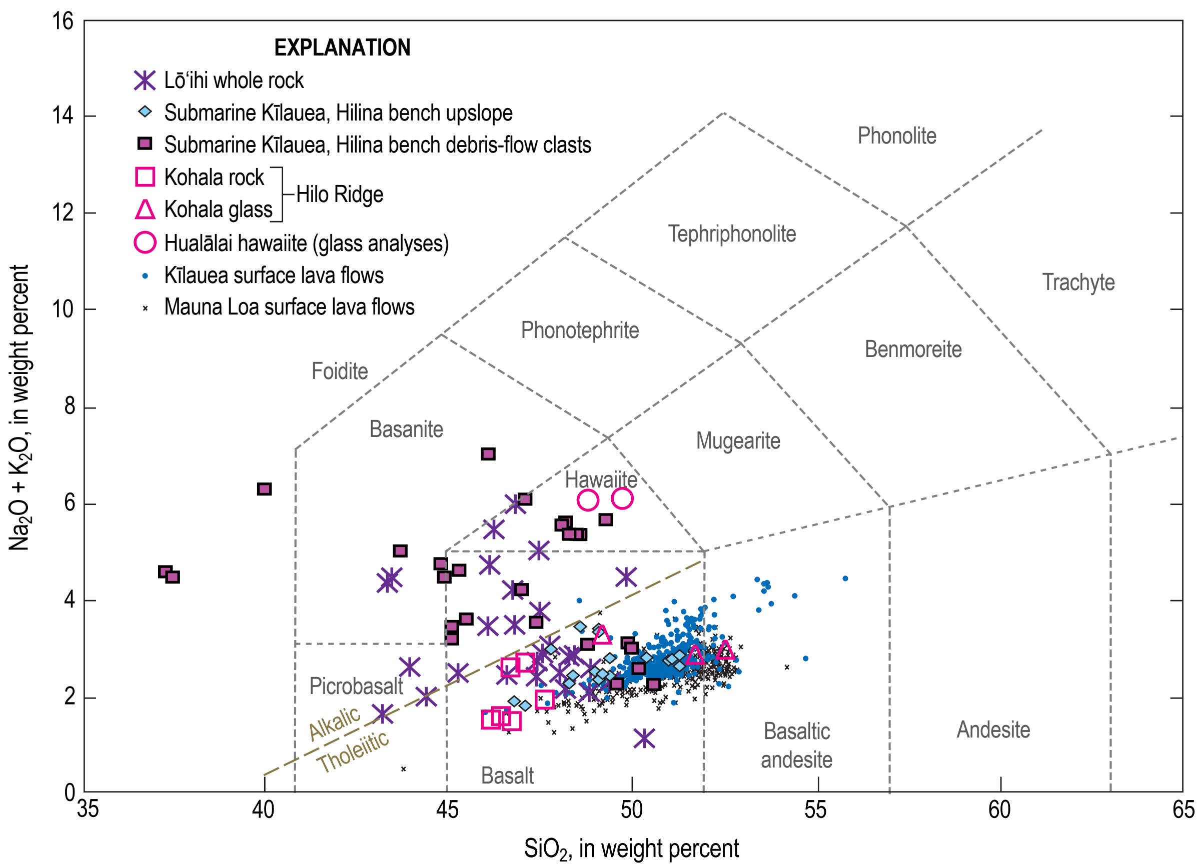


Figure 5. Alkali-silica diagram (Na_2O+K_2O versus SiO_2) for preshield Lō‘ihi and Kīlauea whole-rock analyses and selected glass analyses from Kohala and Hualālai. Rock classification grid from Le Maitre (2002); shown dashed is boundary separating tholeiitic from alkalic basalt (Macdonald and Katsura, 1964). Data from Frey and Clague (1983), Hawkins and Melchior (1983), Garcia and others (1995), Sisson and others (2002), Hammer and others (2006), and Lipman and Calvert (2011, their electronic data repository appendix DR1).

Kīlauea Preshield Stage

Kīlauea was born less than 300,000 years ago (Calvert and Lanphere, 2006). Its preshield-stage lavas range from strongly alkalic (including nephelinite) through alkalic basalt to transitional and tholeiitic (fig. 5; Lipman and others, 2002; Sisson and others, 2002; Coombs and others, 2006; Kimura and others, 2006; Lipman and others, 2006). Ages determined by $^{40}Ar/^{39}Ar$ dating (Calvert and Lanphere, 2006) on a few samples suggest that the transition from preshield to shield stage occurred about 150 ka, but the sampling is insufficient to determine the temporal span of the transition (as indicated by the stratigraphic expanse of interbedded alkalic and tholeiitic lava). Volatiles trapped in glasses show that the earliest strongly alkalic lavas at Kīlauea erupted subaerially or in shallow water, implying that Kīlauea forms only a thin skin on the flank of Mauna Loa (Coombs and others, 2006), an idea that originated with Stearns and Macdonald (1946, p. 131–136 and plate 1 cross sections) and was developed more thoroughly by Lipman and others (2006). In contrast to Lōʻihi Seamount lavas, which have a wide range of isotopic ratios and trace element characteristics (Frey and Clague, 1983; Staudigel and others, 1984; Garcia and others, 1993, 1995, 1998, 2006), Kīlauea preshield-stage lavas have more uniform isotopic ratios and are interpreted as having been derived from a more homogenous source by variable degrees of partial melting (Kimura and others, 2006).

Lipman and others (2006) estimate growth rates near the end of Kīlauea's preshield stage of 0.025 km^3/yr and a total volume of Kīlauea Volcano of 10,000 km^3, only 25–66 percent of previous estimates. Kīlauea's alkalic and strongly alkalic lavas have an estimated volume of 1,250 km^3, and the younger transitional basalts an additional 2,100 km^3, for a total preshield-stage volume of 3,350 km^3 preceding the transition to the shield stage (Lipman and others, 2006).

Kohala Preshield Stage

The Hilo Ridge (fig. 4) was long thought to be a rift zone of Mauna Kea volcano, but more recently Holcomb and others (2000) and Kauahikaua and others (2000) have shown that it is a rift zone of Kohala volcano. Lava samples collected from the distal Hilo Ridge have $^{40}Ar/^{39}Ar$ ages of about 1.1 Ma and are therefore older than any dated subaerial flows from Kohala (Lipman and Calvert, 2011). Compositionally they are tholeiitic basalt (fig. 5), although some of the chemical analyses plot close to the tholeiitic-alkalic boundary. These latter samples may indicate that lava of the preshield stage or earliest shield stage is exposed deep on the rift zone of Kohala volcano (Lipman and Calvert, 2011).

Hualālai Preshield Stage (?)

Hualālai volcano has a small sliver of alkalic lava exposed along a submarine ridge on its lowermost western flank that includes volcaniclastic rocks of hawaiite composition, which Hammer and others (2006) inferred to represent the alkalic preshield stage because of their stratigraphic position. Hammer and others (2006) also concluded that the preshield stage at Hualālai included a long time period with interbedded alkalic and tholeiitic lavas, similar to what was observed at Lōʻihi Seamount (Moore and others, 1982; Garcia and others, 1993, 1995; Clague and others, 2003). An alternate interpretation is that these alkalic lavas may instead have been erupted during the shield stage, as discussed in a later section ("Shield-Stage Alkalic Volcanism") or were perhaps emplaced by slumping of postshield-stage lavas (Lipman and Coombs, 2006). Submarine Kohala and Hualālai have not been sampled as extensively as Kīlauea or Lōʻihi, so alkalic preshield-stage lava exposed on them may be more abundant than our current collections indicate.

Shield Stage

All Hawaiian volcanoes have a shield stage during which voluminous eruptions of tholeiitic basalt dominate. The shield stage is the most productive volcanically, marking the time when a volcano is near the underlying hot spot and its magma system is robust. An estimated 80–95 percent of the volcano's ultimate volume is emplaced during this stage. The volumes of most volcanoes active since 6 Ma, from Niʻihau southeast to Lōʻihi, are compared in figure 6. The pāhoehoe and ʻaʻā lava flows of the ongoing eruption that began in 1983 along Kīlauea's East Rift Zone, 20 km from the volcano's summit, are characteristic of shield-stage volcanism in both style and composition.

The illustrative volume comparison uses the downward-revised estimate for Kīlauea's volume (Lipman and others, 2006), with the previously estimated volume shown dashed (Robinson and Eakins, 2006). Also shown dashed in figure 6 is the proportion that Kīlauea's loss would contribute to Mauna Loa's volume. That reassignment, however, may not be warranted, because the volumes of overlapping volcanoes are customarily calculated by assuming vertical boundaries separating each volcano (Robinson and Eakins, 2006). If accuracy is the goal, then a bolstered Mauna Loa volume (courtesy of Kīlauea's onlap) should be diminished accordingly by Mauna Loa's position upon the flanks of Hualālai and Mauna Kea, which precede it in the volcanic chain. Likewise, the recognition that Hilo Ridge is a Kohala rift zone would transfer some Mauna Kea volume to Kohala volcano (not shown in figure 6 except for the symbols for overestimate and underestimate that accompanied the tabular data of Robinson and Eakins, 2006). Revisions like these are a reminder that error estimates for large volcano volumes are rarely better than 30 percent and commonly worse.

Submerged Volcanoes

At least two, and possibly as many as four, volcanoes lie submerged off the coasts of the major Hawaiian islands (figs. 4, 7). From southeast to northwest, they are Lōʻihi, Māhukona, Penguin Bank, and an edifice on the southwest flank of Ka‘ena Ridge. Lō‘ihi is best known because of its sporadic seismic and eruptive activity; it is discussed more fully above, as a volcano in the preshield stage. The other three are introduced here. Of the four, only Lō‘ihi and Māhukona are widely known to be discrete Quaternary volcanoes, as opposed to rift zones of already known volcanoes.

Māhukona

Māhukona lies adjacent to the Island of Hawai‘i (fig. 7*A*). Its summit is at about 1,100-m water depth. A small, circular depression may mark a caldera (Clague and Moore, 1991). The submarine slope continues upward from there, owing to onlap by Hualālai and Kohala volcanoes. The age of Māhukona's inception is unknown but was likely about 1.5–1 Ma, on the basis of its present distance 140 km or so from the Hawaiian hot spot. Dredged samples suggest that Māhukona survived at least briefly as a subaerial volcano (Clague and Moore, 1991); sunken coral reefs form a stairstepping series of terraces, one of the most notable geomorphic features of the volcano today (fig. 7*A*).

Penguin Bank

Penguin Bank is the bathymetric shelf extending southwest from West Moloka‘i (fig. 7*B*). It may be a West Moloka‘i rift zone or it may be a separate volcano. In some reconstructions, Penguin Bank is the first of the several volcanoes that coalesced to form Maui Nui (Big Maui), a land mass once larger than the present-day Island of Hawai‘i (Price and Elliott-Fisk, 2004). Dredged samples from Penguin Bank are subtly distinct, geochemically, from West Moloka‘i lava (Xu and others, 2007a), which may further substantiate Penguin Bank as a separate volcano. Its summit location is chosen to coincide with a closed bathymetric contour more or less centered in the western part of the bank; a distinct bathymetric saddle separates the shallowest part of Penguin Bank from West Moloka‘i.

Southwest Flank of Ka‘ena Ridge

Ka‘ena Ridge is a submarine ridge extending northwest from the Island of O‘ahu (fig. 7*C*). Recently it was proposed to be a volcanic feature separate from Wai‘anae volcano (Tardona and others, 2011). Two topographically distinct shields (labeled 1, 2) form likely eruptive vents on the southwest flank of the ridge (Smith, 2002; Eakins and others, 2003). Whether either of these shields marks the summit of a separate volcano or whether they are, instead, related to a rift zone of Wai‘anae volcano remains to be resolved. The eastern shield, explored during a dive by remotely operated underwater vehicle in 2001, consists of ‘a‘ā lava flows and rounded beach cobbles of altered vesicular, tholeiitic basalt that was erupted and emplaced subaerially (Coombs and others, 2004). We indicate this eastern shield as the summit of a possible Ka‘ena volcano (fig. 7*C*), in part because the top of this shield is shallower than the one to the west, and because its location is nearer the shallow end of the Ka‘ena Ridge, which may be a rift zone extending from this summit.

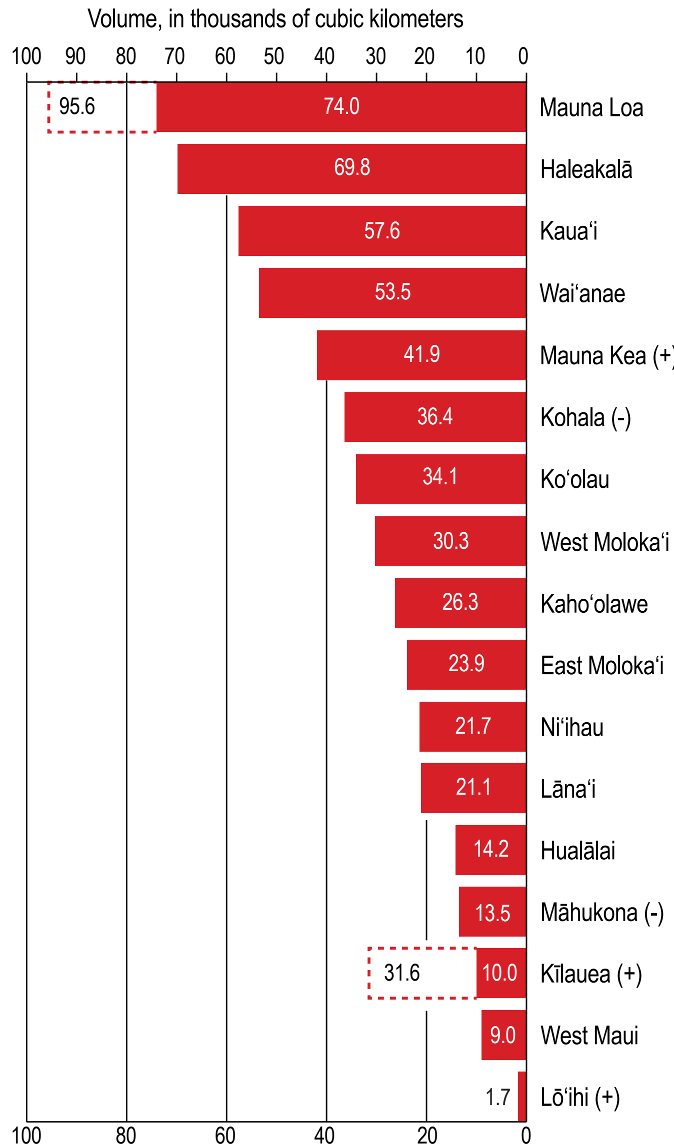


Figure 6. Bar graph of volcano volumes. Shown in order of decreasing volume, for all the volcanoes of the eight major Hawaiian Islands. Data from Robinson and Eakins (2006) except Kīlauea, whose volume is revised downward from their 31,600 km^3 (shown dashed) to 10,000 km^3 (Lipman and others, 2006). The volumetric difference, 21,600 km^3, is added to Mauna Loa's volume, increasing it to 95,600 km^3 (shown dashed). Symbols for likely overestimate (+) and underestimate (-) from Robinson and Eakins (2006). For the Mauna Kea-Kohala pair, the problem arises from the way in which the volcano boundaries partition Hilo Ridge, an offshore Kohala rift zone. For Kīlauea, the overestimate applies to the 31,600-km^3 volume.

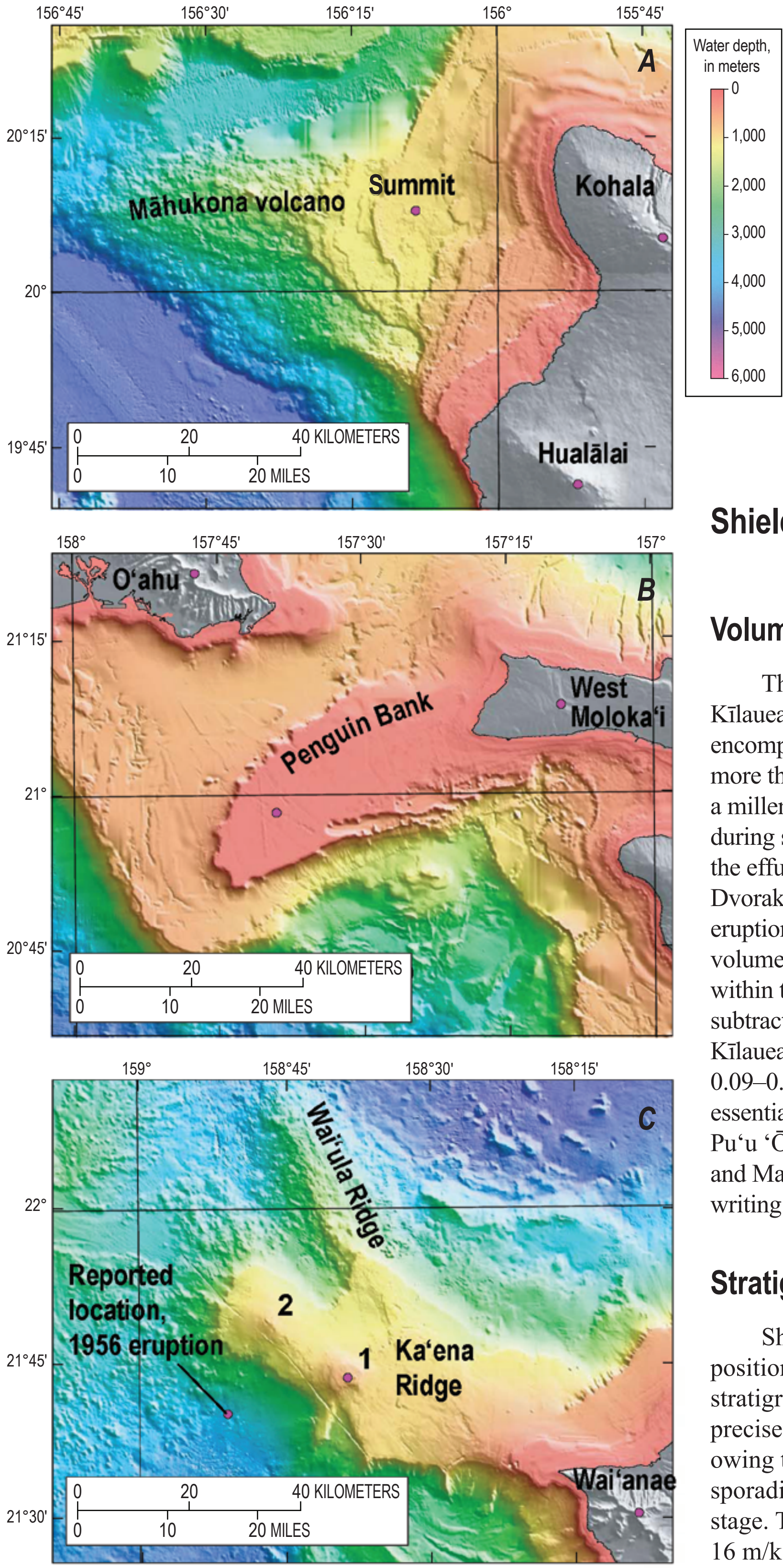


Figure 7. Maps showing bathymetry of submerged volcanoes and suspected volcanoes along the reach of the major Hawaiian Islands. Base is from Eakins and others (2003); geographic names from Coombs and others (2004). Summit locations are from table 1. *A*, Māhukona, a known shield volcano. *B*, Penguin Bank, a suspected volcano that may only be a rift zone of West Molokaʻi volcano. *C*, Kaʻena Ridge and topographic prominences (1, 2) on its southwest flank; the latter two features may form a shield volcano discrete from Kaʻena Ridge (rift zone of Waiʻanae volcano). See Macdonald (1959) for discussion of the suspected 1956 C.E. submarine eruption.

Shield Extrusion Rates

Volumetric Rate

The most precise volumetric rate analyses are for Kīlauea Volcano, where the scientific eruption record now encompasses 100 years, the written historical record is slightly more than twice that, and the oral history of eruptions spans a millennium. Basic to the method is the presumption that during sustained eruptions, in the absence of deformation, the effusion rate is the magma supply rate (Swanson, 1972; Dvorak and Dzurisin, 1993). If deformation accompanies an eruption, then the deformation data can be recalculated as volume change, corresponding to magma storage or discharge within the volcanic edifice; these changes are then added to or subtracted from erupted volume to calculate the throughput. At Kīlauea, the long-term eruption rate for the past 100–200 years, 0.09–0.11 km^3 of dense-rock-equivalent magma per year, is essentially the same as the long-term rate (0.12 km^3/yr) for the Puʻu ʻŌʻo eruption along Kīlauea's East Rift Zone (Heliker and Mattox, 2003), which began in 1983 and continues at this writing.

Stratigraphic Accumulation Rate

Shield accumulation rates are based on stratigraphic positions and ages of multiple samples. Knowledge of stratigraphic separation between samples is commonly precise, but ages of samples often have poor precision, owing to low potassium content, incipient alteration, and sporadic extraneous argon in the tholeiitic lava of the shield stage. The derived rates range from 1 m/k.y. to as much as 16 m/k.y., depending on the part of the stratigraphic sequence sampled and distance from eruptive vents. Lower rates are characteristic of late shield-stage growth far from vents.

Rates for Mauna Kea are calculated from dated core in the 2.7-km-deep Hawaii Deep Scientific Drilling (HDSD) holes (Sharp and others, 1996; Sharp and Renne, 2005). Representing Mauna Kea's mid-to-late shield-stage growth, the rates are as great as 8.6 m/k.y. low in the section, diminishing upsection to 0.9 m/k.y. in the upper 120 m (fig. 8; Sharp and Renne, 2005). The HDSD drill site is located 40–45 km from Mauna Kea's center, and the lower section may have erupted from Kohala along the Hilo Ridge. Decreased rates late in the shield stage, to about 1 m/k.y., are also seen in some dated sections from Wai‘anae (O‘ahu; Guillou and others, 2000), West Maui (Sherrod and others, 2007a), and Ko‘olau volcanoes (O‘ahu; fig. 8; Yamasaki and others, 2011).

Kīlauea data come from Scientific Observation Holes SOH-1 and SOH-4 (Trusdell and others, 1992, 1999), which penetrated about 1.7 km of lava flows along the axis of the East Rift Zone, at a location about as far from Kīlauea's summit as the HDSD site is from Mauna Kea's summit. These age-depth results have proven difficult to interpret. For example, a rate of 3–4 m/k.y. results from fitting a curve to the radiometric ages (Guillou and others, 1997b; Quane and others, 2000; Teanby and others, 2002), but this implies ages between 425 and 565 ka for the bottom of the drill hole, significantly older than dated submarine preshield alkalic rocks of Kīlauea (Calvert and Lanphere, 2006). A substantially higher rate, 16 m/k.y. during the past 45 k.y., was obtained by applying a model depth-age curve drawn from paleomagnetic inclination and intensity data for the upper 800 m of strata in SOH-1 (Teanby and others, 2002). The higher rate may be reasonable for some episodes of shield-stage growth along a rift zone axis but is too high to characterize durations of 100 k.y. or longer. Calvert and Lanphere (2006) similarly urged caution when interpreting the complicated argon geochronologic results from the SOH samples and the calculated accumulation rates.

Using surface exposures for Kīlauea, a rate of 6 m/k.y. is estimated from outcrops in Hilina Pali, where 275–300 m of strata are exposed. The age of those strata is known from radiocarbon ages of 28.3 and ~43 ka (D.A. Clague, quoted in Riley and others, 1999) and the likely occurrence of the Mono Lake (35 ka) and Laschamp (40 ka) geomagnetic excursions in lava flows of the Hilina section (data of Riley and others, 1999, interpreted by Teanby and others, 2002).

Shield-Stage Alkalic Volcanism

Rare submarine alkalic lavas from the base of the southeast flank of Kīlauea's Puna Ridge (Clague and others, 1995; Hanyu and others, 2005; Coombs and others, 2006) and from several cones on the west flank of Mauna Loa volcano (Wanless and others, 2006a) are apparently neither preshield nor postshield lavas, nor do they appear to have erupted during transitions from stage to stage. Emplaced during the shield stage, the Kīlauea lava, the youngest submarine lava recovered from Kīlauea (based on almost complete lack of glass alteration to palagonite), was termed "peripheral" alkalic lavas by Clague and Dixon (2000). The alkalic Kīlauea flow and Mauna Loa cones are located similar distances from the summits of Kīlauea and Mauna Loa, respectively, as preshield lavas of Lō‘ihi or postshield stage lavas of Hualālai and Mauna Kea are from their respective summits, but in directions perpendicular to the orientation of the chain rather than in line with the chain. The alkalic lava on the submarine west flank of Hualālai, interpreted to be preshield alkalic lava (Hammer and others, 2006), may instead be shield-stage peripheral alkalic lava. Additional sampling and radiometric dating should resolve its origin.

Shield Structure: Rift Zones, Radial Vents, and Calderas

Essential features of Hawaiian shield growth have been described for nearly a century, although not necessarily well understood. The past 50 years have seen increasingly sophisticated modeling supported by extensive datasets and spaceborne technology.

The intrusive structure of the shield develops as the volcano grows from the ocean floor. Magmatic pathways within the volcano, including the routes for rift zone intrusions, are established in earliest shield-stage time, as indicated by the existence of a summit caldera and rift zones on Lō‘ihi volcano (Malahoff, 1987; Clague and others, 2003). At the active, well-monitored Kīlauea Volcano, seismicity effectively tracks the passage of magma from mantle depths of 40–60 km (Eaton and Murata, 1960) as it rises into the crust beneath the summit area. As the rate of magma supply increases, storage reservoirs develop at intermediate depths (near the base of the oceanic crust) and shallow depths (1–7 km below caldera floor) (Clague, 1987a; Ryan, 1987). Magma is shunted from the shallow reservoir into the volcano's rift zones, as documented by (1) geodetic and seismic data (Cervelli and Miklius, 2003; Klein and others, 1987); (2) CO_2 discharge, which is much higher from summit vents than from vents on the rift zones (Gerlach and Taylor, 1990); and (3) similar trace-element concentrations that suggest a shared magma source for lava erupted more or less concurrently from both Halema‘uma‘u (summit) and Pu‘u ‘Ō‘ō (19 km down the East Rift Zone) (Thornber and others, 2010) and even farther down the Puna Ridge (Clague and others, 1995).

Rift Zones

A debate still stirs about whether rift-zone intrusions are passive or forceful events (Poland and others, this volume, chap. 5). As the volcano gains in height, its unbuttressed flank or flanks tend to extend by gravitational spreading, which favors the development of rift zones by extensional fractures and lateral injection of dikes (Fiske and Jackson, 1972; Denlinger and Morgan, this volume, chap. 4). But geodetic surveys at Kīlauea have documented compressive uplift of the outer rift-zone flank over time spans of years; thus, forceful intrusion is a necessary component of rift-zone growth (Swanson and others, 1976). Doubtless several conditions are required for the lateral displacement or dilation of the flanks, such as high intrusion rate, low magma viscosity, and low fault strength (Dieterich, 1988).

The concept that Kīlauea's mobile south flank is closely related to its rift-zone structure was suggested in the 1960s (Moore and Krivoy, 1964), but the analysis by Swanson and others (1976) was probably the first to depict dilation reaching to the root of the rift zone, as deep as 8 km and therefore near the volcano-seafloor interface (fig. 9), so that extension is accommodated largely within

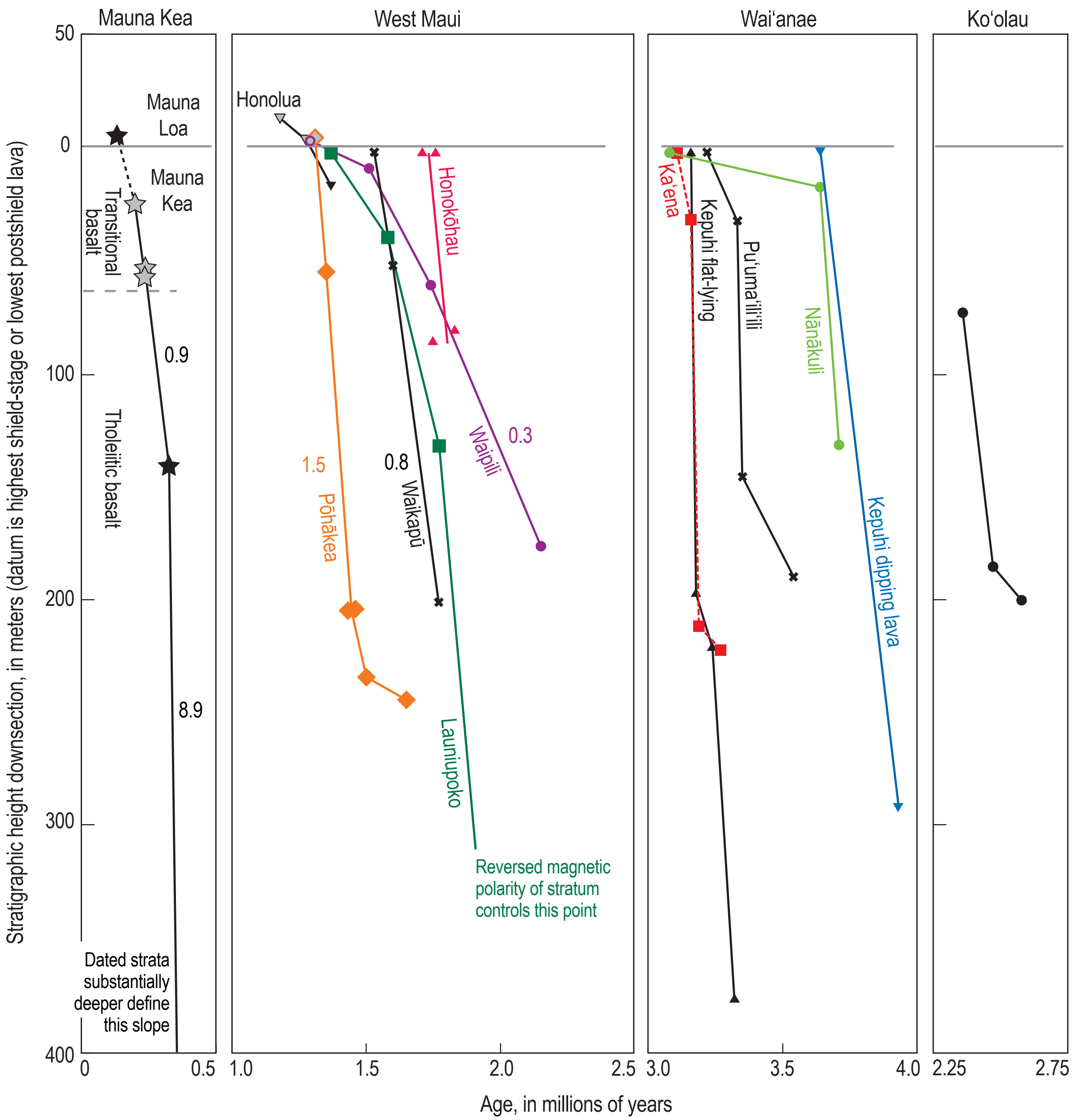


Figure 8. Graphs of age versus stratigraphic height for samples from exposed stratigraphic sequences and drill core at selected Hawaiian volcanoes. Datum is positioned to approximate the top of the shield stage in each volcano. For Mauna Kea, black symbols, shield-stage strata; gray symbols, transitional basalt. For West Maui, gray symbols are postshield lava. Numbers adjacent to some line segments show slope, expressed as meters per 1,000 years. Sources: Mauna Kea data, Sharp and others (1996); Wai'anae data, Guillou and others (2000); West Maui data, Sherrod and others (2007a); Ko'olau data, Yamasaki and others (2011). Graphed lines that extend downward beyond data points are based on stratigraphically lower, dated samples (Mauna Kea) or remanent magnetic polarity (West Maui); in the latter case, the slope defines the highest permissible accumulation rate for that sequence.

the edifice. Deep, low-angle (4°–5°) faults dipping back toward the volcano at such depth (now generally thought to be 9–10 km) were recognized first from seismic evidence (Ando, 1979; Furumoto and Kovach, 1979). These faults may be localized in abyssal sediment (Nakamura, 1982), which provides favorable properties of low strength and normal or excessive pore-fluid pressure. Alternatively, displacement may occur across a zone where "much of the displacement is taken up by many local adjustments within the pillow [lava] complex" (Swanson and others, 1976, p. 25). Lipman and others (1985) proposed, on the basis of deformation during the 1975 Kalapana earthquake, that the Hilina faults connected to this basal low-angle detachment and accommodated deep dilation.

Deep faults are required to model the patterns of subsidence and compression from geodetic measurements and deep seismic hypocenters along Kīlauea's rift zones (Owen and others, 1995, 2000; Cayol and others, 2000). The precise results of the geodetic studies vary, depending on the time period studied, but they converge on a model in which rift-zone intrusions are blade-like dikes that extend upward from the ocean floor-volcano interface (now depressed to depths of 9–10 km by crustal loading) to as shallow as 2–3-km depth, which is the shallow zone of frequent seismicity within the rift zone. Deep rift expansion, whether by passive or forceful intrusion, is interpreted as the primary force driving south-flank motion and seismicity (Owen and others, 2000). Deep horizontal stress may be increased by the formation of olivine cumulates, owing to the additional mass they provide and their ability to flow (Clague and Denlinger, 1994).

The quantitative results emphasize a rift zone's magma-storage capacity and the magnitude of ground deformation. Historical values for dilation across Kīlauea's East Rift Zone require magma emplacement at rates ranging from 0.025 to 0.06 km^3/yr (Delaney and others, 1993; Owen and others, 1995). Add to this the long-term erupted volume of 0.12 km^3/yr of the ongoing East Rift Zone eruption (averaged over the period 1983–2002; Heliker and Mattox, 2003), and the resulting total magma-supply rates are in the range 0.15–0.18 km^3/yr for much or all of the past 20 years (Cayol and others, 2000; Heliker and Mattox, 2003). These values, within the range cited by Dvorak and Dzurisin (1993) for periods of years and even centuries, are larger by 60 percent than previous estimates for magma supply during sustained activity (0.09–0.1 km^3/yr; Swanson, 1972; Dzurisin and others, 1984; Dvorak and Dzurisin, 1993), owing to the magma stored by interpreted deep dike dilation along the East Rift Zone during the past two decades.

Mauna Kea appears to lack rift zones, and its eruptive vents form a shotgun scatter pattern across the summit region. The volcano also lacks submarine features that might be early rift zones. Kaua‘i also lacks obvious rift zones above sea level but below sea level, at least four ridges appear to be rift zones (Eakins and others, 2003).

Radial Vents

Radial vents are well documented on Mauna Loa, where linear eruptive fissures on the west and north flanks of the volcano trend away from the summit caldera (Lockwood and Lipman, 1987). Several examples are found offshore on the west flank, including the submarine 1887 C.E. vents (Fornari and others, 1980; Moore and others, 1985) and additional vents only recently discovered (Wanless and others, 2006b). Other Mauna Loa radial vents crop out as far from the summit as Hilo (Hāla‘i-Puu Honu vent alignment; Buchanan-Banks, 1993) and in the saddle between Mauna Loa and Mauna Kea. Radial vents are probably a consequence of spreading across the arcuate Northeast and Southwest Rift Zones of Mauna Loa, which causes extension on the west and north sides of the volcano. Dikes propagate into this wide extensional zone. Radial vents have not been identified on Kīlauea.

On older volcanoes, dikes are commonly the only exposed clues to the existence of radial vents. At Wai‘anae volcano (O‘ahu), dikes along a southeast-trending rift zone follow a radial pattern as they swing around the south side of the caldera, perhaps in response to the stress field created by caldera growth in late shield time (Zbinden and Sinton, 1988). Scattered dikes of almost all orientations have been mapped on Kaua‘i (Macdonald and others, 1960). Most are near the volcanic center, where varied local stresses may predominate.

Calderas

Calderas are common on Hawaiian shield volcanoes. Their topographic rims crown the summits of the active Kīlauea and Mauna Loa. Erosion has exposed their shallow or mid-depth reaches at older volcanoes, such as Kaho‘olawe, West Maui, East Moloka‘i, Ko‘olau, Wai‘anae, and perhaps Kaua‘i. Once thought to form only late in the shield stage, calderas are now known to appear as early as the preshield stage (for example, Lō‘ihi) and then likely develop and fill repeatedly throughout the shield stage. Thus, calderas go hand-in-hand with the high rate of magmatism that builds the Hawaiian Islands.

The repeated injection of magma into a volcano's summit region results in a complex magma reservoir: a nexus of dikes, sills, and plugs. Over time this complex develops a greater bulk-rock density than the adjacent volcano, owing to the nonvesicular, massive character of the intrusions and crystal accumulation in the deeper parts of the reservoir. In general, Hawaiian calderas are coincident with a positive gravity anomaly centered at the point from which the rift zones radiate, owing in large part to their position above the dense magma column that extends downward through the crust and into the mantle (fig. 10) (Kauahikaua and others, 2000). In older calderas, such as Ko‘olau (O‘ahu), where the reservoir is fully crystallized, the resulting seismic signature includes P-wave velocities (V_P) of 7.7 km/s at depths less than 2 km (Adams and Furumoto, 1965; Furumoto and others, 1965), contrasting with the low V_P of 4.6 km/s in the surrounding material of the shield.

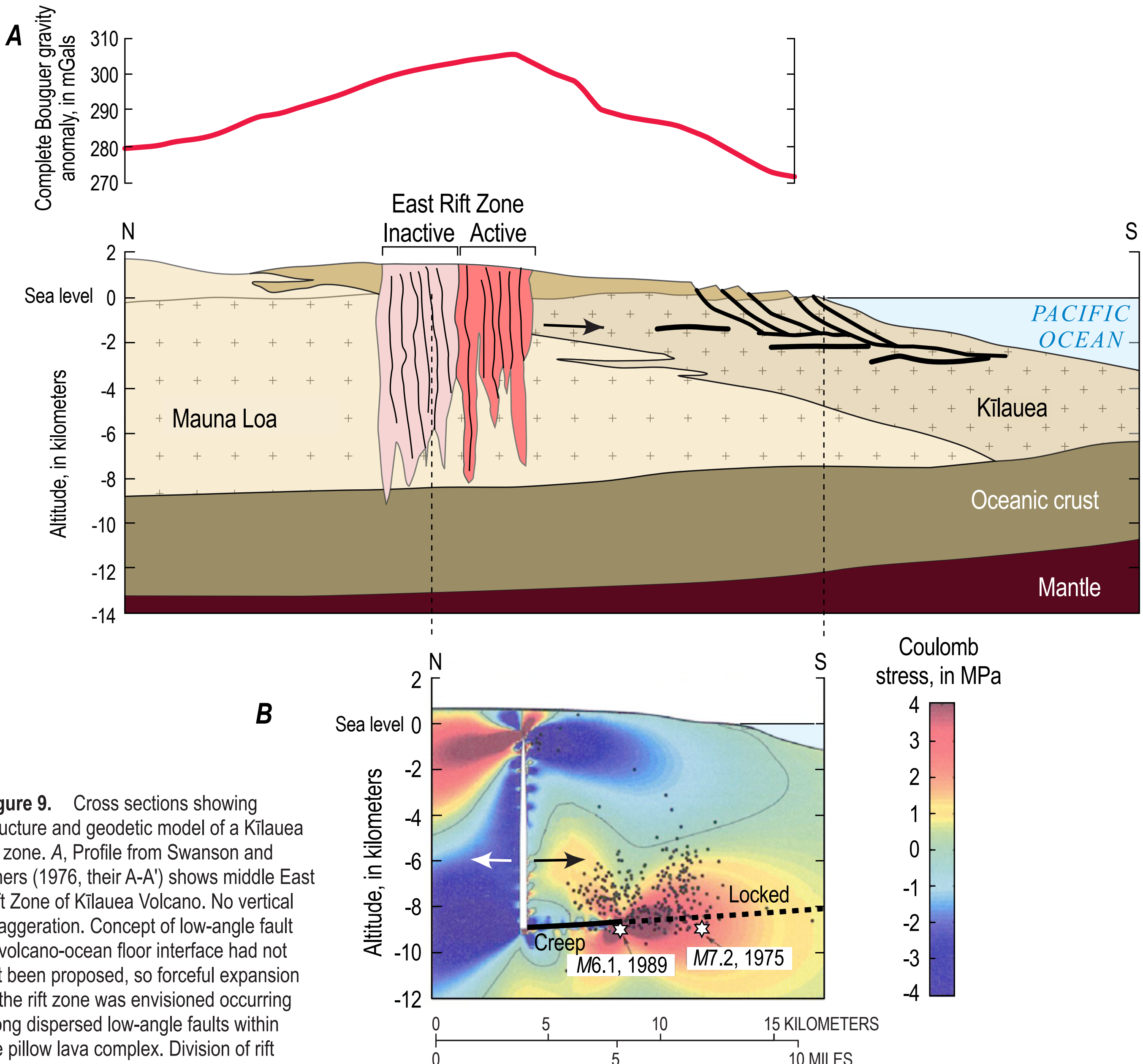
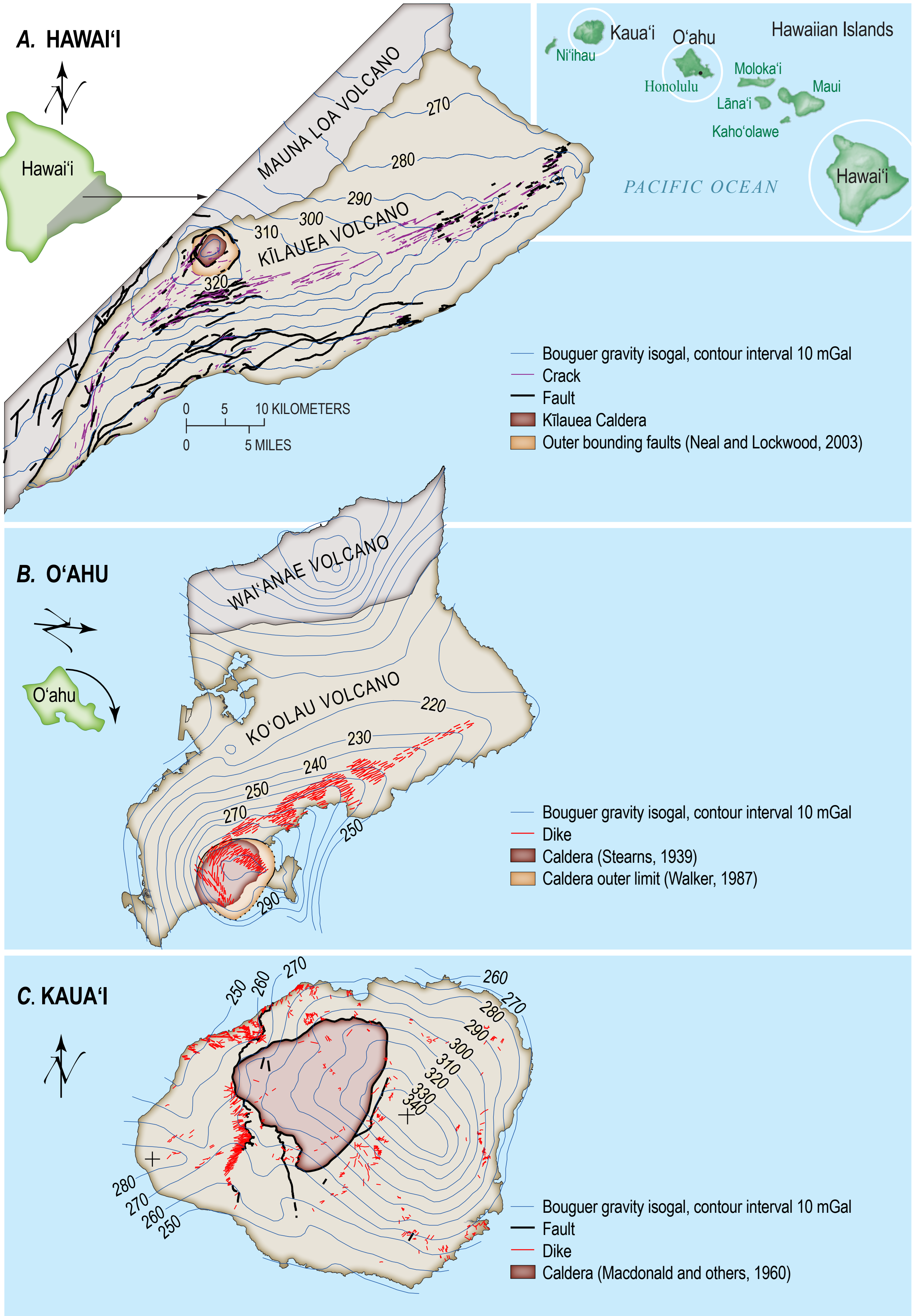


Figure 9. Cross sections showing structure and geodetic model of a Kīlauea rift zone. *A*, Profile from Swanson and others (1976, their A-A') shows middle East Rift Zone of Kīlauea Volcano. No vertical exaggeration. Concept of low-angle fault at volcano-ocean floor interface had not yet been proposed, so forceful expansion of the rift zone was envisioned occurring along dispersed low-angle faults within the pillow lava complex. Division of rift zone dikes into inactive and active part originates from asymmetrical gravity profile and other evidence that rift-zone axis propagates southward through time as a consequence of dilation (Swanson and others, 1976). Gravity profile above section is from dataset of J.P. Kauahikaua (written commun., 2011); mGals, milligals. *B*, Geodetic model and Coulomb stress calculations depicted by Cayol and others (2000), at roughly the same geographic position and scale as cross section in panel *A*. Also shown from the original illustration are focal depths of two large south-flank earthquakes and the division of the deep fault into locked and creeping segments. Contrasting colors for arrows indicating dike expansion are solely for visibility. MPa, megapascals.

Figure 10. Maps showing calderas, rift zones, and Bouguer gravity anomalies at selected Hawaiian volcanoes, all at same scale. *A*, Kīlauea Volcano, Island of Hawaiʻi. Dark brown fill, modern topographic caldera; lighter fill, expanse of caldera defined by outer ring faults. Structural elements shown by faults (black lines). Erosion is too shallow to provide much structural sense from the few dike exposures. Gravity contours from dataset of J.P. Kauahikaua (written commun., 2011); gravity maximum, about 330 mGal, is coincident with caldera. *B*, Koʻolau volcano and caldera, Island of Oʻahu. Note that illustration is rotated 96° clockwise to facilitate comparison with the depiction of Kīlauea Volcano in *A*. Shown by dark brown fill is caldera defined by Stearns (1939); an outer boundary (lighter fill) is inferred from map data of Walker (1987). Rift-zone dike orientation is generalization used by Walker (1987). Large gaps in downrift dike progression correspond to interfluves between canyons, where lava flows at top of volcano bury dike exposures. Bouguer gravity anomalies from Strange and others (1965); gravity maximum about 310 mGal. *C*, Kauaʻi volcano (all of the Island of Kauaʻi). Caldera boundary, faults, and dikes from Macdonald and others (1960). Bouguer gravity contours from Krivoy and others (1965). These contours match the more recent work by Flinders and others (2010), whose graphical depiction does not lend itself readily to presentation as isogal lines.


A. HAWAI'I
Hawai'i
MAUNA LOA VOLCANO
KĪLAUEA VOLCANO
270
280
290
300
310
320
Kaua'i
O'ahu
Hawaiian Islands
Ni'ihau
Honolulu
Moloka'i
Maui
Lāna'i
Kaho'olawe
PACIFIC OCEAN
Hawai'i
Bouguer gravity isogal, contour interval 10 mGal
Crack
Fault
Kīlauea Caldera
Outer bounding faults (Neal and Lockwood, 2003)
0 5 10 KILOMETERS
0 5 MILES
B. O'AHU
O'ahu
WAI'ANAE VOLCANO
KO'OLAU VOLCANO
220
230
240
250
270
250
290
Bouguer gravity isogal, contour interval 10 mGal
Dike
Caldera (Stearns, 1939)
Caldera outer limit (Walker, 1987)
C. KAUA'I
250
260
270
260
270
280
290
300
310
320
330
340
280
270
260
250
Bouguer gravity isogal, contour interval 10 mGal
Fault
Dike
Caldera (Macdonald and others, 1960)

Where they are youthful, Hawaiian calderas form topographic features 2–5 km across. They mark rudely circular zones of subsidence, lava infilling, and intrusion. Subtle arcuate faults may mark the outer limit of caldera-related deformation, which extends much farther outboard than the prominent cliff of the most mobile part of the caldera. Such is the case at Mauna Loa and Kīlauea volcanoes today (fig. 10*A*) (Neal and Lockwood, 2003). Some caldera floors subside at least 800–900 m cumulatively through time, to account for the depth of exposure seen in caldera-filling rocks at deeply eroded volcanoes like Koʻolau (Oʻahu) (Walker, 1987). Whether the subaerially emplaced lava of a caldera sinks substantially farther may never be known, because Hawaiian volcanoes subside into the submarine realm before erosion can expose their deep structural levels.

Older calderas, which may lack any present topographic expression, are mapped on the basis of several features that define the caldera boundary (Macdonald, 1965; Walker, 1987). Caldera-filling lava-lake flows commonly are thick and vesicle poor; others, from fissures across a caldera's floor, may be thin and vesicular. Structurally the lava flows are subhorizontal or dip inward if deformed by caldera subsidence. Caldera-filling lava flows might even dip outward slightly if they were built up around a central-vent location, as around Halemaʻumaʻu (Kīlauea), but the dips of those flows are less than the 2°–10° dips of lava flows on a shield's flanks. In some instances, talus breccia exposed within the rock sequence marks the trace of cliffs that bounded the caldera, as on Kauaʻi (Macdonald and others, 1960) and at Waiʻanae volcano (Oʻahu; Stearns and Vaksvik, 1935; Sinton, 1987). At Koʻolau volcano (Oʻahu), hydrothermal alteration is extensive in the caldera-filling lava sequence (Stearns and Vaksvik, 1935), perhaps a deeper-seated equivalent to the modern fumaroles on the floor of Kīlauea Caldera (Casadevall and Hazlett, 1983). The Koʻolau caldera is also defined, in part, by a paucity of dikes relative to the adjacent rift zone (Walker, 1987), because the caldera's episodic collapse buried or destroyed that part of the stratigraphic sequence, only to be filled anew with intact lava flows.

An enlarging caldera may engulf a previous caldera or shift its central region of subsidence, resulting ultimately in a set of bounding faults that enclose an area larger than that affected in any single caldera-forming event. That process is shown by the overlapping concentric or elliptical rims that form Mauna Loa's caldera today. Thus, what is mapped as a large caldera in older volcanoes may simply be the convenient boundary drawn to encompass exposures of several successive caldera formations. Calderas may expand by the capture of adjacent pit craters (one of the mechanisms suggested by Macdonald, 1965), but the structural relation would be difficult to show, and pit craters may simply be casualties of proximity, not features fundamental to caldera growth.

The caldera on Kauaʻi is unusual for its substantial breadth (see the map of Macdonald and others, 1960); at 16 km by 20 km, it is two to three times larger than other Hawaiian calderas (fig. 10*C*). The Kauaʻi caldera is also unusual, though not unique, in that it does not coincide closely with peak gravity values (Krivoy and others, 1965; Flinders and others, 2010). The mapped caldera may be a subsidence-and-fill feature unrelated or only marginally related to what would have been the shield's original summit caldera (Holcomb and others, 1997; Flinders and others, 2010). The key structural features that could confirm this idea are unidentified because little mapping has taken place on Kauaʻi, especially of the older parts of the volcano, since the 1940s and 1950s (Macdonald and others, 1960), a reminder that basic geologic map data remain incomplete for parts of the Hawaiian Islands, even as we forge ahead in the 21st century.

The prevailing view of caldera formation, at Hawaiʻi and elsewhere, is by subsidence consequent upon withdrawal of magma. The withdrawal removes support from a volcano's summit region, causing it to subside. In an alternative mechanism, subsidence is due to the load of intrusions and cumulate rocks—the trail of present and past magma chambers stacked one above the other as the volcano grows (see, for example, Walker, 1987, 1988). This mass becomes unstable, relative to less dense surroundings, and settles into the crust.

Where does the magma go? The magma-withdrawal hypothesis is budgetary, in that the volume of caldera subsidence should roughly equal the volume of magma withdrawn. Objections have arisen about its application to Hawaiian calderas, because contemporaneous lava flows rarely match the volume of subsidence. With this comparison in mind, Macdonald (1965) compiled data for 13 events presumed to be related to caldera collapse at Kīlauea Volcano in the period 1823–1955. The volumes of subsidence ranged from 0.1 to 0.6 km^3, but subaerially extruded lava volumes (corrected to dense magmatic equivalent) were only a fraction of that, from as little as 2 to 80 percent[5].

The missing volume for some of these caldera-forming events might be accounted for by lava flows erupted in the submarine realm. For example, lava flows with thin sediment cover and therefore relative youthfulness (identified by high sonar backscatter) surround the distal end of Puna Ridge, the submarine part of Kīlauea's East Rift Zone (Holcomb and others, 1988). The youngest of these flows is probably <200 yr old, covers about 600 km^2, and has a volume >6 km^3 if assigned a thickness of 10 m, which is the low value for their flow-margin thickness (Holcomb and others, 1988; Holcomb and Robinson, 2004, their unit Qx). This flow, however, is the lone known example of a shield-stage alkalic lava flow on Kīlauea (Clague and others, 1995; Johnson and others, 2002; Coombs and others, 2006); thus, it probably did not pass through the subcaldera reservoir and rift zone of Kīlauea and is unrelated to caldera subsidence prior to 1790. Adjacent extensive sea-floor lava flows, tholeiitic in

[5]It was noted during technical review that these calculations may have little bearing on the issue of caldera subsidence if the events were simply draining of fluid lava (broad "lakes") into the rift zones, and not the downdropping of solidified lava flows (D.A. Swanson, written commun., 2012).

composition (Clague and others, 1995), are significantly older than the alkalic flow, as are all sampled or observed flows along the crest of the Puna Ridge (Clague and others 1995, Johnson and others, 2002). The large lava flows at the submarine end of the rift could be related to caldera collapse events, but their ages and volumes are poorly constrained, so correlation with known subaerial volcanic events is speculative. Despite these uncertainties, their eruption may contribute substantially to balancing the budget of summit caldera collapses and rift-zone extrusion.

Another objection against the withdrawal hypothesis is that collapse need not accompany voluminous subaerial eruptions. No caldera collapse is known to have accompanied the ‘Ailā‘au eruptions, for example, which shed about 5 km^3 onto the east flank of Kīlauea during a 50-year period about 1445 C.E. Instead, the summit area is thought to have remained intact so that lava could continue to spill eastward (Clague and others, 1999). ‘Ailā‘au may have had little obvious relation to caldera formation, mainly because it was essentially a summit eruption (at rates near historical rates) and therefore did not depressurize the summit magma chamber in the way that rift-zone eruptions do. Regardless, initiation of major collapse of the modern caldera occurred soon after the end of the ‘Ailā‘au eruption (Swanson and others, 2012), which leaves open the suggestion that sustained eruptions may prepare the ground for subsequent subsidence-related deformation, even if not producing a caldera immediately, as in the classic withdrawal model.

Perhaps the answer that overcomes all of these objections to the withdrawal model of caldera formation is the combination of large lava flows, submarine extrusion, the capacity of rift zones to store intruded magma, and the element of time. Caldera collapses may follow years-long periods when roof-rock strength and honeycombing of voids allows the summit region to remain intact while magma is withdrawn. For example, geodetic data suggest that Kīlauea’s East Rift Zone expanded along an 8.5-km-high dike to accommodate about 0.18 km^3/yr of magma during a 6-year, essentially noneruptive time period between large south-flank earthquakes of 1975 and 1982 (Cayol and others, 2000). As modeled, the corresponding rift-zone fault was 47 km long, dilation was 40 cm/yr, and the area of slip on the décollement ultimately covered 132 km^2 (fig. 3 of Cayol and others, 2000). No caldera collapse followed this event, probably because input to the volcano was being shunted away from the summit (as opposed to draining the summit). Regardless, the volume of magma involved reaches into the realm needed for some collapse events. The episodicity of rift-zone intrusion and its possible correlation with specific caldera subsidence events are still to be determined. The geodetic constraint represented by an active rift zone episodically expanding, over a period of a few years, on the order of meters across kilometers-long dimensions of height and length, will likely prove fundamental for understanding shield magmatism, rift-zone growth, and caldera subsidence.

Interactions with Water During the Shield Stage

Water plays a key role in phreatic and phreatomagmatic eruptions and in determining the slope of Hawaiian volcanoes above and below sea level. The widely observed phreatic eruption on Kīlauea in 1924, the earlier 300-year-long period of phreatomagmatic eruptions at Kīlauea that produced the Keanakāko‘i Tephra Member of the Puna Basalt (culminating in 1790 C.E.; Swanson and others, 2012), and the presence of extensive older ash deposits on parts of Kīlauea and Mauna Loa—examples are the Kalanaokuaiki Tephra (Fiske and others, 2009) and the Pāhala Ash (Easton, 1987)—make it clear that water influences the style of eruptions, and the volcanic hazards, at Kīlauea and, presumably, at older volcanoes in the chain.

Clague and Dixon (2000) used a model for formation and solidification of magma chambers (Clague, 1987a), involving hydrothermal cooling of those magma chambers, magmatic degassing, and timing of explosive eruptions, to propose that Hawaiian volcanoes undergo a number of important changes as they grow from the seafloor into tall subaerial mountains. When the volcano is submarine, such as Lō‘ihi Seamount, a shallow magma reservoir will persist as soon as magma flux is large enough that heat input exceeds heat extraction by hydrothermal circulation. The hydrothermal fluids are derived from seawater and interact with magma in the reservoir, where they contaminate resident magma with Cl, Na, and other components that are abundant in seawater (see, for example, Kent and others, 1999) but of low concentration in magma.

As the summit of the volcano grows into shallow water (as deep as 1 km) and then through sea level, significant degassing of magmatic volatiles can take place. Loss of these gases, especially of water, increases the density of the shallowest magma in the reservoir, leading to overturn and magma mixing in the reservoir (Dixon and others, 1991; Wallace and Anderson, 1998). This is also when phreatic and phreatomagmatic eruptions start, although lava fountains can occur even deeper, driven by magmatic volatile losses (as on Lō‘ihi; Clague and others, 2003; Schipper and others, 2010b).

The next transition occurs when the top of the magma chamber reaches sea level as the hydrothermal fluids freshen and magma contamination by seawater diminishes. The final transition takes place when the top of the magma chamber rises above the orographic rain belt on the islands, where hydrothermal fluids are no longer replenished, and rapid cooling of the magma chamber by convection of hydrothermal fluids ceases, as also does fumarolic discharge. Mauna Loa has grown to this stage, but Kīlauea remains with the top of its magma chamber just at, or a little above, sea level, so that explosive eruptions remain common (Easton, 1987; Mastin, 1997; Swanson and others, 2012). All these processes impart important characteristics on the erupted lavas and tephra, including contamination, degassing, mixing, and fractionation, but all also appear to be restricted in time to the late preshield, shield, and perhaps the beginning of the postshield stages.

One notable characteristic of Hawaiian volcanoes is steeper submarine than subaerial slope. This topographic distinction results from the subaqueous chilling of subaerial lava flows by seawater, which tends to increase a lava flow's effective viscosity and diminish its effective density because rock-water has a lower density contrast than rock-air (Mark and Moore, 1987). Fragmentation of lava at the shoreline and greater angle of repose in water also contribute to the increase in slope offshore. On older volcanoes, this slope change has been used to identify shorelines now submerged far below sea level around Hawai‘i (Clague and Moore, 1991; Moore and Clague, 1992), Maui Nui (Price and Elliot-Fisk, 2004; Faichney and others, 2009, 2010), the main Hawaiian Islands (Carson and Clague, 1995), and along the entire Hawaiian-Emperor Seamount chain (Clague, 1996). These shorelines define the areas and sizes of former islands and are a key to understanding subsidence of the volcanoes (the topic of a later section).

Source Components of Shield-Stage Lavas

Chemical differences between shield lavas from adjacent Hawaiian volcanoes have been recognized for many years (see, for example, Tatsumoto, 1978; Frey and Rhodes, 1993). These intervolcano chemical differences, especially in isotopic systematics, correlate strongly with the geographic locations of the volcanoes along two curved subparallel trends, called the Loa and the Kea trends (fig. 11), that are defined through at least the eastern part of the main islands and are named after the largest volcanoes included in each trend—Mauna Kea and Mauna Loa.

Chemical differences in major, trace, and volatile elements and in radiogenic and rare-gas isotopic compositions of Hawaiian lavas have been used widely to define different mantle components involved in partial melting to produce the lavas (for example, Hauri, 1996; Dixon and Clague, 2001; DePaolo and others, 2001; Gaffney and others, 2004; Ren and others, 2004, 2006; Abouchami and others, 2005; Xu and others, 2005, 2007b; Dixon and others, 2008; Huang and others, 2009). A major objective has been to understand the chemical structure of the Hawaiian plume. These various mantle components are commonly named after the volcano whose lavas display the most extreme end-member compositions—hence the KEA and KOO components are named for Mauna Kea and Ko‘olau volcanoes. Other components include a depleted HA component for Hawaiian asthenosphere, and FOZO, an entrained lower mantle component (fig. 12; Dixon and Clague, 2001). All except the depleted upper mantle component are thought to represent different parts of ancient lithosphere subducted a billion or so years ago and stored in the mantle. Other authors have suggested different end-member components, but all models include at least four components, one of which is depleted upper mantle (Helz and others, this volume, chap. 6). Much of the current discussion among scientists is centered on defining the full spectrum of chemical characteristics of the

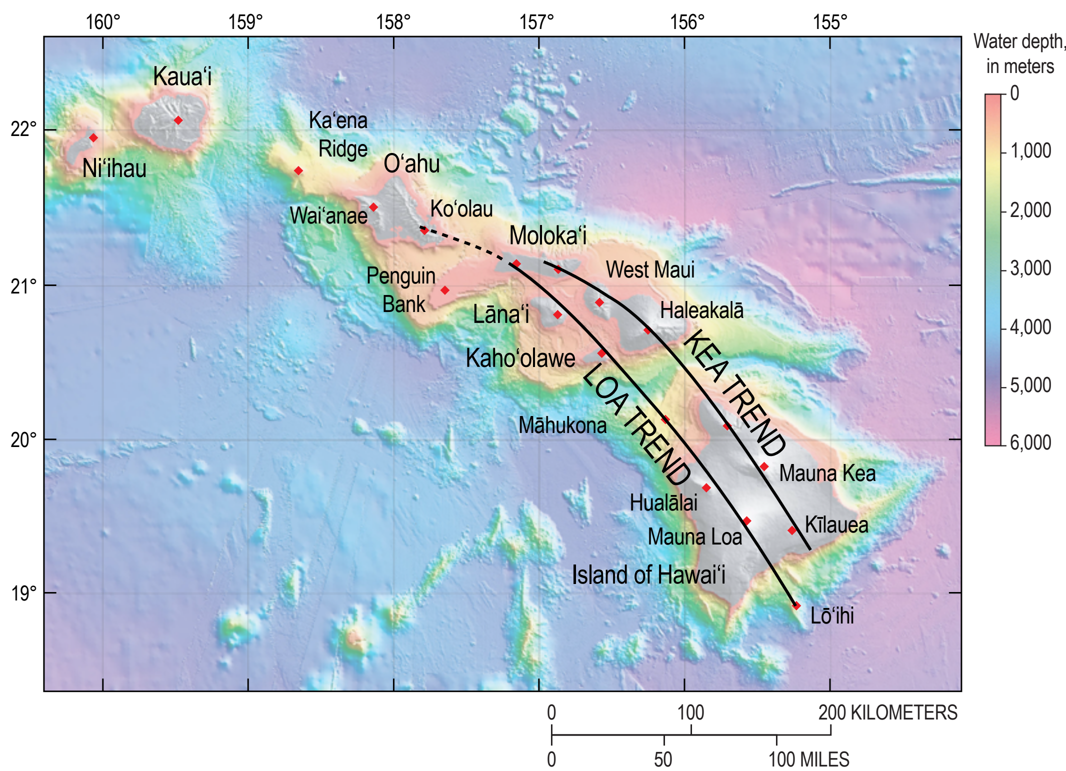


Figure 11. Map showing the Kea and Loa trends of volcanoes in the Hawaiian Islands. Diamonds are volcano summits, locations from table 1. Base from Eakins and others (2003).

end-member components and how these different components are arranged in the mantle source region beneath Hawai'i. Two recent papers specifically address the origins of the chemical differences between Loa-trend and Kea-trend volcanoes (Huang and others 2011; Weis and others 2011) and the role of bilaterally zoned plumes. Matzen and others (2011) recently suggested that primary Hawaiian tholeiitic melts contain 19–21 percent MgO, significantly higher than most previous estimates. This estimate, if confirmed, implies that Hawaiian tholeiitic magmas are generated deeper and at higher potential temperatures than are primary melts with lower MgO.

Transition from Shield to Postshield Stage

Hawaiian volcanoes lose vigor as they drift away from the hot spot. Shallow magma reservoirs that lie only 1–7 km deep during main stage activity cannot be sustained as magma supply decreases (Clague, 1987a), but reservoirs persist between 19-km (Bohrson and Clague, 1988) and 28-km depth (Frey and others, 1990), near the base of the downflexed ocean crust. This solidification of at least shallow magma reservoirs takes place near the end of the shield stage or within the postshield stage as magma supply dwindles.

As might be expected, the shift from shield to postshield stage is transitional. It is expressed geologically by the increasing number of alkalic basalt lava flows found interbedded in the upper part of the main stage sequence (table 2). For example, at Kohala volcano, strata that were interpreted as shield stage show great compositional variation, spanning well into the alkalic range and even crossing from basalt into hawaiite (fig. 3, Pololū Volcanics; Wolfe and Morris, 1996a,b). It is doubtful that any of the Hawaiian volcanoes shift abruptly from shield- to postshield-stage volcanism without first sputtering through a period of transition.

Other lithologic and petrographic changes are associated with lava flows during the transition. At West Maui, for example, the upper 50 m of shield stage strata shows an increase in the proportion of ‘a‘ā and an increase in the size and abundance of olivine and clinopyroxene phenocrysts (Diller, 1982; Sinton,

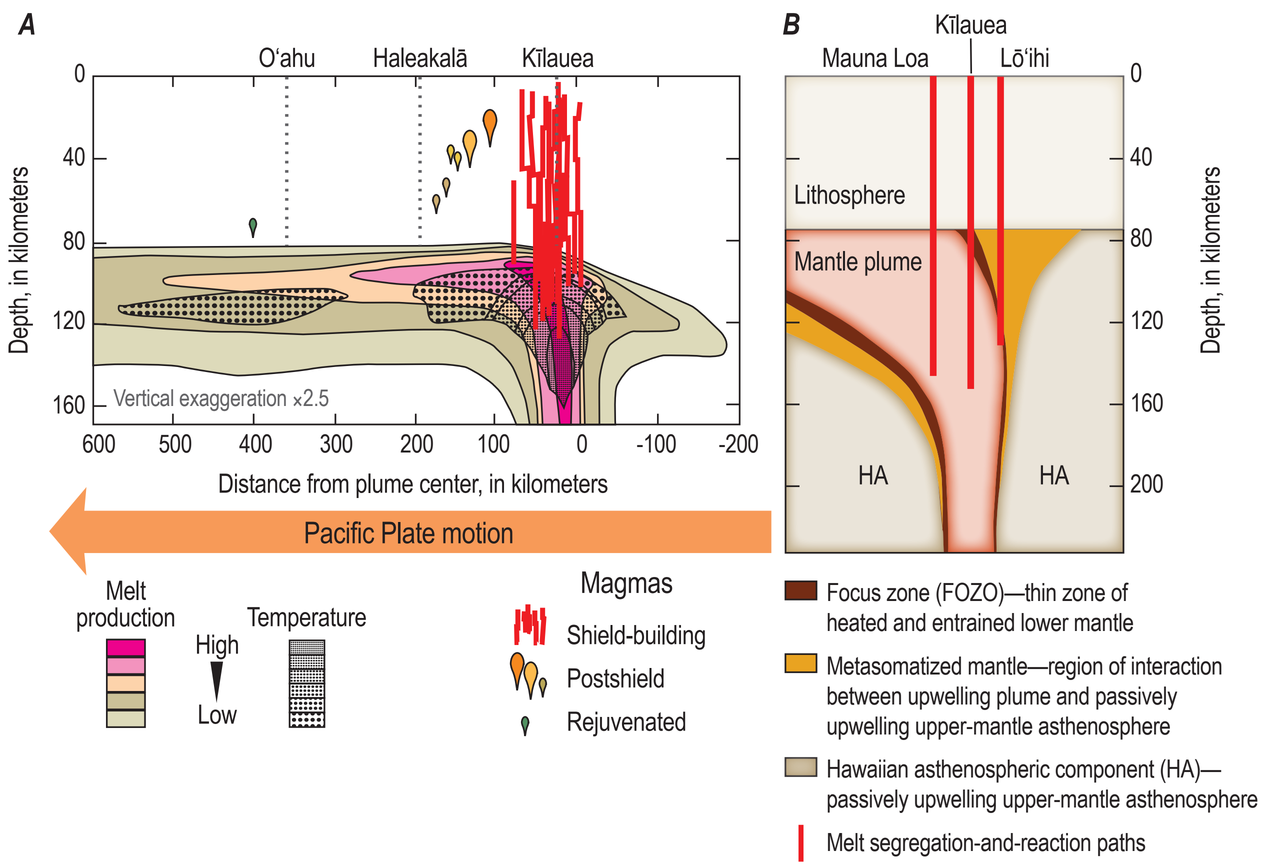


Figure 12. Cross sections showing the inferred structure of the mantle plume below the Hawaiian hot spot. Plate motion is from right to left. *A*, Isotherms and melt-production isopleths (from Ribe and Christensen, 1999). *B*, Compositional components in the plume and surrounding mantle, as illustrated by Rhodes and Hart (1995; based loosely on thermal modeling by Watson and McKenzie, 1991), with additional zonation from Dixon and Clague (2001). Lithospheric thickness differs between panels *A* and *B* because of modeling decisions but is between 70 and 90 km. Both panels show vertical exaggeration ×2.5.

Table 2. Hawaiian volcanic formations and their approximate place in the scheme of shield-, late shield-, postshield-, and rejuvenated-stage volcanism.

[Mauna Loa, Kīlauea, and Lōʻihi are not listed because they are in the shield stage only]

Volcano	Tholeiitic shield exposed	Late shield/postshield alkali basalt[1]	Postshield hawaiite-trachyte	Rejuvenated stage
Niʻihau	Pānīʻau Basalt	Postshield plug (Kaʻeo), dike, and offshore cones	None	Kiʻekiʻe Basalt
Kauaʻi	Waimea Canyon Basalt, Nāpali and Olokele Members	Upper part of Makaweli and Olokele Members	Scattered flows in upper part of Makaweli and Olokele Members	Kōloa Volcanics
Southwest of Kaʻena Ridge(?) (submarine)[2]	Tholeiite recovered by dredge	None	None	Sparse rejuvenated-stage(?) alkalic lava
Waiʻanae (Oʻahu)	Waiʻanae Volcanics, Lualualei Member	Waiʻanae Volcanics, Kamaileunu Member	Waiʻanae Volcanics, Pālehua and Kolekole Members	None
Koʻolau (Oʻahu)	Koʻolau Basalt	None	None	Honolulu Volcanics
Penguin Bank(?) (submarine)[3]	Only tholeiitic rocks have been sampled	None	None	None
West Molokaʻi	West Molokaʻi Volcanics	Spotty	Waiʻeli and other late lava flows	None
East Molokaʻi	Not exposed(?)	East Molokaʻi Volcanics, lower member	East Molokaʻi Volcanics, upper member. As much as 25 percent basanite on basis of published analyses	Kalaupapa Volcanics
Lānaʻi	Lānaʻi Basalt	None	None	None
Kahoʻolawe	Kanapou Volcanics, main shield and caldera-filling strata	Kanapou Volcanics, late shield	Some Kanapou Volcanics are hawaiite and mugearite	None
West Maui	Wailuku Basalt	Spotty	Honolua Volcanics	Lahaina Volcanics
Haleakalā	Not exposed(?)	Honomanū Basalt	Kula and Hāna Volcanics	None
Māhukona (submarine)				None known
Kohala	Pololū Volcanics, lower part(?)	Pololū Volcanics	Hāwī Volcanics	None
Mauna Kea	Drill core	Hāmākua Volcanics	Laupāhoehoe Volcanics	None
Hualālai	Submarine dredged samples; drill core	Hualālai Volcanics (Waawaa Trachyte Member at base)	Hualālai Volcanics, Waawaa Trachyte Member	None

[1]It is not our goal to impose a new stage name (late shield), but instead to identify for the reader those stratigraphic units that pose the greatest problem of assignment within a rigid scheme of stages. Each Hawaiian volcano brings its own fingerprint to the story, which makes generalizations difficult.

[2]A topographic prominence southwest of Kaʻena Ridge was demarcated as a separate volcano by Eakins and others (2003). More commonly, it and Kaʻena Ridge are considered a westerly rift zone of Waiʻanae volcano (Oʻahu). For example, Kaʻena Ridge was considered part of Waiʻanae for volume calculations of individual volcanoes in the Hawaiian chain (Robinson and Eakins, 2006).

[3]Penguin Bank was proposed as a separate volcano by Carson and Clague (1995). On that basis it was used in calculations that describe the topographic history of Maui Nui, the multivolcano complex that encompasses the islands of Molokaʻi, Lānaʻi, Kahoʻolawe, and Maui (Price and Elliot-Fisk, 2004). More common is the assignment of Penguin Bank as a rift zone of West Molokaʻi volcano (for example, Robinson and Eakins, 2006).

2005). At both West Maui and Wai‘anae (O‘ahu) volcanoes, ash beds and soil horizons are increasingly common upsection, the latter indicating a general decrease in eruption frequency (Macdonald, 1968; Sinton, 1987). The ash beds indicate a landscape increasingly speckled by scoria cones and small domes that produced ash and lapilli, in contrast to the spatter-rich vents characteristic of shield-stage eruptions. Some interpret this change as a general increase in explosivity of eruptions during this transitional time. Instead of being more explosive in the transitional and postshield phases, however, a Hawaiian volcano may produce less lava relative to vent deposits, so we see more of the Strombolian products. During this transition, vents also become scattered more widely, so the likelihood of widely distributed tephra might increase.

Postshield Stage

Lava flows and associated tephra in the stratigraphic formations attributed to postshield-stage volcanism are more alkalic and commonly more differentiated than the tholeiitic lava of the shield stage. Most common are rocks with compositions in the range hawaiite to benmoreite; trachyte is rare (fig. 13). Alkalic basalt may also be present.

The petrogenetic cause for these changes was stated succinctly by Sinton (2005):

> A consistent characteristic of lava compositions from most postshield formations is evidence for post-melting evolution at moderately high pressures (3–7 kb). Thus, the mapped shield to postshield transitions primarily reflect the disappearance of shallow magma chambers (and associated calderas) in Hawaiian volcanoes. . . . Petrological signatures of high-pressure evolution are high-temperature crystallization of clinopyroxene and delayed crystallization of plagioclase, commonly to <3 percent MgO.

This description builds on earlier ideas about postshield volcanism (Clague, 1987a), such as loss of shallow magma chambers, the end of caldera formation, and the predominance of magma-storage zones at deep crustal to uppermost mantle depths in excess of 15 km. Deep differentiation of magmas by crystal fractionation leads to the more fractionated lava flows of the postshield stage.

Only two volcanoes among the Hawaiian Islands lack the alkalic rocks that characterize postshield volcanism. Ko‘olau (O‘ahu) entered the rejuvenated stage following a hiatus of 1 m.y. after ending the shield stage. Lāna‘i lacks any volcanism younger than the shield stage, which ended there about 1.3 Ma. Excluded from this count are the three youngest volcanoes (Mauna Loa, Kīlauea, and Lō‘ihi), which lack postshield volcanism simply because they have yet to progress fully through the shield stage. Figure 14 shows the stages and timing for volcanoes at each of the main Hawaiian Islands.

At some volcanoes the postshield-stage stratigraphic sequence can be subdivided into members that have fairly discrete geochemical groupings. At Mauna Kea (fig. 13*A*), the trend is toward increasingly silicic lava upward in the Laupāhoehoe Volcanics (Wolfe and others, 1997). At Wai‘anae volcano (fig. 13*B*), the trend is opposite, from the hawaiite-mugearite of the Pālehua Member of the Wai‘anae Volcanics to alkali basalt of the overlying Kolekole Member (as defined by Presley and others, 1997). The trend at Haleakalā (fig. 13*C*) is less sharp, but the lava is increasingly alkaline upsection from the lower to the upper part of the Kula Volcanics. The overlying Hāna Volcanics is geochemically similar to the upper part of the Kula (Sherrod and others, 2003).

Distribution

Lava of the postshield stage forms thick sequences on Wai‘anae (O‘ahu), East Moloka‘i, West Maui, Haleakalā, Kohala, Mauna Kea, and Hualālai volcanoes. The postshield stage is represented by only a few flows and small volumes on Ni‘ihau, Kaua‘i, West Moloka‘i, and Kaho‘olawe volcanoes. Postshield stage lava is absent from Ko‘olau and Lāna‘i volcanoes.

Onset

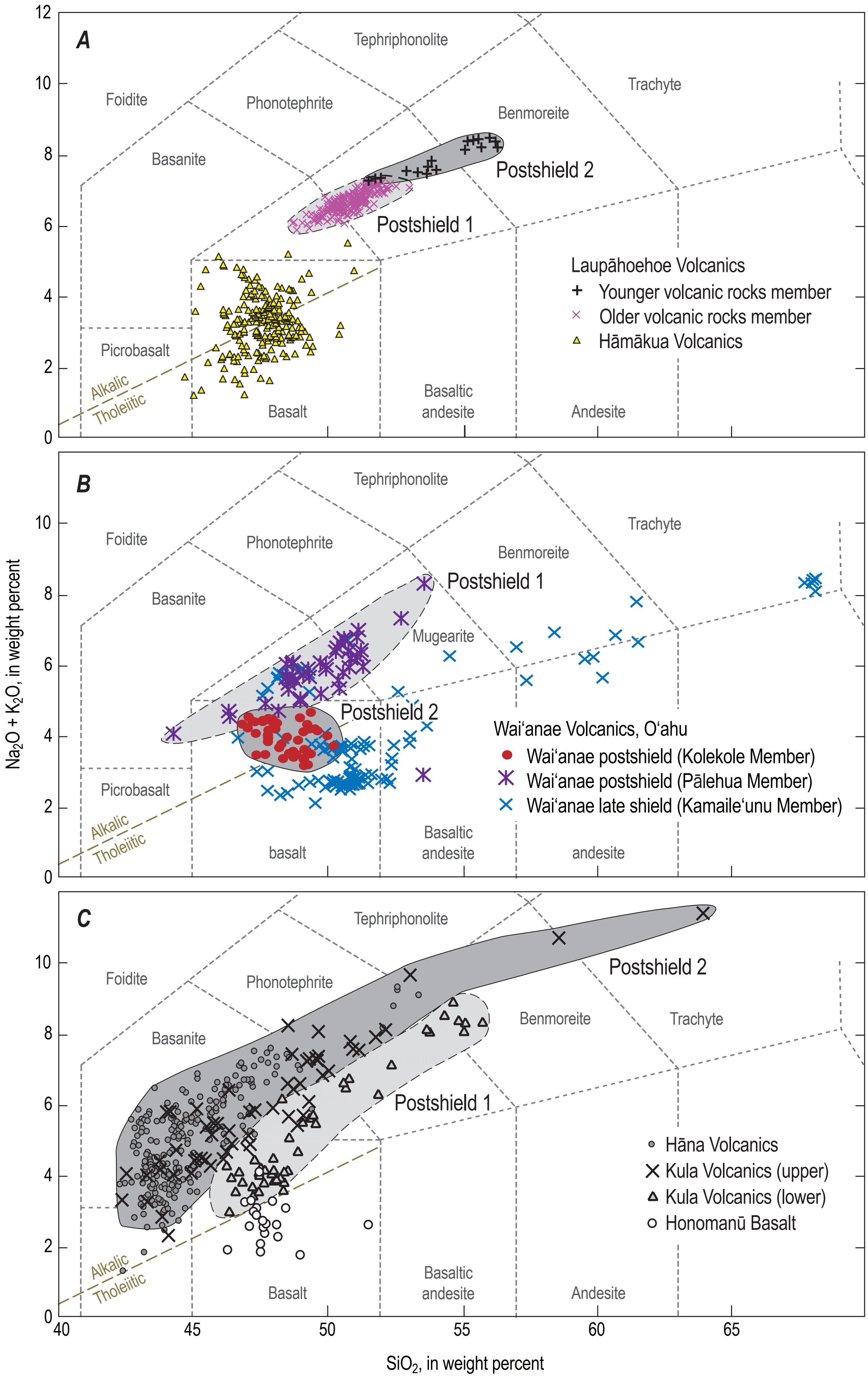
Postshield-stage volcanism follows immediately after the shield stage. At some volcanoes, like Kaua‘i, a discrete postshield sequence is ill-defined, but alkalic basalt, hawaiite, and mugearite—rocks characteristic of postshield strata at other volcanoes—are present in the upper part of the shield-stage Waimea Canyon Basalt.

No temporal gap between late shield and postshield stages is evident at volcanoes that have a distinct, readily mapped postshield stratigraphic sequence. If a hiatus exists, it is too brief to date by K-Ar or $^{40}Ar/^{39}Ar$ geochronology. This brevity is indicated in the dating archive by an overlap of radiometric ages (and their analytical errors), even where the field evidence indicates no stratigraphic interfingering. In the field the stratigraphic break is sharp but concordant, suggesting little erosion during the transition.

On West Maui, for example, ages of the shield-stage Wailuku Basalt range from about 2 to 1.35 Ma, and those of the postshield Honolua Volcanics range from 1.35 to 1.2 Ma (McDougall, 1964; Naughton and others, 1980; Sherrod and others, 2007a). The statistical overlap of ages at about 1.3 Ma suggests that very little time elapsed during the switchover from stage to stage. No field-based evidence of interfingering is known, so on West Maui, the terminal period of shield-stage volcanism was relatively brief, not protracted across many hundreds of thousands of years.

A similarly brief or nonexistent hiatus marks the transition from shield to postshield stage on West Moloka‘i. There, two dated postshield cones have ages of 1.80 and 1.73 Ma (Clague, 1987b), whereas fractionated tholeiite near the top of the shield sequence has an age of 1.84 Ma (McDougall, 1964). The analytical error for these three ages permits them to be roughly synchronous.

Figure 13. Postshield volcanic sequences from *A,* Mauna Kea; *B,* Waiʻanae; and *C,* Haleakalā; compared using the alkali-silica diagram (Na_2O+K_2O versus SiO_2). Rock classification grid from Le Maitre (2002); shown dashed is boundary separating tholeiitic from alkalic basalt (Macdonald and Katsura, 1964). Data from multiple sources compiled in a Hawaii statewide whole-rock geochemistry GIS database (Sherrod and others, 2007b). Stratigraphic nomenclature for Waiʻanae volcano is that of Sinton (1987) and Presley and others (1997).



Duration of Postshield-Stage Volcanism

Once underway, postshield-stage volcanism typically persists for 100,000–500,000 years but may continue for as long as 1 m.y., as at Haleakalā (table 3; fig. 14). Short-duration examples include East Molokaʻi, where lava flows and domes as thick as 520 m accrued in the period between 1.49 and 1.35 Ma; and West Maui, where postshield strata 120 m thick accumulated in the period 1.35–1.2 Ma (Sherrod and others, 2007a). At Mauna Kea, postshield-stage volcanism has been ongoing for 265,000 years (Wolfe and Morris, 1996a). Hualālai, too, is in the postshield stage, persisting already for about 115,000 years (Cousens and others, 2003). On Waiʻanae volcano, the postshield Pālehua Member has a narrow age range from about 3.06 to 2.98 Ma (fig. 15; Presley and others, 1997), suggesting eruption in as little as 100,000 years, and the overlying Kolekole Member extends the postshield duration by only another 140,000 years. Where transitions mark the beginning and end of postshield activity (as is the case at Kauaʻi), the duration of the postshield stage has large uncertainty.

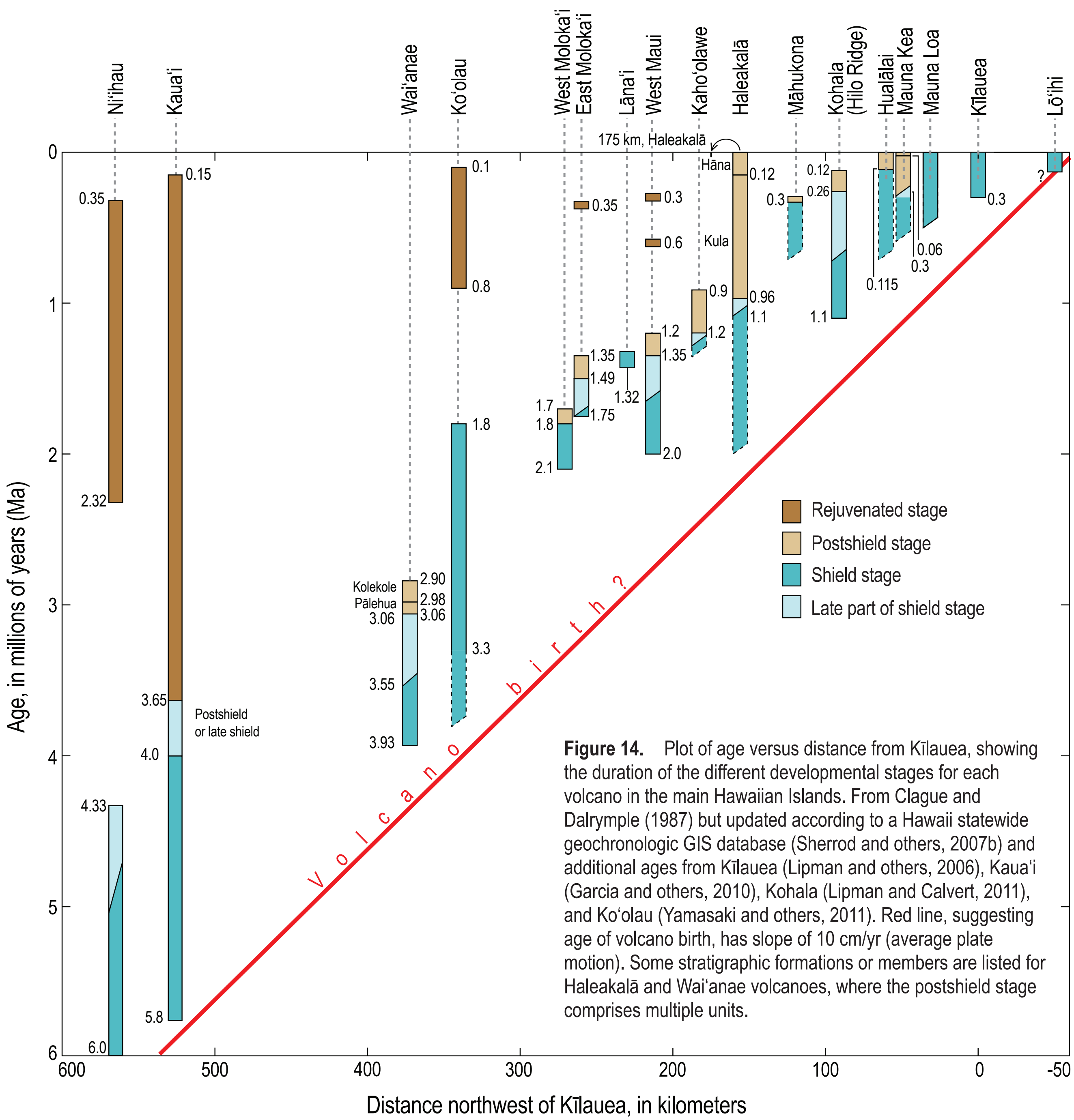


Figure 14. Plot of age versus distance from Kīlauea, showing the duration of the different developmental stages for each volcano in the main Hawaiian Islands. From Clague and Dalrymple (1987) but updated according to a Hawaii statewide geochronologic GIS database (Sherrod and others, 2007b) and additional ages from Kīlauea (Lipman and others, 2006), Kauaʻi (Garcia and others, 2010), Kohala (Lipman and Calvert, 2011), and Koʻolau (Yamasaki and others, 2011). Red line, suggesting age of volcano birth, has slope of 10 cm/yr (average plate motion). Some stratigraphic formations or members are listed for Haleakalā and Waiʻanae volcanoes, where the postshield stage comprises multiple units.

Ni‘ihau

At Ni‘ihau, the postshield-stage duration is ill-defined, owing to large analytical uncertainty in the radiometric ages. An alkalic dike and the eroded remnants of two cones represent the postshield stage onshore, and a few additional postshield cones are located offshore. Four onshore postshield samples yielded K-Ar ages ranging from 5.15±0.225 to 4.67±0.16 Ma (G.B. Dalrymple, data in Sherrod and others, 2007b), and $^{40}Ar/^{39}Ar$ isochron ages from two offshore postshield cones are 4.93±0.44 and 4.74±0.54 Ma (table 4), within the range of the on-land samples. These ages allow that postshield activity on Ni‘ihau could be as brief as 100,000–200,000 years or as lengthy as about 500,000 years.

Kaua‘i

On Kaua‘i, postshield lava flows of hawaiite and mugearite with ages in the range 3.84–3.81 Ma occur at the top of the Olokele and Makaweli Members of the Waimea Canyon Basalt (Clague and Dalrymple, 1988). Clasts of other probable postshield-stage alkalic basalts occur in conglomerate recovered in water wells from the southeastern part of the island (Reiners and others, 1999). The oldest dated lava with postshield chemical affinity, an irregular dike of alkalic basalt from Kālepa Ridge, has an $^{40}Ar/^{39}Ar$ plateau age of 4.39±0.19 Ma and an isochron age of 4.39±0.07 Ma (table 4); the spread of ages from oldest to youngest suggests the postshield stage lasted roughly 600,000 years (more than

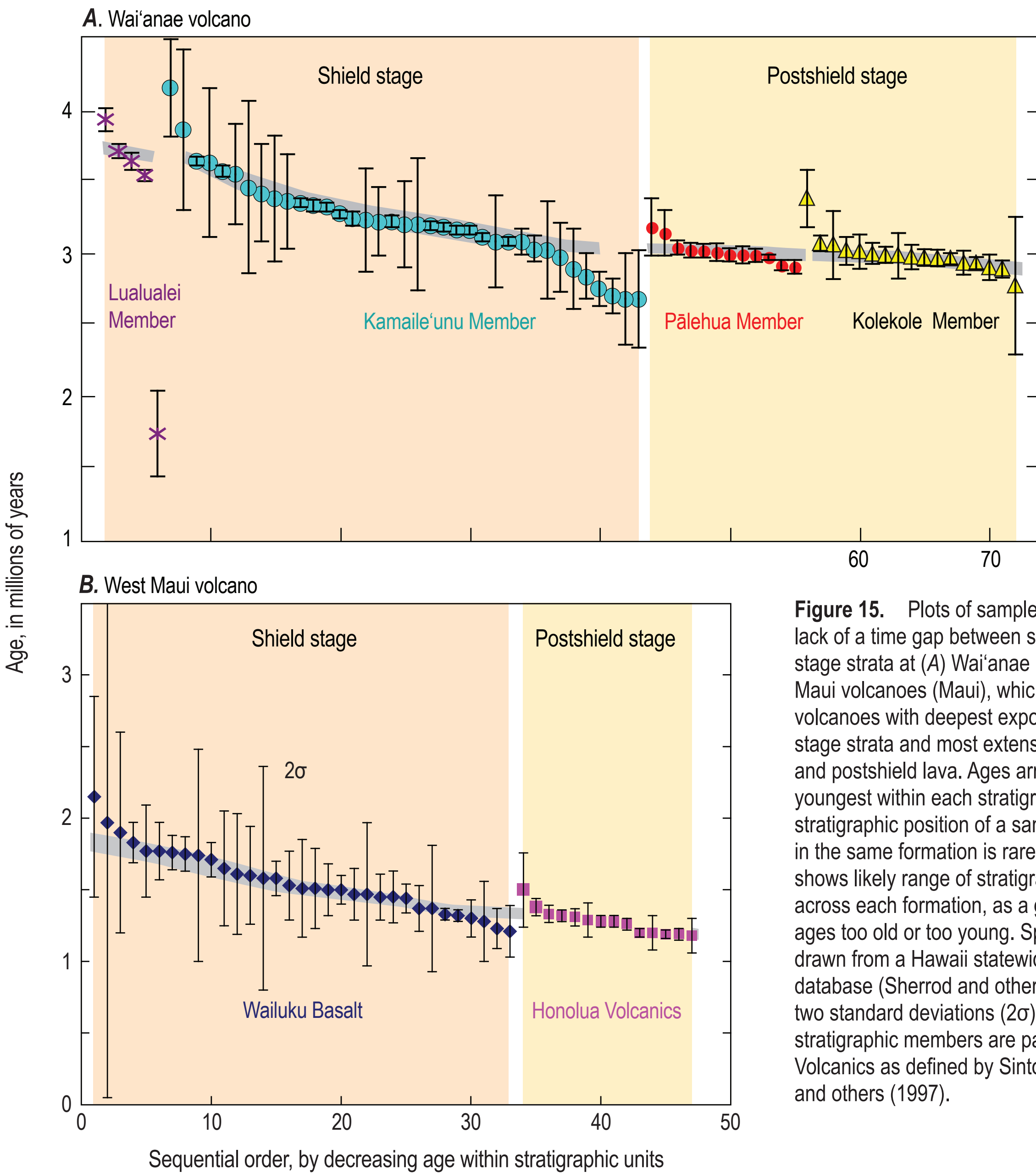


Figure 15. Plots of sample ages showing the lack of a time gap between shield- and postshield-stage strata at (*A*) Wai‘anae (O‘ahu) and (*B*) West Maui volcanoes (Maui), which are the two Hawaiian volcanoes with deepest exposures into the shield-stage strata and most extensive dating of shield and postshield lava. Ages arranged from oldest to youngest within each stratigraphic unit, but precise stratigraphic position of a sample relative to others in the same formation is rarely known. Gray band shows likely range of stratigraphically valid ages across each formation, as a guide to recognizing ages too old or too young. Specific data sources are drawn from a Hawaii statewide geochronologic GIS database (Sherrod and others, 2007b). Error bars are two standard deviations (2σ). For Wai‘anae volcano, stratigraphic members are part of the Wai‘anae Volcanics as defined by Sinton (1987) and Presley and others (1997).

Table 3. Thickness and duration of postshield-stage volcanism at Hawaiian volcanoes with well-defined hawaiite-trachyte suites above shield-stage stratigraphic sequences.

[Coverage indicates percent of volcano's subaerial surface mantled by postshield deposits. Volume not corrected to dense-rock equivalence. Duration of postshield activity in millions of years (m.y.); the age of the activity is in millions of years ago (Ma)]

Volcano	Postshield occurrence and coverage	Thickness	Volume, in km^3	Duration
Niʻihau	One small intrusion	n.a.		--
Kauaʻi	Scattered lava flows, not mapped separately	--	--	--
Waiʻanae	20% covered	≤180 m		0.22 m.y. (3.06–2.84 Ma)
Koʻolau	None	0	0	0
West Molokaʻi	3 small lava flows, 16% covered		n.d.	<0.1 m.y. (?)
East Molokaʻi	50% covered	≤520 m	n.d.	0.14 m.y. (1.49–1.35 Ma)
Lānaʻi	None	0	0	0
Kahoʻolawe	Thin extensive cover, 77%			
West Maui	18% covered	120 m		0.15 m.y. (1.35–1.2 Ma)
Haleakalā	Continuous thick cover, 95% (Kula and Hāna Volcanics)	1 km	300[1]	0.95 m.y., ongoing
Kohala	44% covered (Hāwī Volcanics)			0.14 m.y.
Mauna Kea		950 m	200–500[2]	0.25 m.y., ongoing
Hualālai			300[3]	0.1 m.y., ongoing

[1]Haleakalā postshield volume from Sherrod and others (2003).

[2]Mauna Kea postshield volume is crude estimate corresponding to area of Laupāhoehoe Volcanics and upper part of Hāmākua Volcanics multiplied by thickness range 50–200 m.

[3]Hualālai postshield volume is crude estimate corresponding to volume of volcano above sea level.

Table 4. New $^{40}Ar/^{39}Ar$ incremental heating ages for samples from Niʻihau and Kauaʻi.

[Niʻihau ages analyzed by W.C. McIntosh, New Mexico Geochronology Research Laboratory, New Mexico Institute of Mining and Technology, Socorro, New Mexico. Kauaʻi ages analyzed by John Huard, Noble Gas Mass Spectrometry Lab, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon. Irrad. No., irradiation run sequence. The value n shows number of step increments used to determine the plateau age. MSWD, mean square of weighted deviates. WGS84, datum of World Geodetic System 1984. Sample altitude relative to mean sea level; negative altitudes are depths below sea level]

Sample	Volcano stage	Lab no.	Irrad. no.	Age method	n	% ^{39}Ar	MSWD	K/Ca±2σ	Age±2σ, in Ma	Longitude, WGS84	Latitude, WGS84	Altitude, in meters
						Island of Niʻihau						
T322-R17	Shield	55320-01	NM-185F	Plateau	7	90.8	2.6	0.2±0.1	5.42±0.11	–160.2233	22.09420	–1092
T321-R7	Postshield	55336-01	NM-185J	Isochron	9	22.2	--	0.4±0.6	4.93±0.44	–160.3529	21.9463	–821
T321-R6	Postshield	55332-01	NM-185H	Isochron	8	22.3	--	0.3±0.3	4.74±0.54	–160.3521	21.9458	–852
T317-R6	Rejuvenated	55316-02	NM-185F	Plateau	2	27.4	4.6	0.1±0	1.37±0.32	--	--	--
T317-R9	Rejuvenated	55318-01	NM-185F	Plateau	9	94.1	2.5	0.1±0.2	0.50±0.04	–160.2488	22.1310	–1692
T317-R8	Rejuvenated	55338-01	NM-185J	Plateau	8	91.7	3.4	0.1±0.1	0.50±0.10	–160.2489	22.1305	–1700
T322-R6	Rejuvenated	55334-01	NM-185J	Plateau	8	89.7	1.6	0.1±0.1	0.39±0.09	–160.2317	22.0913	–1407
						Island of Kauaʻi						
86KA3	Postshield	05c3516	OSUSF05	Plateau	3	65.1	0.2	0.58±0.19	4.39±0.19	–159.3576	22.0022	183
86KA2	Rejuvenated	05c3492	OSUSF05	Plateau	3	61.2	4.1	0.03±0.08	2.18±0.27[1]	–159.6008	22.0125	451
75K1	Rejuvenated	05c3524	OSUSF05	Plateau	6	97.9	0.8	0.02±0.03	0.68±0.04[2]	–159.5244	21.9153	244
76K1	Rejuvenated	05c3486	OSUSF05	Plateau	5	98.2	1.0	0.02±0.03	0.52±0.03[3]	–159.3583	22.0376	37

For Kauaʻi samples, superscripted ages indicate samples also dated by Clague and Dalrymple (1988), with the following resulting K-Ar ages and ±1σ error:

[1]1.914±0.023 Ma

[2]0.648±0.034 Ma

[3]0.554±0.023 Ma

shown on fig. 14). Also assigned to the uppermost part of the Waimea Canyon Basalt (corresponding to postshield-stage volcanism) are three basanite samples with K-Ar ages in the range 3.92±0.03 to 3.85±0.06 Ma (Garcia and others, 2010). These samples share chemical and isotopic characteristics with other younger Kōloa lavas. Their ages and isotope chemistry, in conjunction with those of the dated hawaiite and mugearite, suggest that the transition from postshield to rejuvenated stages may be gradational (interbedded stratigraphically) and that an eruptive hiatus need not necessarily occur in order to define the onset of the rejuvenated stage.

Wai‘anae

The postshield sequence on Wai‘anae volcano (O‘ahu) comprises the Pālehua and Kolekole Members of the Wai‘anae Volcanics (mapping of J.M. Sinton, plate 3 in Sherrod and others, 2007b). The Pālehua, 3.06–2.98 Ma in age, contains hawaiite and mugearite, whereas the overlying Kolekole, 2.98–2.90 Ma, is tholeiitic (Presley and others, 1997). The Kolekole Member, which contains the youngest of the lava flows on Wai‘anae volcano, was once interpreted as a rejuvenated-stage formation, but it has been reclassified as late postshield stage, partly because it follows so closely on the deposition of the Pālehua Member (Presley and others, 1997). Chemically, Kolekole lava flows are distinct from rejuvenated-stage lavas by virtue of their higher SiO_2 (compare figs. 13*B* and 17). They and the underlying Pālehua Member form an unusual postshield sequence, however, because the younger part (Kolekole) is generally lower in total alkali content than the older part (Pālehua; fig. 13*B*).

Haleakalā

Much longer postshield stages characterize a few volcanoes. At Haleakalā volcano, the Kula Volcanics erupted from 0.96 Ma until 0.12 Ma, and activity was continuous with the overlying Hāna Volcanics (Sherrod and others, 2003). These two formations form a cap 1 km thick across the summit of Haleakalā.

In a matter of clarification, the Hāna Volcanics stratigraphic unit was long considered a rejuvenated-stage formation on the basis of a presumed depositional hiatus that separated it from the Kula Volcanics (Stearns and Macdonald, 1942). Erosion of large valleys on East Maui, which preceded emplacement of the Hāna, was thought to require substantial time. Detailed dating at Haleakalā, however, shows that as little as 0.03 m.y. may have been required to deeply scallop the landscape. The Hāna Volcanics unit is geochemically similar to the upper part of Haleakalā’s postshield formation, the Kula Volcanics. The lack of any intervening hiatus favors an interpretation that the Hāna is merely the waning phase of postshield volcanism (Sherrod and others, 2003).

Kaho‘olawe

The Kaho‘olawe volcanic complex exposes the youngest part of shield-building strata, including what were described as postcaldera strata (Stearns, 1940). More recently, geochemical analyses suggest that these postcaldera lava flows, which range from tholeiitic basalt to hawaiite, correspond to a transition into the postshield volcanic stage (Fodor and others, 1992; Leeman and others, 1994). The extent of likely postshield-stage strata, as shown on the geologic map of Hawai‘i (plate 6 of Sherrod and others, 2007b), is derived from an unpublished compilation by Harold Stearns (courtesy of M.O. Garcia).

Kaho‘olawe’s youngest volcanic products are found on the east side of the island. These lava flows and tephra, tholeiitic in composition, overlie older strata with pronounced discordance, probably owing to a preceding episode of slope collapse. In the absence of dating, this discordance was taken as evidence that substantial time intervened before eruption of the mantling volcanic rocks (Stearns, 1940), which were thought to be part of rejuvenated-stage volcanism (Langenheim and Clague, 1987). However, new ages of about 0.98 Ma (Sano and others, 2006) show that the mantling lava flows are coeval with Kaho‘olawe’s postshield strata, and their chemistry makes them similar to those strata. The structural discordance between the two is a rare instance where the age of a slope-failure event has been dated directly.

Distribution of Postshield-Stage Cones and Eruptive Fissures

Postshield cinder and spatter cones are concentrated along preexisting rift zones on West Moloka‘i, Haleakalā, and Hualālai, whereas they are more dispersed on Kohala, East Moloka‘i, and Wai‘anae. On Mauna Kea, the cones are scattered over a large region of the summit and upper slopes.

Xenoliths in Postshield Lava and Tephra

Xenoliths are abundant in postshield lavas and cinder on Mauna Kea (Fodor and Vandermeyden, 1988; Fodor and Galar, 1997; Fodor, 2001) and Hualālai (Jackson, 1968; Jackson and others, 1981; Bohrson and Clague, 1988; Clague and Bohrson, 1991; Chen and others, 1992; Shamberger and Hammer, 2006). Xenoliths in postshield lavas are also present at Kohala, East Moloka‘i, West Maui, and Wai‘anae but are much less common and smaller (Jackson and others, 1982). All xenoliths in postshield eruptive products are mid-to-deep crustal cumulates, including rare ocean crust gabbro (Clague, 1987a). The ultramafic xenoliths are dominated by dunite, clinopyroxenite, and wehrlite rather than the mantle lithologies lherzolite and pyroxenite (with or without garnet) or harzburgite that predominate in rejuvenated-stage tephra and lavas and in rare preshield-stage lavas from Lō‘ihi Seamount (Clague, 1988).

Isotopes Indicate Changing Source Composition Through Time

Fractionation and changes in source composition accompany the development of postshield-stage volcanic sequences, although such distinctions are difficult to recognize at those Hawaiian volcanoes where the accumulated strata are thin or unevenly distributed. Where the postshield sequence is thick, however, or where the episode was sufficiently long-lived, chemical variation through time can commonly be documented.

At Haleakalā, the Hawaiian volcano with the greatest exposed thickness of postshield strata, strontium isotopic ratios diminish upsection, from 0.70355 (in the lower part of Kula Volcanics) to as low as 0.70308 (upper part of Kula and overlying Hāna Volcanics; fig. 16*A*; data of West and Leeman, 1987, 1994; West, 1988; Chen and others, 1991). An even greater span is seen if the stratigraphically transitional lava of the Honomanū Basalt is considered (fig. 16*A*). The strontium isotopes indicate that the contribution of various source components in the underlying mantle changed during the lengthy history of postshield-stage volcanism at Haleakalā (Chen and others, 1991). For East Molokaʻi, a similar pattern may apply, but there the postshield stratigraphic sequence is too thin to define an extensive change (fig. 16*B*).

Rejuvenated-Stage Volcanism

The rejuvenated stage encompasses those volcanic deposits that form the latest stage in a Hawaiian volcano's history. As classically defined, the term "rejuvenated stage" was conceived to account for volcanism that resumed following a period of quiescence. Indeed, rejuvenated-stage volcanism was first recognized because field evidence indicated an intervening period of inactivity—for example, weathering contrasts among older and younger lava flows, the preservation of primary geomorphic features in young lava flows or vents and their absence in older ones, or evidence that substantial erosion preceded the emplacement of lava flows in canyons or across alluvial fans. By these criteria, 5 of the 15 emergent volcanoes on the 8 major Hawaiian Islands have rejuvenated-stage volcanism: Niʻihau, Kauaʻi, Koʻolau (Oʻahu), East Molokaʻi, and West Maui volcanoes. Rejuvenated-stage eruptions include the youngest eruptions on the Islands of Niʻihau, Kauaʻi, Oʻahu, and Molokaʻi. Rejuvenated-stage lavas of West Maui volcano are older than postshield-stage eruptions of Haleakalā on the same island, and no volcano on the Island of Hawaiʻi has reached the rejuvenated stage.

Rejuvenated-stage lava flows and vent deposits diminish greatly in areal extent southeastward along the island chain. About 35 percent of both Niʻihau and Kauaʻi are covered by rejuvenated-stage products. In contrast, at Koʻolau volcano (Oʻahu) the coverage is only 6 percent. Coverage of East Molokaʻi is only about 2 percent, where this stage is represented only by the single Kalaupapa shield (Clague and others, 1982) and perhaps two islets off the east end of Molokaʻi (Stearns and Macdonald, 1947). On West Maui the coverage is a mere 0.6 percent, the consequence of four scoria cones and two lava-flow units (Tagami and others, 2003). This areal comparison, from simple GIS calculations (Sherrod and others, 2007b), lacks the significance of volume calculations. But volume decreases likely are similar in magnitude or even more substantial southeastward, because the extensive lava sequences on the northwestern islands include more basin-filling, thick deposits. Erosion has stripped some products, and substantial areas of rejuvenated-stage lava flows are flooded in the offshore reaches of the islands, which further limits the comparison. The time span of emplacement is longer on Niʻihau and Kauaʻi (2.5–3.5 m.y) than on the other three islands (only the past 1 m.y.). Even so, normalization for age will not compensate for these differences in areal extent.

Rejuvenated-stage rocks share some similarities with postshield-stage rocks. Both are alkalic. Eruptive products are scoria, cinder, and ash cones, and lava flows, chiefly ʻaʻā. Vent loci are scattered without regard to the alignment of rift zones that were active in shield-stage time.

Does a Time Gap or Chemical Change Define Rejuvenated-Stage Volcanism?

Where a time gap occurs between postshield and rejuvenated stages, that hiatus in volcanism ranges from 0.6 m.y (West Maui; Tagami and others, 2003) to ~2 m.y. (Niʻihau; Clague and Dalrymple, 1987). The hiatus can be estimated confidently where rejuvenated-stage eruptive vents are few, because the entire rejuvenated-stage sequence can be dated. Helpful, too, is adequate dating of the underlying late shield or postshield lava flows emplaced before the quiescence. It is only in the last decade that these goals have been reached for many of the Hawaiian volcanoes.

But is a time gap a requirement to define rejuvenated-stage volcanism? The past two decades brought an onslaught of geochemical analyses and isotopic dating to Hawaiian volcano investigations. Discoveries have brought surprises, not the least of which is the exceedingly brief time gap that separates some volcanic stratigraphic units that once were thought divided by substantial interludes. Lengthy time gaps simplify the assignment of strata to growth stages, whereas transitions during brief interludes confound the task. The definition of Hawaiian rejuvenated-stage volcanism is currently a dilemma. No single chemical criterion adequately distinguishes between postshield- and rejuvenated-stage volcanism. And if a hiatus is required, then what is the definitive duration? Herein we first address the general characteristics of rejuvenated-stage volcanism and then return to the question of definitions.

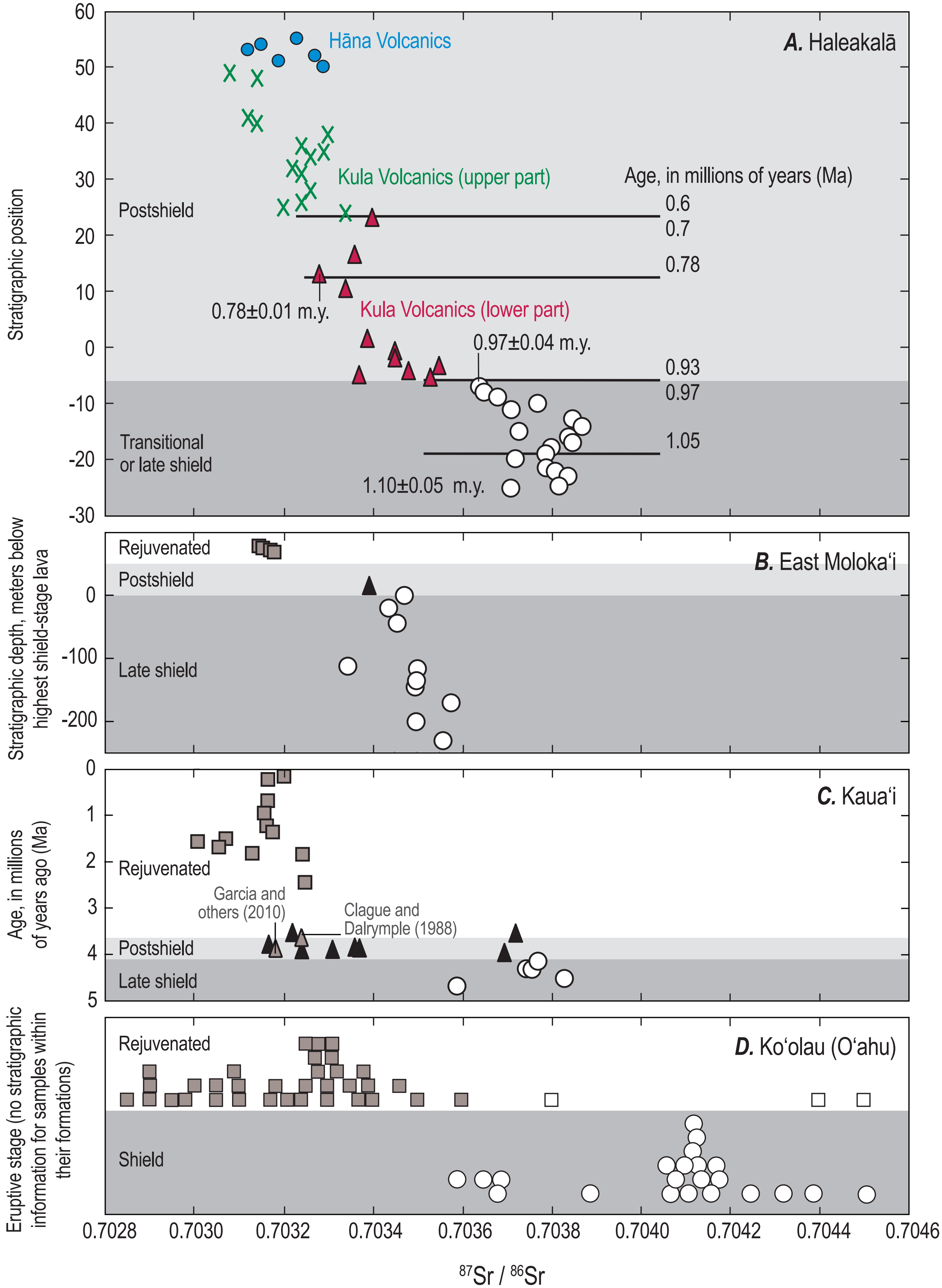

A. Haleakalā
Hāna Volcanics
Kula Volcanics (upper part)
Kula Volcanics (lower part)
Age, in millions of years (Ma)
0.6
0.7
0.78
0.93
0.97
1.05
0.78±0.01 m.y.
0.97±0.04 m.y.
1.10±0.05 m.y.
Postshield
Transitional or late shield
Stratigraphic position
B. East Moloka‘i
Rejuvenated
Postshield
Late shield
Stratigraphic depth, meters below highest shield-stage lava
C. Kaua‘i
Rejuvenated
Garcia and others (2010)
Clague and Dalrymple (1988)
Postshield
Late shield
Age, in millions of years ago (Ma)
D. Ko‘olau (O‘ahu)
Rejuvenated
Shield
Eruptive stage (no stratigraphic information for samples within their formations)
$^{87}Sr / ^{86}Sr$

Figure 16. Graphs showing strontium isotopic ratio ($^{87}Sr/^{86}Sr$), relative to stratigraphic position for strata of late shield, postshield, and rejuvenated stages at selected Hawaiian volcanoes. *A*, Haleakalā volcano. Data from West and Leeman (1987) and Chen and others (1991). "Stratigraphic position" corresponds to numbering system of West and Leeman (1994) for lava flows of Kula Volcanics. Samples plotted in stratigraphic positions 0 to –6 are from underlying strata now considered part of the Kula (Macdonald and others, 1983), and the top of Honomanū Basalt is placed lower. Stratigraphic positions for Hāna Volcanics assigned by using location data in West (1988) and mapping and dating by Sherrod and McGeehin (1999). Ages, in millions of years ago (Ma), from isotopically analyzed samples from Chen and others (1991). Generalized, nonlinear time scale relies on magnetic polarity data and the few ages available from samples with Sr isotope data (chiefly from Chen and others, 1991). *B*, East Moloka'i volcano. Isotopic data from Xu and others (2005) for samples collected along Kalaupapa Trail traverse along the cliffy north flank of Moloka'i, where lava flows are subhorizontal in attitude. Sample altitudes, reported by Sherrod and others (2007b), were recalculated to stratigraphic depth by using datum of highest shield-stage lava. *C*, Kaua'i volcano. Isotopic analyses and ages from Clague and Dalrymple (1988) and Garcia and others (2010). *D*, Ko'olau volcano. Samples analyzed for isotopic ratio lack stratigraphic control aside from stratigraphic formation assignment. Not shown are four rejuvenated-stage analyses in range 0.7025–0.7027, to conserve space in the presentation. Discounted are three rejuvenated-stage analyses (unshaded squares) that range from 0.7038 to 0.7045 (Lessing and Catanzaro, 1964), as high as any of the shield-stage results. Vague descriptions permit those three samples to be stream boulders or accidental lithic inclusions in tuff cones.

Youngest Rejuvenated-Stage Lava Flows Along the Island Chain

Sustained, sporadic rejuvenated-stage eruptions have continued into relatively recent time on five of the major islands, even though the age of the shield stage (and therefore of most of the lava volume) decreases from northwest (Ni'ihau) to southeast (Hawai'i). Indeed, when postshield-stage volcanism is added to the mix, every island except Lāna'i and Kaho'olawe has had an eruption in the past 0.4 m.y.

On Ni'ihau, rejuvenated-stage volcanic rocks (the Ki'eki'e Basalt) are as young as 350 ka (fig. 14; G.B. Dalrymple, in Sherrod and others, 2007b). Four samples from offshore range in age from 1.39 to 0.39 Ma (table 4). On Kaua'i, the rejuvenated-stage Kōloa Volcanics has ages as young as 150 ka, with 10 samples younger than 500 ka (Garcia and others, 2010). On O'ahu's Ko'olau volcano, subaerial deposits of the Honolulu Volcanics generally yield youngest ages of about 100 ka (see results and discussion in Ozawa and others, 2005); younger ages have been reported but never corroborated. Offshore, submarine samples from the Koko Rift, also part of the Honolulu Volcanics, yielded youngest ages of about 140 ka (Clague and others, 2006). On East Moloka'i, the Kalaupapa Volcanics have an age of about 350 ka (Clague and others, 1982). On West Maui, lava flows of the Lahaina Volcanics are clustered into two age groups: about 600 ka and 300 ka (Tagami and others, 2003).

In summary, the youngest rejuvenated-stage lavas on Ni'ihau, Kaua'i, Ko'olau (O'ahu), East Moloka'i, and West Maui are in the age range 350–100 ka. The duration of the rejuvenated stage, coupled with youngest ages of volcanic rocks, means that future eruptions on these islands are conceivable, despite their present distances from the Hawaiian hot spot. The infrequency of rejuvenated-stage eruptions, however, reduces the risk they pose to society to very low levels.

A Volumetrically Insignificant Part of Hawaiian Volcanoes

Rejuvenated-stage volcanism has long been known to contribute much less than 1 percent to the cumulative volume of a Hawaiian shield volcano (Macdonald and others, 1983; Clague, 1987a; Clague and Dalrymple, 1987). This estimate recently has been quantified for Kaua'i, which has the most extensive rejuvenated-stage products among all the islands. About 60 km^3 of rejuvenated-stage lava and tephra has been emplaced on the island (Garcia and others, 2010). A conversion to dense-rock-equivalent magma would reduce that volume by about 25 percent, because most of the lava is 'a'ā. Given Kaua'i's total shield volume of 57,600 km^3 (Robinson and Eakins, 2006), the rejuvenated-stage lava is only about 0.1 percent of the total (Garcia and others, 2010).

Ni'ihau is second in the abundance of rejuvenated-stage products (Holcomb and Robinson, 2004; Dixon and others, 2008). At Ni'ihau, a substantial but poorly assessed volume of such products lies offshore (Clague and others, 2000)—but that is still insufficient to amass even 1 percent of the volcano's volume. Rejuvenated-stage lava flows are also widespread offshore around Ka'ula, an islet 37 km southwest of Ni'ihau (Holcomb and Robinson, 2004; Garcia and others, 2008). Offshore lava flows and cones are rare around O'ahu (Clague and others, 2006), Moloka'i (Clague and Moore, 2002), and Kaua'i (Holcomb and Robinson, 2004). They are unknown offshore near any other Hawaiian islands.

However, volcanism resembling rejuvenated stage has occurred on the sea floor at somewhat greater distances from the islands themselves. An extensive young lava field (330 km along its northeast-trending axis) was emplaced on the deep seafloor 100–400 km north of O'ahu (the North Arch field; Clague and others, 1990). These flows cover some 24,000 km^2 and have an estimated volume of 1,000–1,250 km^3 (Clague and others, 2002), about 20 times the volume of rejuvenated-stage lava on Kaua'i. They were erupted from more than 100 vents, whose form ranges from low shields to steep cones. Geochemically the flows are similar to Hawaiian rejuvenated-stage lavas (Yang and others, 2003; Hanyu and others, 2007) by virtue of their high abundance of incompatible elements, depleted rare gases, higher $^{143}Nd/^{144}Nd$, and lower $^{87}Sr/^{86}Sr$ relative to shield-stage lava. Other examples are seen southwest of O'ahu and at several places along the Hawaiian chain as far west as the Midway Islands (Holcomb and Robinson, 2004). These submarine flows call into question the concept of the rejuvenated stage, because they occur at locations that lack prior shield-stage activity, yet they have geochemical characteristics indicating similar magmatic sources and origins as the island-mantling rejuvenated-stage volcanic rocks (Yang and others, 2003).

Other submarine alkalic lavas, similar in many, but not all, aspects to rejuvenated-stage lavas, occur on the Hawaiian Arch south of Hawai‘i (Lipman and others, 1989; Hanyu and others, 2005). They are richer in H_2O and have higher, more primitive He isotopic ratios than rejuvenated-stage lavas (Dixon and Clague, 2001; Hanyu and others, 2005).

Geochemical Characteristics

The products of some rejuvenated-stage volcanism have silica contents that range down to values as low or lower than rocks of the shield and postshield stages, in the range 35–45 percent SiO_2. Rejuvenated and shield-stage compositions are nearly distinct, but the fields for rejuvenated and postshield analyses overlap substantially (fig. 17). As another example, at high MgO content (10–15 percent), contents of incompatible elements, such as Rb (15–40 ppm), are similar to the enriched values seen in postshield rocks.

Strontium isotopic ratios for rejuvenated-stage lava are lower than those of late-shield rocks, but they overlap with those of postshield flows and tephra. On East Moloka‘i, where the volcanic stages are clearly demarcated, rejuvenated-stage lava (Kalaupapa Volcanics) has $^{87}Sr/^{86}Sr$ less than 0.7032, and underlying postshield and shield-stage lava has ratios greater than 0.7033 (fig. 16*B*). At Ko‘olau volcano (O‘ahu), where the postshield stage is lacking, $^{87}Sr/^{86}Sr$ is in the range 0.7025–0.7036 for rejuvenated-stage lava (Honolulu Volcanics) and 0.7036–0.7045 for shield-stage lava (fig. 16*D*). On Kaua‘i, Sr isotopic ratios of rejuvenated-stage lava (0.7030–0.7033) are only slightly lower than those of several of the postshield-stage rocks (~0.7033; fig. 16*C*). Indeed, on Kaua‘i, the notable shift toward lower $^{87}Sr/^{86}Sr$ values occurs in the postshield stage before the largest time gap in activity, but with both high and low Sr isotopic ratios in samples erupted at nearly the same time.

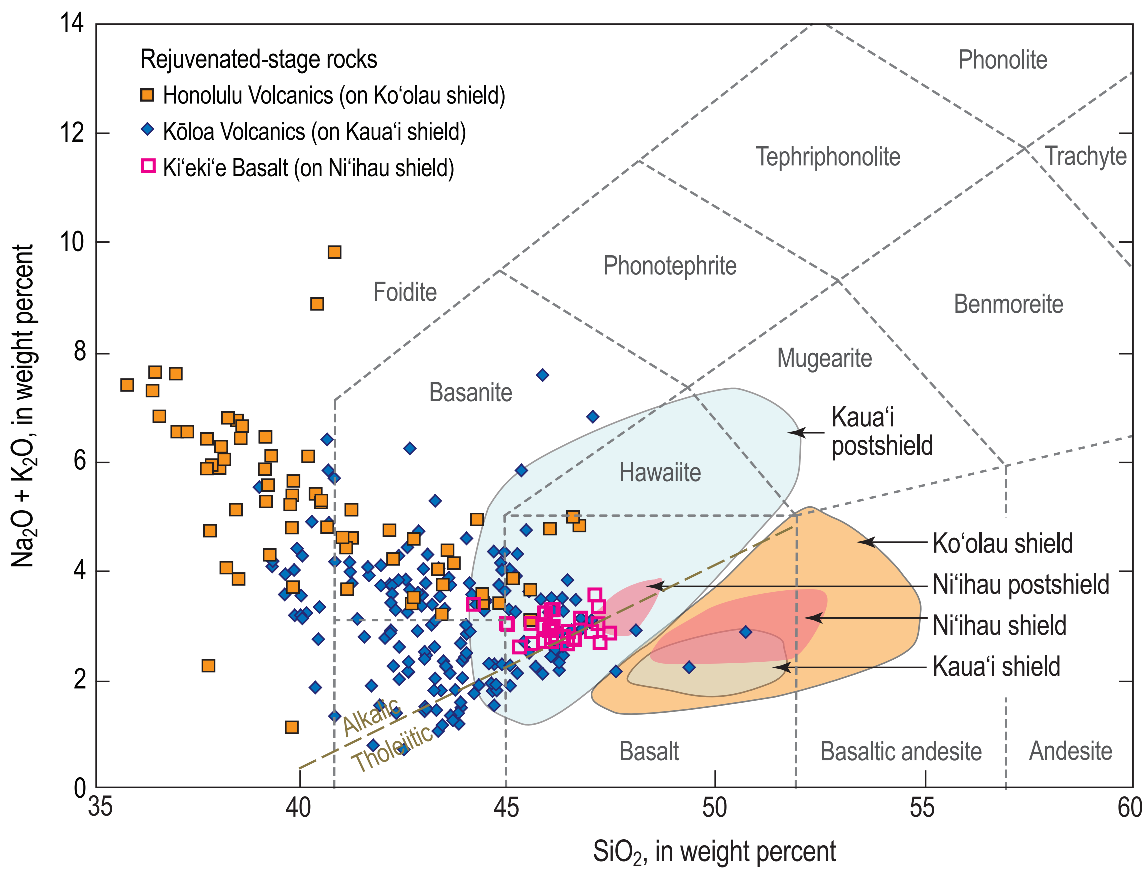


Figure 17. Alkali-silica diagram (Na_2O+K_2O versus SiO_2) for rejuvenated-stage volcanic rocks on Ni‘ihau, Kaua‘i, and O‘ahu. Also shown are the fields of the shield and postshield rocks on those volcanoes. Rock classification grid from Le Maitre (2002); shown dashed is boundary separating tholeiitic from alkalic basalt (Macdonald and Katsura, 1964). Listed in appendix are the specific data sources for these data, on the basis of a published Hawaii-statewide whole-rock geochemistry GIS database (Sherrod and others, 2007b).

Duration of Quiescence

The hiatus in volcanism, where such exists, between postshield and rejuvenated stages ranges from 0.6 m.y. (West Maui; Tagami and others, 2003) to ~2 m.y. (Niʻihau; Clague and Dalrymple, 1987). Estimating the hiatus can be done with some confidence where rejuvenated-stage eruptive vents are few, because the entire rejuvenated-stage sequence can be dated, and the youngest underlying late shield or postshield lava flows are also well dated. These conditions have been reached in the last decade for many of the islands' volcanoes.

For Kauaʻi, Rejuvenated Stage Is Gradational from Postshield Stage

For the Island of Kauaʻi, the age and chemistry of earliest rejuvenated-stage volcanism suggests no hiatus in eruptive activity in the progression from postshield stage. Radiometric dating in the 1980s suggested an odd feature of Kauaʻi's rejuvenated stage compared to that of other Hawaiian volcanoes—an exceedingly brief quiescence preceding the rejuvenated stage but a lengthy pause from 3.65 to 2.59 Ma within rejuvenated time (Clague and Dalrymple, 1988). This "start-pause-resume" history may be the result of an incompletely sampled sequence of volcanic rocks.

Recently, $^{40}Ar/^{39}Ar$ ages as old as about 3.4 Ma were obtained from drill cuttings from the Hanamāʻulu well, which penetrates a deep basin on the east side of Kauaʻi (Izuka and Sherrod, 2011). The ages are 3.11±0.56, 3.22±0.26, and 3.42±0.24 Ma at downhole depths of 160, 210, and 270 m, respectively. All lavas in the Hanamāʻulu well are geochemically similar to rejuvenated-stage lavas (Reiners and others, 1999). Thus, even with their large analytical errors, these new ages fill much of the gap in the preexisting dating archive of rejuvenated-stage lava in the range 3.6–3.0 Ma. The hiatus disappears completely if three basanite lava flows—described by Garcia and others (2010) as postshield with ages of 3.92, 3.85, and 3.58 Ma—are assigned instead to the Kōloa Volcanics, as their low Sr isotopic values suggest (<0.70322 for all three). Regardless of how these controversial samples are finally assigned across the postshield-rejuvenated-stage boundary, any hiatus before rejuvenated-stage activity on Kauaʻi was extremely brief, as was any hiatus between shield and postshield activity. Plausibly, volcanic activity on Kauaʻi continued uninterrupted from shield to postshield to rejuvenated stage, and the change in isotopic signature (especially Sr) at about 3.9–3.8 Ma marks a significant change in the magma source region.

Hypotheses of Rejuvenated-Stage Magma Generation

Rejuvenated-stage volcanism probably originates from lithospheric sources (Lassiter and others, 2000) that undergo decompression melting—for example, as the lithosphere rebounds from the zone of depression beneath the largest young volcanoes (Jackson and Wright, 1970; Bianco and others, 2005) or when hot mantle, dragged initially downward in response to plate motion, rises naturally by its lower density until pressure and temperature are suitable for melt production (Ribe and Christensen, 1999). A low degree of melting of recently metasomatized depleted mantle has been the general model for the formation of rejuvenated-stage magmas for nearly 30 years (Clague and Frey, 1982). As modeled by Garcia and others (2010), mantle in the upper part of the plume undergoes a low degree of partial melting, less than 3 percent. More recent studies have focused on the mantle components included in the melting or on the nature and amount of carbonatitic and silicate melt metasomatism (Dixon and others, 2008).

An alternative explanation for rejuvenated-stage magmas invokes lithospheric melting by conductive heating (Gurriet, 1987), but this is inconsistent with Pb isotopic data from Kauaʻi and Oʻahu (Garcia and others, 2010). It appears that the mantle plume contributes little or no source material (Yang and others, 2003; Hanyu and others, 2005). In any model, enhanced crustal fracturing, such as might result from the lithospheric rebound, may enable magma to percolate upward more easily (Clague and others, 1990).

Degradation and Eventual Submergence of Hawaiian Volcanoes

A spectrum of processes work to degrade the volcanoes once they have formed. Primary among these are subaerial erosion, landslides, and subsidence.

Erosion

Hawaiian volcanoes, especially those that grow high above sea level, experience high rainfall, particularly on their northeastern sides that face the trade winds. Mean annual rainfall amounts locally exceed 9 m (Giambelluca and others, 1986; Haleakala Climate Network, 2011), leading to rapid erosion that carves deep canyons in <1 million years, as seen at Kohala on the Island of Hawaiʻi. Other features once thought to be entirely erosional, such as the pali (cliff) on the north side of East Molokaʻi, are now interpreted as landslide headwalls (on Molokaʻi, of the Wailau slide) or backstepping of those headwalls (Clague and Moore, 2002).

Landslides

Landslides occur at all scales in Hawaiʻi, ranging from small slides that modify coastal cliffs and canyon walls to giant slides that displace large parts of islands (Denlinger and Morgan, this volume, chap. 4). The idea that Hawaiian volcanoes, particularly Koʻolau (Oʻahu) and East Molokaʻi, had been modified by giant landslides was first proposed by Moore (1964). The enormous scale of the landslides made the idea controversial at first, but the evidence became firmly established when the U.S. Geological Survey's Marine Geology Program mapped the newly established 370-km (200 nautical miles) Exclusive Economic Zone around Hawaiʻi in the mid to late 1980s, using the GLORIA sidescan sonar system. Those surveys showed extensive debris fields strewn across the deep sea floor several hundred kilometers from the islands, as well as rotational slumps characterized by large segmented blocks (Moore and others, 1989). The debris fields were proposed to have formed during catastrophic debris avalanches spawned on the upper submarine flanks of the islands.

Seventeen discrete slides that formed in the past 5 m.y. were identified around the main Hawaiian Islands (Moore and others, 1989), and fully 70 are known along the Hawaiian Ridge between Midway Islands and the Island of Hawaiʻi, formed during a 30-m.y. period of emplacement (Holcomb and Robinson, 2004). The corresponding rates of occurrence—one per 300 k.y. and one per 400–450 k.y., respectively—must be minima, because many slides likely occur along the leading (southeast) edge of the chain and are buried by growth of subsequent volcanoes. For example, the entire summit caldera and north rift of Niʻihau are missing, yet no corresponding seafloor deposit has been recognized (Moore and others, 1989). The growth of the Kauaʻi edifice has presumably covered the area northeast of Niʻihau where the landslide would have gone. Likewise, the summit of West Molokaʻi apparently slumped to the east, leaving only some small east-facing fault scarps, and was buried by growth of East Molokaʻi. The eastern half of the caldera on Kahoʻolawe is also missing, now presumably buried beneath Haleakalā and, perhaps, Māhukona and Kohala volcanoes.

Are large landslides more likely during particular growth stages at a volcano? The large slides seem most likely to occur during the most active volcano growth phases—from the late preshield to the early postshield stage. A zone of hot, deforming olivine cumulate inside the active volcanoes may provide some of the force needed to slide a volcano's flank (Clague and Denlinger, 1994), providing a rationale for why the slides may occur mainly during the active growth stages of the volcano's lifespan. The relation between the movement of Kīlauea's south flank (and the southeast and west flanks of Mauna Loa) and the Hilina Pali slump identified in the offshore sonar and bathymetric maps (Morgan and others, 2003) suggests that tectonics of the active volcanoes may trigger the slides. On the other hand, the abundance of the slides along the entire chain suggests that they could also occur long after the volcanoes become inactive. It remains uncertain how, why, and when the slides occur. Would we recognize the precursors, if there were any, should one happen now? The question of slide timing is not an academic one, as slides that could occur at any stage in the life of a volcano pose significantly higher risk to the populations of the older Hawaiian Islands than would catastrophic slides limited to only the active, and sparsely populated, flanks of Kīlauea and Mauna Loa volcanoes.

Landslides on the rainy windward sides of the islands are associated with deep erosional canyons (Clague and Moore, 2002). High rainfall may lead to deep erosion, as well as high pore pressure on the windward (north and northeast) sides of the volcanoes, contributing to flank instability and failures while the rift and magma reservoir systems are actively spreading. Landslides, however, are equally common on the lee or dry sides of the islands. Studies of the submarine slides on the west flank of Mauna Loa have shown that the slides may move along surfaces that also serve as hot fluid pathways, forming greenschist facies metamorphic rocks along those surfaces (Morgan and Clague, 2003; Morgan and others, 2007).

Megatsunami

A significant hazard created by giant landslides at the Hawaiian Islands is the large displacement of seawater to generate catastrophic giant waves (megatsunami). The geologic evidence for megatsunami in the Hawaiian Islands was recognized first on Lānaʻi and Molokaʻi, where chaotic coral and lava-clast breccia is preserved as high as 155 m above sea level (J.G. Moore and Moore, 1984; G.W. Moore and Moore, 1988; Moore and others, 1994). This interpretation has been debated in numerous papers (for example, Grigg and Jones, 1997; Felton and others, 2000; Rubin and others, 2000; Keating and Helsey, 2002), which argue that these high-stand deposits are the result of island uplift. No other data suggest that Lānaʻi is, or has been, uplifted, however, and evidence to the contrary has been gleaned from drowned reefs south of Lānaʻi (Webster and others, 2006, 2007). McMurtry and others (2004) describe a similar deposit near the shoreline on Kohala volcano that is close in age to an offshore drowned reef now at nearly 400-m depth, suggesting that the megatsunami that produced this deposit washed up the slope of Kohala at least 400 m. Roughly one-third of the giant landslides from the Hawaiian Islands and the Hawaiian Ridge are debris avalanches with the capacity to generate huge tsunami that sweep hundreds of meters up the slopes of nearby islands. Such tsunami from future, though infrequent, landslides pose a large but unquantified risk to the State of Hawaii and possibly to coastal lands along the Pacific rim.

Subsidence

Subsidence of Hawaiian volcanoes occurs by two processes that overlap in time and space (Moore, 1987). The first process occurs as the increasing mass of a growing volcano depresses the underlying lithosphere. This rapid phase of subsidence, which lasts perhaps 1 m.y., submerges shorelines and reef complexes by more than 1 km. The rate of subsidence is high beneath young islands: for example, a rate of 2.6 m/k.y. was estimated off the northwest coast of the Island of Hawaiʻi by dating drowned coral reefs (Ludwig and others, 1991). Smaller volcanoes may completely submerge during the short period of rapid subsidence, as did, for example, Māhukona volcano (Clague and Moore, 1991; Clague and Calvert, 2009) and many volcanoes in the northwestern Hawaiian Islands. Once a volcano has submerged by more than the glacioeustatic variations in sea level (~125 m), it is unlikely to reemerge. Drowned coral reefs are the primary evidence for this early period of rapid subsidence, and modeling has shown that the reefs drown during deglacial periods of rising sea level (Webster and others, 2009). Very high rates of sea-level rise during meltwater pulses of deglacial periods, coupled with rapid subsidence, may be required to rapidly submerge the reef (Webster and others, 2004). The drowned reefs surrounding each island formed and drowned during the period of rapid subsidence caused by lithospheric flexure during the active growth of each volcano, so reefs around Lāna‘i, for example, are older than reefs around Hawai‘i (Webster and others, 2010).

Concurrently, the lithosphere beneath the islands ages and thermally contracts. The rate of this subsidence diminishes exponentially as a function of lithospheric age. Along much of the Hawaiian Ridge and Emperor Seamounts, this subsidence rate is ~0.01 m/k.y. (Clague and others, 2010) and, thus, is insignificant for human culture.

The flexural loading of the lithosphere from the weight of the growing volcanic edifices causes a small amount of uplift, focused at a distance several hundred kilometers out from the center of the magma supply zone, to form the Hawaiian Arch (Deitz and Menard, 1953). Onshore evidence for a small amount of uplift comes from O‘ahu, where coral reef deposits of oxygen-isotope substage 5e (133–115 ka; Shackleton and others, 2003) are exposed around the entire island (Stearns, 1974; Muhs and Szabo, 1994) and a ~334-ka coral reef now stands 21 m above sea level (McMurtry and others, 2010).

Large Hawaiian volcanoes can persist as islands through the rapid subsidence by building upward rapidly enough. But in the long run, the inexorable thermal contraction-induced subsidence, coupled with surface erosion, erases any volcanic remnant above sea level in about 15 m.y. Gardner Pinnacles, of that age, is the oldest surviving island in the chain with subaerially exposed volcanic rock. Beyond Gardner Pinnacles to the northwest are small sand islands and atolls, interspersed with smaller volcanoes whose summits submerged soon after the volcano formed. Many of the atolls have long and complex histories of carbonate deposition; at Kōkō Seamount in the southern Emperor Seamounts, deposition lasted from about 50 Ma to 16 Ma (Clague and others, 2010), when the last deep-water coralline algae finally submerged below their growth limit of –150 m. For the Hawaiian chain, a complex interplay of subsidence, northward movement into cooler waters, and rapid climate change is required to drown the reefs (Clague and others, 2010), because corals can grow faster than the slow rates of subsidence caused by thermal contraction of the lithosphere. The atolls and sand islands along the Hawaiian chain have undergone complicated growth, emergence, and subsidence histories related to Pleistocene and earlier sea level changes, but only Midway Islands atoll has been sampled well enough (Ladd and others, 1970) to perhaps decipher this history. In the Hawaiian chain, these changes conspire to drown the reefs about 33 m.y. after the underlying volcanoes formed, at which time the last of the atolls submerge to become guyots. Grigg (1982, 1997) called this time the Darwin Point. All the volcanoes west of Midway Islands and Kure Atoll are submerged, and most are guyots.

Future Work

In assembling the enormous amount of information about the geology of the Hawaiian Islands for this overview, we were struck by how much of our understanding of the evolution of Hawai‘i is built on three basic building blocks: detailed geologic mapping, radiometric dating, and geochemical analyses. Many of these framework studies were done decades ago and are now in dire need of updating. A fourth building block—that of submarine studies of the flanks and submarine rifts of the islands—has come into its own mainly during the past 25 years. If we expect to continue to develop new ideas and improve our knowledge of Hawaiian geology in the coming years, the Hawaiian Volcano Observatory should continue to foster broad interest and studies in the geology of all the Hawaiian Islands.

Acknowledgments

The authors thank Pete Lipman, John Sinton, Don Swanson, and Peter Stauffer for penetrating comments that greatly improved the presentation and content of the manuscript. We appreciate their time and effort in wading through such a long treatise. Jim Kauahikaua kindly provided the gravity data shown in figure 10. Our views on Hawaiian geology have developed over many years of interactions, collaborations, discussions, and arguments with many other scientists, most notably Michelle Coombs, Brian Cousens, Brent Dalrymple, Roger Denlinger, Jackie Dixon, Dan Dzurisin, Fred Frey, Mike Garcia, Roz Helz, Shichun Huang, Jim Kauahikaua, Pete Lipman, Jack Lockwood, Jim Moore, Julia Morgan, John Sinton, Don Swanson, Frank Trusdell, Jody Webster, and Guangping Xu.

References Cited

Abouchami, W., Hofmann, A.W., Galer, S.J.G., Frey, F.A., Eisele, J., and Feigenson, M., 2005, Lead isotopes reveal bilateral asymmetry and vertical continuity in the Hawaiian mantle plume: Nature, v. 434, no. 7035, p. 851–856, doi:10.1038/nature03402.

Adams, W.M., and Furumoto, A.S., 1965, A seismic refraction study of the Koolau volcanic plug: Pacific Science, v. 19, no. 3, p. 296–305. [Also available at http://hdl.handle.net/10125/10747.]

Ando, M., 1979, The Hawaii earthquake of November 29, 1975; low dip angle faulting due to forceful injection of magma: Journal of Geophysical Research, v. 84, no. B13, p. 7616–7626, doi:10.1029/JB084iB13p07616.

Atwater, T., and Severinghaus, J., 1989, Tectonic maps of the northeast Pacific, chap. 3 *of* Winterer, E.L., Hussong, D.M., and Decker, R.W., eds., The Eastern Pacific Ocean and Hawaii: Geological Society of America, The Geology of North America Series, v. N, p. 15–20, pls. 3A, 3B, 3C [in slipcase].

Bargar, K.E., and Jackson, E.D., 1974, Calculated volumes of individual shield volcanoes along the Hawaiian-Emperor chain: U.S. Geological Survey Journal of Research, v. 2, no. 5, p. 545–550.

Bauer, G.R., Fodor, R.V., Husler, J.W., and Keil, K., 1973, Contributions to the mineral chemistry of Hawaiian rocks; III. Composition and mineralogy of a new rhyodacite occurrence on Oahu, Hawaii: Contributions to Mineralogy and Petrology, v. 40, no. 3, p. 183–194, doi:10.1007/BF00371038.

Beeson, M.H., 1976, Petrology, mineralogy, and geochemistry of the East Molokai Volcanic Series, Hawaii: U.S. Geological Survey Professional Paper 961, 53 p. [Also available at http://pubs.usgs.gov/pp/0961/report.pdf.]

Bergmanis, E.C., 1998, Rejuvenated volcanism along the southwest rift zone, East Maui, Hawaii; eruptive history of the Hana Volcanics: Honolulu, University of Hawai‘i at Mānoa, M.S. thesis, 70 p.

Bergmanis, E.C., Sinton, J.M., and Trusdell, F.A., 2000, Rejuvenated volcanism along the southwest rift zone, East Maui, Hawai‘i: Bulletin of Volcanology, v. 62, nos. 4–5, p. 239–255, doi:10.1007/s004450000091.

Bianco, T.A., Ito, G., Becker, J.M., and Garcia, M.O., 2005, Secondary Hawaiian volcanism formed by flexural arch decompression: Geochemistry, Geophysics, Geosystems (G^3), v. 6, no. 8, Q08009, 24 p., doi:10.1029/2005GC000945.

Bohrson, W.A., and Clague, D.A., 1988, Origin of ultramafic xenoliths containing exsolved pyroxenes from Hualalai Volcano, Hawaii: Contributions to Mineralogy and Petrology, v. 100, no. 2, p. 139–155, doi:10.1007/BF00373581.

Brill, R.C., 1975, The geology of the lower southwest rift of Haleakala, Hawaii: Honolulu, University of Hawai‘i at Mānoa, M.S. thesis, 65 p., folded map in pocket, scale 1:24,000.

Buchanan-Banks, J.M., 1993, Geologic map of the Hilo 7½′ quadrangle, Island of Hawaii: U.S. Geological Survey Miscellaneous Investigations Series Map I–2274, 17 p., scale 1:24,000. [Also available at http://pubs.usgs.gov/imap/2274/.]

Calvert, A.T., and Lanphere, M.A., 2006, Argon geochronology of Kilauea’s early submarine history, *in* Coombs, M.L., Eakins, B.W., and Cervelli, P.F., eds., Growth and collapse of Hawaiian volcanoes: Journal of Volcanology and Geothermal Research, v. 151, nos. 1–3 (special issue), p. 1–18, doi:10.1016/j.jvolgeores.2005.07.023.

Carson, H.L., and Clague, D.A., 1995, Geology and biogeography of the Hawaiian Islands, chap. 2 *of* Wagner, W.L., and Funk, V.A., eds., Hawaiian biogeography; evolution on a hot-spot archipelago: Washington, D.C., Smithsonian Institution Press, p. 14–29.

Casadevall, T.J., and Hazlett, R.W., 1983, Thermal areas on Kilauea and Mauna Loa volcanoes, Hawaii: Journal of Volcanology and Geothermal Research, v. 16, nos. 3–4, p. 173–188, doi:10.1016/0377-0273(83)90028-8.

Cayol, V., Dieterich, J.H., Okamura, A.T., and Miklius, A., 2000, High magma storage rates before the 1983 eruption of Kilauea, Hawaii: Science, v. 288, no. 5475, p. 2343–2346, doi:10.1126/science.288.5475.2343.

Cervelli, P.F., and Miklius, A., 2003, The shallow magmatic system of Kīlauea Volcano, *in* Heliker, C., Swanson, D.A., and Takahashi, T.J., eds., The Pu‘u ‘Ō‘ō-Kūpaianaha eruption of Kīlauea Volcano, Hawai‘i; the first 20 years: U.S. Geological Survey Professional Paper 1676, p. 149–163. [Also available at http://pubs.usgs.gov/pp/pp1676/.]

Chen, C.-Y., Frey, F.A., and Garcia, M.O., 1990, Evolution of alkalic lavas at Haleakala Volcano, east Maui, Hawaii; major, trace element and isotopic constraints: Contributions to Mineralogy and Petrology, v. 105, no. 2, p. 197–218, doi:10.1007/BF00678986.

Chen, C.-Y., Frey, F.A., Garcia, M.O., Dalrymple, G.B., and Hart, S.R., 1991, The tholeiite to alkalic basalt transition at Haleakala Volcano, Maui, Hawaii: Contributions to Mineralogy and Petrology, v. 106, no. 2, p. 183–200, doi:10.1007/BF00306433.

Chen, C.-Y., Presnall, D.C., and Stern, R.J., 1992, Petrogenesis of ultramafic xenoliths from the 1800 Kaupulehu flow, Hualalai Volcano, Hawaii: Journal of Petrology, v. 33, no. 1, p. 163–202, doi:10.1093/petrology/33.1.163.

Clague, D.A., 1987a, Hawaiian xenolith populations, magma supply rates, and development of magma chambers: Bulletin of Volcanology, v. 49, no. 4, p. 577–587, doi:10.1007/BF01079963.

Clague, D.A., 1987b, Petrology of West Molokai Volcano [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 366, accessed May 31, 2013, at https://irma.nps.gov/App/Reference/Profile/635288/.

Clague, D.A., 1988, Petrology of ultramafic xenoliths from Loihi Seamount, Hawaii: Journal of Petrology, v. 29, no. 6, p. 1161–1186, doi:10.1093/petrology/29.6.1161.

Clague, D.A., 1996, The growth and subsidence of the Hawaiian-Emperor volcanic chain, *in* Keast, A., and Miller, S.E., eds., The origin and evolution of Pacific Island biotas, New Guinea to Eastern Polynesia; patterns and processes: The Netherlands, SPB Academic Publishing, p. 35–50.

Clague, D.A., 2009, Accumulation rates of volcaniclastic sediment on Loihi Seamount, Hawaii: Bulletin of Volcanology, v. 71, no. 6, p. 705–710, doi:10.1007/s00445-009-0281-y.

Clague, D.A., and Beeson, M.H., 1980, Trace element geochemistry of the East Molokai Volcanic Series, Hawaii, *in* Irving, A.J., and Dungan, M.A., eds., The Jackson volume: American Journal of Science, v. 280–A, pt. 2, p. 820–844.

Clague, D.A., and Bohrson, W.A., 1991, Origin of xenoliths in the trachyte at Puu Waawaa, Hualalai Volcano, Hawaii: Contributions to Mineralogy and Petrology, v. 108, no. 4, p. 439–452, doi:10.1007/BF00303448.

Clague, D.A., and Calvert, A.T., 2009, Postshield stage transitional volcanism on Mahukona Volcano, Hawaii: Bulletin of Volcanology, v. 71, no. 5, p. 533–539, doi:10.1007/s00445-008-0240z.

Clague, D.A., and Dalrymple, G.B., 1987, The Hawaiian-Emperor volcanic chain; part I. Geologic evolution, chap. 1 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 5–54. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Clague, D.A., and Dalrymple, G.B., 1988, Age and petrology of alkalic postshield and rejuvenated-stage lava from Kauai, Hawaii: Contributions to Mineralogy and Petrology, v. 99, no. 2, p. 202–218, doi:10.1007/BF00371461.

Clague, D.A., and Denlinger, R.P., 1994, Role of olivine cumulates in destabilizing the flanks of Hawaiian volcanoes: Bulletin of Volcanology, v. 56, nos. 6–7, p. 425–434, doi:10.1007/BF00302824.

Clague, D.A., and Dixon, J.E., 2000, Extrinsic controls on the evolution of Hawaiian ocean volcanoes: Geochemistry, Geophysics, Geosystems (G^3), v. 1, no. 4, 1010, 9 p., doi:10.1029/1999GC000023.

Clague, D.A., and Frey, F.A., 1982, Petrology and trace element geochemistry of the Honolulu Volcanics, Oahu; implications for the oceanic mantle below Hawaii: Journal of Petrology, v. 23, no. 3, p. 447–504, doi:10.1093/petrology/23.3.447.

Clague, D.A., and Moore, J.G., 1991, Geology and petrology of Mahukona Volcano, Hawaii: Bulletin of Volcanology, v. 53, no. 3, p. 159–172, doi:10.1007/BF00301227.

Clague, D.A., and Moore, J.G., 2002, The proximal part of the giant submarine Wailau landslide, Molokai, Hawaii: Journal of Volcanology and Geothermal Research, v. 113, nos. 1–2, p. 259–287, doi:10.1016/S0377-0273(01)00261-X.

Clague, D.A., Dao-gong, C., Murnane, R., Beeson, M.H., Lanphere, M.A., Dalrymple, G.B., Friesen, W., and Holcomb, R.T., 1982, Age and petrology of the Kalaupapa Basalt, Molokai, Hawaii: Pacific Science, v. 36, no. 4, p. 411–420. [Also available at http://hdl.handle.net/10125/474.]

Clague, D.A., Holcomb, R.T., Sinton, J.M., Detrick, R.S., and Torresan, M.E., 1990, Pliocene and Pleistocene alkalic flood basalts on the seafloor north of the Hawaiian islands: Earth and Planetary Science Letters, v. 98, no. 2, p. 175–191, doi:10.1016/0012-821X(90)90058-6.

Clague, D.A., Moore, J.G., Dixon, J.E., and Friesen, W.B., 1995, Petrology of submarine lavas from Kilauea's Puna Ridge, Hawaii: Journal of Petrology, v. 36, no. 2, p. 299–349, doi:10.1093/petrology/36.2.299.

Clague, D.A., Hagstrum, J.T., Champion, D.E., and Beeson, M.H., 1999, Kīlauea summit overflows; their ages and distribution in the Puna District, Hawai‘i: Bulletin of Volcanology, v. 61, no. 6, p. 363–381, doi:10.1007/s004450050279.

Clague, D.A., Moore, J.G., and Reynolds, J.R., 2000, Formation of submarine flat-topped volcanic cones in Hawai‘i: Bulletin of Volcanology, v. 62, no. 3, p. 214–233, doi:10.1007/s004450000088.

Clague, D.A., Uto, K., Satake, K., and Davis, A.S., 2002, Eruption style and flow emplacement in the submarine North Arch Volcanic Field, Hawaii, *in* Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., and Aramaki, S., eds., Hawaiian volcanoes; deep underwater perspectives: American Geophysical Union Geophysical Monograph 128, p. 65–84, doi:10.1029/GM128p0065.

Clague, D.A., Batiza, R., Head, J.W., III, and Davis, A.S., 2003, Pyroclastic and hydroclastic deposits on Loihi Seamount, Hawaii, *in* White, J.D.L., Smellie, J.L., and Clague, D.A., eds., Explosive subaqueous volcanism: American Geophysical Union Geophysical Monograph 140, p. 73–95, doi:10.1029/140GM05.

Clague, D.A., Paduan, J.B., McIntosh, W.C., Cousens, B.L., Davis, A.S., and Reynolds, J.R., 2006, A submarine perspective of the Honolulu Volcanics, Oahu: Journal of Volcanology and Geothermal Research, v. 151, nos. 1–3, p. 279–307, doi:10.1016/j.jvolgeores.2005.07.036.

Clague, D.A., Braga, J.C., Bassi, D., Fullagar, P.D., Renema, W., and Webster, J.M., 2010, The maximum age of Hawaiian terrestrial lineages; geological constraints from Kōko Seamount: Journal of Biogeography, v. 37, no. 6, p. 1022–1033, doi:10.1111/j.1365-2699.2009.02235.x.

Coombs, M.L., Clague, D.A., Moore, G.F., and Cousens, B.L., 2004, Growth and collapse of Waianae Volcano, Hawaii, as revealed by exploration of its submarine flanks: Geochemistry, Geophysics, Geosystems (G^3), v. 5, no. 5, Q08006, 30 p., doi:10.1029/2004GC000717.

Coombs, M., Sisson, T., and Lipman, P., 2006, Growth history of Kilauea inferred from volatile concentrations in submarine-collected basalts, *in* Coombs, M.L., Eakins, B.W., and Cervelli, P.F., eds., Growth and collapse of Hawaiian volcanoes: Journal of Volcanology and Geothermal Research, v. 151, nos. 1–3 (special issue), p. 19–49, doi:10.1016/j.jvolgeores.2005.07.037.

Cousens, B.L., Clague, D.A., and Sharp, W.D., 2003, Chronology, chemistry, and origin of trachytes from Hualalai Volcano, Hawaii: Geochemistry, Geophysics, Geosystems (G^3), v. 4, no. 9, 1078, 27 p., doi:10.1029/2003GC000560.

Cross, W., 1915, Lavas of Hawaii and their relations: U.S. Geological Survey Professional Paper 88, 97 p. [Also available at http://pubs.usgs.gov/pp/0088/report.pdf.]

Davis, A.S., and Clague, D.A., 1998, Changes in the hydrothermal system at Loihi Seamount after the formation of Pele's pit in 1996: Geology, v. 26, no. 5, p. 399–402, doi:10.1130/0091-7613(1998)026<0399:CITHSA>2.3.CO;2.

Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., 1987, Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, 2 v., 1,667 p. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Deitz, R.S., and Menard, H.W., 1953, Hawaiian Swell, Deep, and Arch, and subsidence of the Hawaiian Islands: The Journal of Geology, v. 61, no. 2, p. 99–113, doi:10.1086/626059.

Delaney, P.T., Miklius, A., Árnadóttir, T., Okamura, A.T., and Sako, M.K., 1993, Motion of Kilauea volcano during sustained eruption from the Puu Oo and Kupaianaha Vents, 1983–1991: Journal of Geophysical Research, v. 98, no. B10, p. 17801–17820, doi:10.1029/93JB01819.

Denlinger, R.P., and Morgan, J.K., 2014, Instability of Hawaiian volcanoes, chap. 4 *of* Poland, M.P., Takahashi, T.J., and Landowski, C.M., eds., Characteristics of Hawaiian volcanoes: U.S. Geological Survey Professional Paper 1801 (this volume).

DePaolo, D.J., and Stolper, E.M., 1996, Models of Hawaiian volcano growth and plume structure; implications of results from the Hawaii Scientific Drilling Project, *in* Results of the Hawaii Scientific Drilling Project 1-km core hole at Hilo, Hawaii: Journal of Geophysical Research, v. 101, no. B5 (special section), p. 11643–11654, doi:10.1029/96JB00070.

DePaolo, D.J., Bryce, J.G., Dodson, A., Shuster, D.L., and Kennedy, B.M., 2001, Isotopic evolution of Mauna Loa and the chemical structure of the Hawaiian plume: Geochemistry, Geophysics, Geosystems (G^3), v. 2, no. 7, 1044, 32 p., doi:10.1029/2000GC000139.

Dieterich, J.H., 1988, Growth and persistence of Hawaiian volcanic rift zones: Journal of Geophysical Research, v. 93, no. B5, p. 4258–4270, doi:10.1029/JB093iB05p04258.

Diller, D.E., 1982, Contributions to the geology of West Maui Volcano, Hawaii: Honolulu, University of Hawai‘i at Mānoa, M.S. thesis, 237 p., folded map in pocket, scale 1:24,000.

Dixon, J.E., and Clague, D.A., 2001, Volatiles in basaltic glass from Loihi seamount, Hawaii; evidence for a relatively dry plume component: Journal of Petrology, v. 42, no. 3, p. 627–654, doi:10.1093/petrology/42.3.627.

Dixon, J.E., Clague, D.A., and Stolper, E.M., 1991, Degassing history of water, sulfur, and carbon in submarine lavas from Kilauea Volcano, Hawaii: The Journal of Geology, v. 99, no. 3, p. 371–394, doi:10.1086/629501.

Dixon, J.E., Clague, D.A., Cousens, B.L., Monsalve, M.L., and Uhl, J., 2008, Carbonatite and silicate melt metasomatism of the mantle surrounding the Hawaiian plume; evidence from volatiles, trace elements, and radiogenic isotopes in rejuvenated-stage lavas from Niihau, Hawaii: Geochemistry, Geophysics, Geosystems (G^3), v. 9, no. 9, Q09005, 34 p., doi:10.1029/2008GC002076.

Duncan, R.A., and Keller, R.A., 2004, Radiometric ages for basement rocks from the Emperor Seamounts, ODP Leg 197: Geochemistry, Geophysics, Geosystems (G^3), v. 5, no. 8, Q08L03, 13 p., doi:10.1029/2004GC000704.

Dvorak, J.J., and Dzurisin, D., 1993, Variations in magma supply rate at Kilauea Volcano, Hawaii: Journal of Geophysical Research, v. 98, no. B12, p. 22255–22268, doi:10.1029/93JB02765.

Dzurisin, D., Koyanagi, R.Y., and English, T.T., 1984, Magma supply and storage at Kilauea Volcano, Hawaii, 1956–1983: Journal of Volcanology and Geothermal Research, v. 21, nos. 3–4, p. 177–206, doi:10.1016/0377-0273(84)90022-2.

Eakins, B.W., Robinson, J.E., Kanamatsu, T., Naka, J., Smith, J.R., Takahashi, E., and Clague, D.A., 2003, Hawaii's volcanoes revealed: U.S. Geological Survey Geologic Investigations Series Map I–2809, scale ~1:850,000. (Prepared in cooperation with the Japan Marine Science and Technology Center, the University of Hawai‘i at Mānoa, School of Ocean and Earth Science and Technology, and the Monterey Bay Aquarium Research Institute). [Also available at http://pubs.usgs.gov/imap/2809/pdf/i2809.pdf.]

Easton, R.M., 1987, Stratigraphy of Kilauea Volcano, chap. 11 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 243–260. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Eaton, J.P., and Murata, K.J., 1960, How volcanoes grow: Science, v. 132, no. 3430p3dermeyden, H.J., 1988, Petrology of gabbroic xenoliths from Mauna Kea volcano, Hawaii: Journal of Geophysical Research, v. 93, no. B5, p. 4435–4452, doi:10.1029/JB093iB05p04435.

Faichney, I.D.E., Webster, J.M., Clague, D.A., Kelley, C., Appelgate, B., and Moore, J.G., 2009, The morphology and distribution of submerged reefs in the Maui-Nui complex, Hawaii; new insights into their evolution since the Early Pleistocene: Marine Geology, v. 265, nos. 3–4, p. 130–145, doi:10.1016/j.margeo.2009.07.002.

Faichney, I.D.E., Webster, J.M., Clague, D.A., Paduan, J.B., and Fullagar, P.D., 2010, Unraveling the tilting history of the submerged reefs surrounding Oahu and the Maui-Nui Complex, Hawaii: Geochemistry, Geophysics, Geosystems (G^3), v. 11, Q07002, 20 p., doi:10.1029/2010GC003044.

Feigenson, M.D., 1984, Geochemistry of Kauai volcanics and a mixing model for the origin of Hawaiian alkali basalts: Contributions to Mineralogy and Petrology, v. 87, no. 2, p. 109–119, doi:10.1007/BF00376217.

Felton, E.A., Crook, K.A.W., and Keating, B.H., 2000, The Hulopoe Gravel, Lanai, Hawaii; new sedimentological data and their bearing on the "giant wave" (mega-tsunami) emplacement hypothesis: Pure and Applied Geophysics, v. 157, nos. 6–8, p. 1257–1284, doi:10.1007/s000240050025.

Fiske, R.S., and Jackson, E.D., 1972, Orientation and growth of Hawaiian volcanic rifts; the effect of regional structure and gravitational stresses: Proceedings of the Royal Society of London, ser. A, v. 329, p. 299–326, doi:10.1098/rspa.1972.0115.

Fiske, R.S., Rose, T.R., Swanson, D.A., Champion, D.E., and McGeehin, J.P., 2009, Kulanaokuaiki Tephra (ca. A.D. 400–1000); newly recognized evidence for highly explosive eruptions at Kīlauea Volcano, Hawai‘i: Geological Society of America Bulletin, v. 121, nos. 5–6, p. 712–728, doi:10.1130/B26327.1.

Flinders, A.F., Ito, G., and Garcia, M.O., 2010, Gravity anomalies of the Northern Hawaiian Islands; implications on the shield evolutions of Kauai and Niihau: Journal of Geophysical Research, v. 115, B08412, 15 p., doi:10.1029/2009JB006877.

Fodor, R.V., 2001, The role of tonalite and diorite in Mauna Kea volcano, Hawaii, magmatism; petrology of summit-region leucocratic xenoliths: Journal of Petrology, v. 42, no. 9, p. 1685–1704, doi:10.1093/petrology/42.9.1685.

Fodor, R.V., and Galar, P., 1997, A view into the subsurface of Mauna Kea volcano, Hawaii; crystallization processes interpreted through petrology and petrography of gabbroic and ultramafic xenoliths: Journal of Petrology, v. 38, no. 5, p. 581–624, doi:10.1093/petroj/38.5.581.

Fodor, R.V., and Vandermeyden, H.J., 1988, Petrology of gabbroic xenoliths from Mauna Kea volcano, Hawaii: Journal of Geophysical Research, v. 93, no. B5, p. 4435–4452, doi:10.1029/JB093iB05p04435.

Fodor, R.V., Frey, F.A., Bauer, G.R., and Clague, D.A., 1992, Ages, rare-earth element enrichment, and petrogenesis of tholeiitic and alkalic basalts from Kahoolawe Island, Hawaii: Contributions to Mineralogy and Petrology, v. 110, no. 4, p. 442–462, doi:10.1007/BF00344080.

Fornari, D.J., Lockwood, J.P., Lipman, P.W., Rawson, M., and Malahoff, A., 1980, Submarine volcanic features west of Kealakekua Bay, Hawaii, *in* McBirney, A.R., ed., Gordon A. Macdonald memorial volume: Journal of Volcanology and Geothermal Research, v. 7, nos. 3–4 (special issue), p. 323–337, doi:10.1016/0377-0273(80)90036-0.

Fornari, D.J., Garcia, M.O., Tyce, R.C., and Gallo, D.G., 1988, Morphology and structure of Loihi seamount based on Seabeam sonar mapping: Journal of Geophysical Research, v. 93, no. B12, p. 15227–15238, doi:10.1029/JB093iB12p15227.

Frey, F.A., and Clague, D.A., 1983, Geochemistry of diverse basalt types from Loihi Seamount, Hawaii; petrogenetic implications, *in* Loihi Seamount; collected papers: Earth and Planetary Science Letters, v. 66, December, p. 337–355, doi:10.1016/0012-821X(83)90150-4.

Frey, F.A., and Rhodes, J.M., 1993, Intershield geochemical differences among Hawaiian volcanoes; implications for source compositions, melting process and magma ascent paths: Philosophical Transactions of the Royal Society of London, ser. A, v. 342, no. 1663, p. 121–136, doi:10.1098/rsta.1993.0009.

Frey, F.A., Wise, W., Garcia, M.O., West, H., Kwon, S.-T., and Kennedy, A., 1990, Evolution of Mauna Kea Volcano, Hawaii; petrologic and geochemical constraints on postshield volcanism: Journal of Geophysical Research, v. 95, no. B2, p. 1271–1300, doi:10.1029/JB095iB02p01271.

Frey, F.A., Garcia, M.O., and Roden, M.F., 1994, Geochemical characteristics of Koolau Volcano; implications of intershield differences among Hawaiian volcanoes: Geochimica et Cosmochimica Acta, v. 58, no. 5, p. 1441–1462, doi:10.1016/0016-7037(94)90548-7.

Furumoto, A.S., and Kovach, R.L., 1979, The Kalapana earthquake of November 29, 1975; an intra-plate earthquake and its relation to geothermal processes: Physics of the Earth and Planetary Interiors, v. 18, no. 3, p. 197–208, doi:10.1016/0031-9201(79)90114-6.

Furumoto, A.S., Thompson, N.J., and Woollard, G.P., 1965, The structure of Koolau volcano from seismic refractions studies: Pacific Science, v. 19, no. 3, p. 306–314. [Also available at http://hdl.handle.net/10125/10748.]

Gaffney, A.M., Nelson, B.K., and Blichert-Toft, J., 2004, Geochemical constraints on the role of oceanic lithosphere in intra-volcano heterogeneity at West Maui, Hawaii: Journal of Petrology, v. 45, no. 8, p. 1663–1687, doi:10.1093/petrology/egh029.

Garcia, M.O., Kurz, M.D., and Muenow, D.W., 1990, Mahukona; the missing Hawaiian volcano: Geology, v. 18, no. 11, p. 1111–1114, doi:10.1130/0091-7613(1990)018<1111:MTMHV>2.3.CO;2.

Garcia, M.O., Jorgenson, B.A., Mahoney, J.J., Ito, E., and Irving, A.J., 1993, An evaluation of temporal geochemical evolution of Loihi summit lavas; results from *Alvin* submersible dives: Journal of Geophysical Research, v. 98, no. B1, p. 537–550, doi:10.1029/92JB01707.

Garcia, M.O., Foss, D.J.P., West, H.B., and Mahoney, J.J., 1995, Geochemical and isotopic evolution of Loihi Volcano, Hawaii: Journal of Petrology, v. 36, no. 6, p. 1647–1674. (Correction to figure 10 published in Journal of Petrology, 1996, v. 37, no. 3, p. 729, doi:10.1093/petrology/37.3.729.)

Garcia, M.O., Rubin, K.H., Norman, M.D., Rhodes, J.M., Graham, D.W., Muenow, D.W., and Spencer, K., 1998, Petrology and geochronology of basalt breccia from the 1996 earthquake swarm of Loihi seamount, Hawaii; magmatic history of its 1996 eruption: Bulletin of Volcanology, v. 59, no. 8, p. 577–592, doi:10.1007/s004450050211.

Garcia, M.O., Caplan-Auerbach, J., De Carlo, E.H., Kurz, M.D., and Becker, N., 2006, Geology, geochemistry and earthquake history of Lō`ihi Seamount, Hawai`i's youngest volcano: Chemie der Erde Geochemistry, v. 66, no. 2, p. 81–108, doi:10.1016/j.chemer.2005.09.002.

Garcia, M.O., Ito, G., Weis, D., Geist, D., Swinnard, L., Bianco, T., Flinders, A., Taylor, B., Appelgate, B., Blay, C., Hanano, D., Silva, I.N., Naumann, T., Maerschalk, C., Harpp, K., Christensen, B., Sciaroni, L., Tagami, T., and Yamasaki, S., 2008, Widespread secondary volcanism near northern Hawaiian Islands: Eos (American Geophysical Union Transactions), v. 89, no. 52, p. 542–543, doi:10.1029/2008EO520002.

Garcia, M.O., Swinnard, L., Weis, D., Greene, A.R., Tagami, T., Sano, H., and Gandy, C.E., 2010, Petrology, geochemistry and geochronology of Kaua‘i lavas over 4.5 Myr; implications for the origin of rejuvenated volcanism and the evolution of the Hawaiian plume: Journal of Petrology, v. 51, no. 7, p. 1507–1540, doi:10.1093/petrology/egq027.

Gerlach, T.M., and Taylor, B.E., 1990, Carbon isotope constraints on degassing of carbon dioxide from Kilauea Volcano: Geochimica et Cosmochimica Acta, v. 54, no. 7, p. 2051–2058, doi:10.1016/0016-7037(90)90270-U.

Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A., 1986, Rainfall atlas of Hawai'i: Honolulu, Hawaii State Department of Land and Natural Resources, Report R76, 25 p.

Grigg, R.W., 1982, Darwin Point; a threshold for atoll formation: Coral Reefs, v. 1, no. 1, p. 29–34, doi:10.1007/BF00286537.

Grigg, R.W., 1997, Paleoceanography of coral reefs in the Hawaiian-Emperor Chain—revisited: Coral Reefs, v. 16, no. 5, supp., p. S33–S38, doi:10.1007/s003380050239.

Grigg, R.W., and Jones, A.T., 1997, Uplift caused by lithospheric flexure in the Hawaiian Archipelago as revealed by elevated coral deposits: Marine Geology, v. 141, nos. 1–4, p. 11–25, doi:10.1016/S0025-3227(97)00069-8.

Guillou, H., Garcia, M.O., and Turpin, L., 1997a, Unspiked K-Ar dating of young volcanic rocks from Loihi and Pitcairn hot-spot volcanoes: Journal of Volcanology and Geothermal Research, v. 78, nos. 3–4, p. 239–249, doi:10.1016/S0377-0273(97)00012-7.

Guillou, H., Turpin, L., Garnier, F., Charbit, S., and Thomas, D.M., 1997b, Unspiked K-Ar dating of Pleistocene tholeiitic basalts from the deep core SOH–4, Kilauea, Hawaii: Chemical Geology, v. 140, nos. 1–2, p. 81–88, doi:10.1016/S0009-2541(97)00044-2.

Guillou, H., Sinton, J., Laj, C., Kissel, C., and Szeremeta, N., 2000, New K-Ar ages of shield lavas from Waianae volcano, Oahu, Hawaiian Archipelago: Journal of Volcanology and Geothermal Research, v. 96, nos. 3–4, p. 229–242, doi:10.1016/S0377-0273(99)00153-5.

Gurriet, P., 1987, A thermal model for the origin of post-erosional alkalic lava: Earth and Planetary Science Letters, v. 82, nos. 1–2, p. 153–158, doi:10.1016/0012-821X(87)90115-4.

Haleakala Climate Network, 2011, Site 164, Big Bog, East Maui: Haleakala Climate Network, accessed November 2011 at http://climate.socialsciences.hawaii.edu/HaleNet/Index.htm.

Hammer, J.E., Coombs, M.L., Shamberger, P.J., and Kimura, J.-I., 2006, Submarine sliver in North Kona; a window into the early magmatic and growth history of Hualalai Volcano, Hawaii, *in* Coombs, M.L., Eakins, B.W., and Cervelli, P.F., eds., Growth and collapse of Hawaiian volcanoes: Journal of Volcanology and Geothermal Research, v. 151, nos. 1–3 (special issue), p. 157–188, doi:10.1016/j.jvolgeores.2005.07.028.

Hanyu, T., Clague, D.A., Kaneoka, I., Dunai, T.J., and Davies, G.R., 2005, Noble gas systematics of submarine alkalic lavas near the Hawaiian hotspot: Chemical Geology, v. 214, nos. 1–2, p. 135–155, doi:10.1016/j.chemgeo.2004.08.051.

Hanyu, T., Johnson, K.T.M., Hirano, N., and Ren, Z.-Y., 2007, Noble gas and geochronologic study of the Hana Ridge, Haleakala volcano, Hawaii; implications to the temporal change of magma source and the structural evolution of the submarine ridge: Chemical Geology, v. 238, nos. 1–2, p. 1–18, doi:10.1016/j.chemgeo.2006.09.008.

Haskins, E.H., and Garcia, M.O., 2004, Scientific drilling reveals geochemical heterogeneity within the Ko'olau shield, Hawai'i: Contributions to Mineralogy and Petrology, v. 147, no. 2, p. 162–188, doi:10.1007/s00410-003-0546-y.

Hauri, E.H., 1996, Major-element variability in the Hawaiian mantle plume: Nature, v. 382, no. 6590, p. 415–419, doi:10.1038/382415a0.

Hawkins, J., and Melchior, J., 1983, Petrology of basalts from Loihi Seamount, Hawaii, *in* Loihi Seamount; collected papers: Earth and Planetary Science Letters, v. 66, December, p. 356–368, doi:10.1016/0012-821X(83)90151-6.

Heliker, C., and Mattox, T.N., 2003, The first two decades of the Pu‘u ‘Ō‘ō-Kūpaianaha eruption; chronology and selected bibliography, *in* Heliker, C., Swanson, D.A., and Takahashi, T.J., eds., The Pu‘u ‘Ō‘ō-Kūpaianaha eruption of Kīlauea Volcano, Hawai‘i; the first 20 years: U.S. Geological Survey Professional Paper 1676, p. 1–27. [Also available at http://pubs.usgs.gov/pp/pp1676/.]

Helz, R.T., Clague, D.A., Sisson, T.W., and Thornber, C.R., 2014, Petrologic insights into basaltic volcanism at historically active Hawaiian volcanoes, chap. 6 *of* Poland, M.P., Takahashi, T.J., and Landowski, C.M., eds., Characteristics of Hawaiian volcanoes: U.S. Geological Survey Professional Paper 1801 (this volume).

Holcomb, R.T., and Robinson, J.E., 2004, Maps of Hawaiian Islands Exclusive Economic Zone interpreted from GLORIA sidescan-sonar imagery: U.S. Geological Survey Scientific Investigations Map 2824, 9 p., scale 1:2,000,000. [Also available at http://pubs.usgs.gov/sim/2004/2824/.]

Holcomb, R.T., Moore, J.G., Lipman, P.W., and Belderson, R.H., 1988, Voluminous submarine lava flows from Hawaiian volcanoes: Geology, v. 16, no. 5, p. 400–404, doi:10.1130/0091-7613(1988)016<0400:VSLFFH>2.3.CO;2.

Holcomb, R.T., Reiners, P.W., Nelson, B.K., and Sawyer, N.-L., 1997, Evidence for two shield volcanoes exposed on the island of Kauai, Hawaii: Geology, v. 25, no. 9, p. 811–814, doi:10.1130/0091-7613(1997)025<0811:EFTSVE>2.3.CO;2.

Holcomb, R.T., Nelson, B.K., Reiners, P.W., and Sawyer, N.-L., 2000, Overlapping volcanoes; the origin of Hilo Ridge, Hawaii: Geology, v. 28, no. 6, p. 547–550, doi:10.1130/0091-7613(2000)28<547:OVTOOH>2.0.CO;2.

Horton, K.A., 1977, Geology of the upper southwest rift zone of Haleakala volcano, Maui, Hawaii: Honolulu, University of Hawaiʻi at Mānoa, M.S. thesis, 115 p.

Huang, S., Abouchami, W., Blichert-Toft, J., Clague, D.A., Cousens, B.L., Frey, F.A., and Humayun, M., 2009, Ancient carbonate sedimentary signature in the Hawaiian plume; evidence from Mahukona volcano, Hawaii: Geochemistry, Geophysics, Geosystems (G^3), v. 10, Q08002, 30 p., doi:10.1029/2009GC002418.

Huang, S., Hall, P.S., and Jackson, M.G., 2011, Geochemical zoning of volcanic chains associated with Pacific hotspots: Nature Geoscience, v. 4, no. 12, p. 874–878, doi:10.1038/NGEO1263.

Izuka, S.K., and Sherrod, D.R., 2011, Radiometric ages for the Koloa Volcanics from the deep subsurface in the Lihuʻe basin, Kauaʻi, Hawaiʻi [abs.]: American Geophysical Union, Fall Meeting 2011 Abstracts, abstract no. V41A–2478, accessed April 28, 2014, at http://abstractsearch.agu.org/meetings/2011/FM/sections/V/sessions/V41A/abstracts/V41A-2478.html.

Jackson, E.D., 1968, The character of the lower crust and upper mantle beneath the Hawaiian Islands: Proceedings of the 23d International Geological Congress, v. 1, p. 135–150.

Jackson, E.D., and Wright, T.L., 1970, Xenoliths in the Honolulu Volcanic Series, Hawaii: Journal of Petrology, v. 11, no. 2, p. 405–430, doi:10.1093/petrology/11.2.405.

Jackson, E.D., Clague, D.A., Engleman, E., Friesen, W.B., and Norton, D., 1981, Xenoliths in the alkalic basalt flows from Hualalai volcano, Hawaii: U.S. Geological Survey Open-File Report 81–1031, 33 p. [Also available at http://pubs.usgs.gov/of/1981/1031/report.pdf.]

Jackson, E.D., Clague, D.A., and Beeson, M.H., 1982, Miscellaneous Hawaiian xenolith localities: U.S. Geological Survey Open-File Report 82–304, 27 p. [Also available at http://pubs.usgs.gov/of/1982/0304/report.pdf.]

Johnson, K.T.M., Reynolds, J.R., Vonderhaar, D., Smith, D.K., and Kong, L.S.L., 2002, Petrological systematics of submarine basalt glasses from the Puna Ridge, Hawaiʻi; implications for rift zone plumbing and magmatic processes, *in* Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., and Aramaki, S., eds., Hawaiian volcanoes; deep underwater perspectives: American Geophysical Union Geophysical Monograph 128, p. 143–159, doi:10.1029/GM128p0143.

Kauahikaua, J., Hildenbrand, T., and Webring, M., 2000, Deep magmatic structures of Hawaiian volcanoes, imaged by three-dimensional gravity methods: Geology, v. 28, no. 10, p. 883–886, doi:10.1130/0091-7613(2000)28<883:DMSOHV>2.0.CO;2.

Kay, R.W., and Gast, P.W., 1973, The rare earth content and origin of alkali-rich basalts: The Journal of Geology, v. 81, no. 6, p. 653–682, doi:10.1086/627919.

Keating, B.H., and Helsey, C.E., 2002, The ancient shorelines of Lanai, Hawaii, revisited: Sedimentary Geology, v. 150, nos. 1–2, p. 3–15, doi:10.1016/S0037-0738(01)00264-0.

Keller, R.A., Fisk, M.R., and Duncan, R.A., 1995, Geochemistry and $^{40}Ar/^{39}Ar$ geochronology of basalts from ODP Leg 145 (North Pacific Transect), chap. 22 of Rea, D.K., Basov, I.A., Scholl, D.W., and Allan, J.F., eds., Proceedings of the Ocean Drilling Program, Scientific Results: College Station, Texas, v. 145, p. 333–344, doi:10.2973/odp.proc.sr.145.131.1995. [Also available at http://www-odp.tamu.edu/publications/.]

Kent, A.J.R., Clague, D.A., Honda, M., Stolper, E.M., Hutcheon, I., and Norman, M.D., 1999, Widespread assimilation of a seawater-derived component at Loihi seamount, Hawaii: Geochimica et Cosmochimica Acta, v. 63, no. 18, p. 2749–2762, doi:10.1016/S0016-7037(99)00215-X.

Kimura J., Sisson, T.W., Nakano, N., Coombs, M.L., and Lipman, P.W., 2006, Isotope geochemistry of early Kilauea magmas from the submarine Hilina bench; the nature of the Hilina mantle component, *in* Coombs, M.L., Eakins, B.W., and Cervelli, P.F., eds., Growth and collapse of Hawaiian volcanoes: Journal of Volcanology and Geothermal Research, v. 151, nos. 1–3 (special issue), p. 51–72, doi:10.1016/j.jvolgeores.2005.07.024.

Klein, F.W., Koyanagi, R.Y., Nakata, J.S., and Tanigawa, W.R., 1987, The seismicity of Kilauea's magma system, chap. 43 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 2, p. 1019–1185. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Krivoy, H.L., Baker, M., Jr., and Moe, E.E., 1965, A reconnaissance gravity survey of the Island of Kauai, Hawaii: Pacific Science, v. 19, no. 3, p. 354–358. [Also available at http://hdl.handle.net/10125/10760.]

Ladd, H.S., Tracey, J.I., Jr., and Gross, M.G., 1970, Deep drilling on Midway Atoll: U.S. Geological Survey Professional Paper 680–A, 22 p. [Also available at http://pubs.usgs.gov/pp/0680a/report.pdf.]

Langenheim, V.A.M., and Clague, D.A., 1987, The Hawaiian-Emperor volcanic chain; part II. Stratigraphic framework of volcanic rocks of the Hawaiian Islands, chap. 1 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 55–84. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Lassiter, J.C., Hauri, E.H., Reiners, P.W., and Garcia, M.O., 2000, Generation of Hawaiian post-erosional lavas by melting of a mixed lherzolite/pyroxenite source: Earth and Planetary Science Letters, v. 178, nos. 3–4, p. 269–284, doi:10.1016/S0012-821X(00)00084-4.

Le Maitre, R.W., ed., 2002, Igneous rocks; a classification and glossary of terms—Recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks (2d ed.): Cambridge, Cambridge University Press, 236 p.

Leeman, W.P., Gerlach, D.C., Garcia, M.O., and West, H.B., 1994, Geochemical variations in lavas from Kahoolawe volcano, Hawaii; evidence for open system evolution of plume-derived magmas: Contributions to Mineralogy and Petrology, v. 116, nos. 1–2, p. 62–77, doi:10.1007/BF00310690.

Lessing, P., and Catanzaro, E.J., 1964, Sr^{87}/Sr^{86} ratios in Hawaiian lavas: Journal of Geophysical Research, v. 69, no. 8, p. 1599–1601, doi:10.1029/JZ069i008p01599.

Lipman, P.W., and Calvert, A.T., 2011, Early growth of Kohala volcano and formation of long Hawaiian rift zones: Geology, v. 39, no. 7, p. 659–662, doi:10.1130/G31929.1.

Lipman, P.W., and Coombs, M.L., 2006, North Kona slump; submarine flank failure during the early(?) tholeiitic shield stage of Hualalai Volcano, *in* Coombs, M.L., Eakins, B.W., and Cervelli, P.F., eds., Growth and collapse of Hawaiian volcanoes: Journal of Volcanology and Geothermal Research, v. 151, nos. 1–3 (special issue), p. 189–216, doi:10.1016/j.jvolgeores.2005.07.029.

Lipman, P.W., Lockwood, J.P., Okamura, R.T., Swanson, D.A., and Yamashita, K.M., 1985, Ground deformation associated with the 1975 magnitude-7.2 earthquake and resulting changes in activity of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 1276, 45 p. [Also available at http://pubs.usgs.gov/pp/1276/report.pdf.]

Lipman, P.W., Clague, D.A., Moore, J.G., and Holcomb, R.T., 1989, South Arch volcanic field—Newly identified young lava flows on the sea floor south of the Hawaiian Ridge: Geology, v. 17, no. 7, p. 611–614, doi:10.1130/0091-7613(1989)017<061.

Lipman, P.W., Sisson, T.W., Ui, T., Naka, J., and Smith, J.R., 2002, Ancestral submarine growth of Kīlauea volcano and instability of its south flank, *in* Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., and Aramaki, S., eds., Hawaiian volcanoes; deep underwater perspectives: American Geophysical Union Geophysical Monograph 128, p. 161–191, doi:10.1029/GM128p0161/GM128p0161, accessed June 4, 2013, at http://www.agu.org/books/gm/v128/GM128p0161/GM128p0161.pdf.

Lipman, P.W., Sisson, T.W., Coombs, M.L., Calvert, A., and Kimura, J., 2006, Piggyback tectonics; long-term growth of Kilauea on the south flank of Mauna Loa, *in* Coombs, M.L., Eakins, B.W., and Cervelli, P.F., eds., Growth and collapse of Hawaiian volcanoes: Journal of Volcanology and Geothermal Research, v. 151, nos. 1–3 (special issue), p. 73–108, doi:10.1016/j.jvolgeores.2005.07.032.

Lockwood, J.P., and Lipman, P.W., 1987, Holocene eruptive history of Mauna Loa volcano, chap. 18 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 509–535. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Loihi Science Team (The 1996), 1997, Researchers rapidly respond to submarine activity at Loihi volcano, Hawaii: Eos (American Geophysical Union Transactions), v. 78, no. 22, p. 229–233, doi:10.1029/97EO00150.

Ludwig, K.R., Szabo, B.J., Moore, J.G., and Simmons, K.R., 1991, Crustal subsidence rates off Hawaii determined from $^{234}U/^{238}U$ ages of drowned coral reefs: Geology, v. 19, no. 2, p. 171–174, doi:10.1130/0091-7613(1991)019<0171:CSROHD>2.3.CO;2.

Maaløe, S., James, D., Smedley, P., Petersen, S., and Garmann, L.B., 1992, The Koloa volcanic suite of Kauai, Hawaii: Journal of Petrology, v. 33, no. 4, p. 761–784, doi:10.1093/petrology/33.4.761.

Macdonald, G.A., 1959, The activity of Hawaiian volcanoes during the years 1951–1956: Bulletin of Volcanology, v. 22, no. 1, p. 3–70, doi:10.1007/BF02596579.

Macdonald, G.A., 1965, Hawaiian calderas: Pacific Science, v. 19, no. 3, p. 320–334. [Also available at http://hdl.handle.net/10125/10752.]

Macdonald, G.A., 1968, Composition and origin of Hawaiian lavas, *in* Coats, R.R., Hay, R.L., and Anderson, C.A., eds., Studies in volcanology—A memoir in honor of Howel Williams: Geological Society of America Memoir 116, p. 477–522, accessed May 31, 2013, at http://memoirs.gsapubs.org/content/116/477.full.pdf.

Macdonald, G.A., 1971, Geologic map of the Mauna Loa quadrangle, Hawaii: U.S. Geological Survey Geologic Quadrangle Map GQ–897, scale 1:24,000. [Also available at http://pubs.er.usgs.gov/publication/gq897.]

Macdonald, G.A., and Katsura, T., 1964, Chemical composition of Hawaiian lavas: Journal of Petrology, v. 5, no. 1, p. 82–133, doi:10.1093/petrology/5.1.82.

Macdonald, G.A., and Powers, H.A., 1946, Contribution to the petrography of Haleakala volcano, Hawaii: Geological Society of America Bulletin, v. 57, no. 1, p. 115–123, doi:10.1130/0016-7606(1946)57[115:CTTPOH]2.0.CO;2.

Macdonald, G.A., and Powers, H.A., 1968, A further contribution to the petrology of Haleakala Volcano, Hawaii: Geological Society of American Bulletin, v. 79, no. 7, p. 877–887, doi:10.1130/0016-7606(1968)79[877:AFCTTP]2.0.CO;2.

Macdonald, G.A., Davis, D.A., and Cox, D.C., 1960, Geology and ground-water resources of the Island of Kauai, Hawaii: Hawaii (Terr.) Division of Hydrography Bulletin 13, 212 p., 2 folded maps in pocket, scale, pl. 1, 1:62,500; pl. 2, 1:180,000. [Also available at http://pubs.usgs.gov/misc/stearns/Kauai.pdf.]

Macdonald, G.A., Abbott, A.T., and Peterson, F.L., 1983, Volcanoes in the sea (2d ed.): Honolulu, University of Hawai‘i Press, 517 p.

Malahoff, A., 1987, Geology of the summit of Loihi submarine volcano, chap. 6 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 133–144. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Mark, R.K., and Moore, J.G., 1987, Slopes of the Hawaiian Ridge, chap. 3 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 101–107. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Mastin, L.G., 1997, Evidence for water influx from a caldera lake during the explosive hydromagmatic eruption of 1790, Kilauea volcano, Hawaii: Journal of Geophysical Research, v. 102, no. B9, p. 20093–20109, doi:10.1029/97JB01426.

Matzen, A.K., Baker, M.B., Beckett, J.R., and Stolper, E.M., 2011, Fe-Mg partitioning between olivine and high-magnesian melts and the nature of Hawaiian parental liquids: Journal of Petrology, v. 52, nos. 7–8, p. 1243–1263, doi:10.1093/petrology/egq089.

McDougall, I., 1964, Potassium-argon ages from lavas of the Hawaiian Islands: Geological Society of America Bulletin, v. 75, no. 2, p. 107–127, doi:10.1130/0016-7606(1964)75[107:PAFLOT]2.0.CO;2.

McMurtry, G.M., Fryer, G.J., Tappin, D.R., Wilkinson, I.P., Williams, M., Fietzke, J., Garbe-Schoenberg, D., and Watts, P., 2004, Megatsunami deposits on Kohala volcano, Hawaii, from flank collapse of Mauna Loa: Geology, v. 32, no. 9, p. 741–744, doi:10.1130/G20642.1.

McMurtry, G.M., Campbell, J.F., Fryer, G.J., and Fietzke, J., 2010, Uplift of Oahu, Hawaii, during the past 500 k.y. as recorded by elevated reef deposits: Geology, v. 38, no. 1, p. 27–30, doi:10.1130/G30378.1.

Miklius, A., Iwatsubo, E.I., Denlinger, R., Okamura, A.T., Sako, M.K., and Yamashita, K., 1994, GPS measurements on the Island of Hawaii in 1992: U.S. Geological Survey Open-File Report 94–288, 44 p. [Also available at http://pubs.usgs.gov/of/1994/0288/report.pdf.]

Moore, G.W., and Moore, J.G., 1988, Large-scale bedforms in boulder gravel produced by giant waves in Hawaii, *in* Clifton, H.E., ed., Sedimentologic consequences of convulsive geologic events: Geological Society of America Special Paper 229, p. 101–110, doi:10.1130/SPE229-p101.

Moore, J.G., 1964, Giant submarine landslides on the Hawaiian Ridge, *in* Geological Survey Research 1964, chap. D: U.S. Geological Survey Professional Paper 501–D, p. D95–D98. [Also available at http://pubs.usgs.gov/pp/0501d/report.pdf.]

Moore, J.G., 1987, Subsidence of the Hawaiian Ridge, chap. 2 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 85–100. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Moore, J.G., and Clague, D.A., 1992, Volcano growth and evolution of the island of Hawaii: Geological Society of America Bulletin, v. 104, no. 11, p. 1471–1484, doi:10.1130/0016-7606(1992)10.

Moore, J.G., and Krivoy, H.L., 1964, The 1962 flank eruption of Kilauea volcano and structure of the east rift zone: Journal of Geophysical Research, v. 69, no. 10, p. 2033–2045, doi:10.1029/JZ069i010p02033.

Moore, J.G., and Moore, G.W., 1984, Deposit from a giant wave on the Island of Lanai, Hawaii: Science, v. 226, no. 4680, p. 1312–1315, doi:10.1126/science.226.4680.1312.

Moore, J.G., Clague, D.A., and Normark, W.R., 1982, Diverse basalt types from Loihi seamount, Hawaii: Geology, v. 10, no. 2, p. 88–92, doi:10.1130/0091-7613(1982).

Moore, J.G., Fornari, D.J., and Clague, D.A., 1985, Basalts from the 1887 submarine eruption of Mauna Loa, Hawaii; new data on the variation of palagonitization rate with temperature: U.S. Geological Survey Bulletin 1163, 11 p. [Also available at http://pubs.usgs.gov/bul/1663/report.pdf.]

Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., and Torresan, M.E., 1989, Prodigious submarine landslides on the Hawaiian Ridge: Journal of Geophysical Research, v. 94, no. B12, p. 17465–17484, doi:10.1029/JB094iB12p17465.

Moore, J.G., Bryan, W.B., and Ludwig, K.R., 1994, Chaotic deposition by a giant wave, Molokai, Hawaii: Geological Society of America Bulletin, v. 106, no. 7, p. 962–967, doi:10.1130/0016-7606(1994)106<0962:CDBAGW>2.3.CO;2.

Morgan, J.K., and Clague, D.A., 2003, Volcanic spreading on Mauna Loa volcano, Hawaii; evidence from accretion, alteration, and exhumation of volcaniclastic sediments: Geology, v. 31, no. 5, p. 411–414, doi:10.1130/0091-7613(2003)031<0411:VSOMLV>2.0.CO;2.

Morgan, J.K., Moore, G.F., and Clague, D.A., 2003, Slope failure and volcanic spreading along the submarine south flank of Kilauea Volcano, Hawaii: Journal of Geophysical Research, v. 108, no. B9, 2415, 23 p., doi:10.1029/2003JB002411.

Morgan, J.K., Clague, D.A., Borchers, D.C., Davis, A.S., and Milliken, K.L., 2007, Mauna Loa’s submarine western flank; landsliding, deep volcanic spreading, and hydrothermal alteration: Geochemistry, Geophysics, Geosystems (G^3), v. 8, Q05002, 42 p., doi:10.1029/2006GC001420.

Morgan, W.J., 1972, Deep mantle convection plumes and plate motions: American Association of Petroleum Geologists Bulletin, v. 56, no. 2, p. 203–213.

Muhs, D.R., and Szabo, B.J., 1994, New uranium-series ages of the Waimanalo Limestone, Oahu, Hawaii; implications for sea level during the last interglacial period: Marine Geology, v. 118, nos. 3–4, p. 315–326, doi:10.1016/0025-3227(94)90091-4.

Muir, I.D., and Tilley, C.E., 1963, Contributions to the petrology of Hawaiian basalts; II. The tholeiitic basalts of Mauna Loa and Kilauea (with chemical analyses by J.H. Scoon): American Journal of Science, v. 261, no. 2, p. 111–128, doi:10.2475/ajs.261.2.111.

Müller, R.D., Roest, W.R., Royer, J.-Y., Gahagan, L.M., and Sclater, J.G., 1997, Digital isochrons of the world's ocean floor: Journal of Geophysical Research, v. 102, no. B2, p. 3211–3214, doi:10.1029/96JB01781.

Nakamura, K., 1982, Why do long rift zones develop in Hawaiian volcanoes—A possible role of thick oceanic sediments, *in* Proceedings of the International Symposium on the Activity of Oceanic Volcanoes: Ponta Delgada, University of the Azores, Natural Sciences Series, v. 3, p. 59–73. (Originally published, in Japanese, in Bulletin of the Volcanological Society of Japan, 1980, v. 25, p. 255–269.)

Naughton, J.J., Macdonald, G.A., and Greenberg, V.A., 1980, Some additional potassium-argon ages of Hawaiian rocks; the Maui volcanic complex of Molokai, Maui, Lanai and Kahoolawe: Journal of Volcanology and Geothermal Research, v. 7, nos. 3–4, p. 339–355, doi:10.1016/0377-0273(80)90037-2.

Neal, C.A., and Lockwood, J.P., 2003, Geologic map of the summit region of Kīlauea Volcano, Hawaii: U.S. Geological Survey Geologic Investigations Series I–2759, 14 p., scale 1:24,000. [Also available at http://pubs.usgs.gov/imap/i2759/.]

Owen, S., Segall, P., Freymueller, J.T., Miklius, A., Denlinger, R.P., Árnadóttir, T., Sako, M.K., and Bürgmann, R., 1995, Rapid deformation of the south flank of Kilauea volcano, Hawaii: Science, v. 267, no. 5202, p. 1328–1332, doi:10.1126/science.267.5202.1328.

Owen, S., Segall, P., Lisowski, M., Miklius, A., Denlinger, R., and Sako, M., 2000, Rapid deformation of Kilauea Volcano; Global Positioning System measurements between 1990 and 1996: Journal of Geophysical Research, v. 105, no. B8, p. 18983–18998, doi:2000JB900109.

Ozawa, A., Tagami, T., and Garcia, M.O., 2005, Unspiked K-Ar dating of the Honolulu rejuvenated and Koʻolau shield volcanism on Oʻahu, Hawaiʻi: Earth and Planetary Science Letters, v. 232, nos. 1–2, p. 1–11, doi:10.1016/j.epsl.2005.01.021.

Palmiter, D.B., 1975, Geology of the Koloa Volcanic Series of the south coast of Kauai, Hawaii: Honolulu, University of Hawaiʻi at Mānoa, M.S. thesis, 87 p., folded map in pocket, scale 1:24,000.

Pauley, B.D., Schiffman, P., Zierenberg, R.A., and Clague, D.A., 2011, Environmental and chemical controls on palagonitization: Geochemistry, Geophysics, Geosystems (G^3), v. 12, Q12017, 26 p., doi:10.1029/2011GC003639.

Peterson, D.W., and Moore, R.B., 1987, Geologic history and evolution of geologic concepts, Island of Hawaii, chap. 7 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 149–189. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Poland, M.P., Miklius, A., and Montgomery-Brown, E.K., 2014, Magma supply, storage, and transport at shield-stage Hawaiian volcanoes, chap. 5 *of* Poland, M.P., Takahashi, T.J., and Landowski, C.M., eds., Characteristics of Hawaiian volcanoes: U.S. Geological Survey Professional Paper 1801 (this volume).

Presley, T.K., Sinton, J.M., and Pringle, M., 1997, Postshield volcanism and catastrophic wasting of the Waianae Volcano, Oahu, Hawaii: Bulletin of Volcanology, v. 58, no. 8, p. 597–616, doi:10.1007/s004450050165.

Price, J.P., and Elliott-Fisk, D., 2004, Topographic history of the Maui Nui complex, Hawaiʻi, and its implications for biogeography: Pacific Science, v. 58, no. 1, p. 27–45, doi:10.1353/psc.2004.0008.

Quane, S.L., Garcia, M.O., Guillou, H., and Hulsebosch, T.P., 2000, Magmatic history of the East Rift Zone of Kilauea Volcano, Hawaii based on drill core from SOH 1: Journal of Volcanology and Geothermal Research, v. 102, nos. 3–4, p. 319–338, doi:10.1016/S0377-0273(00)00194-3.

Reiners, P.W., and Nelson, B.K., 1998, Temporal-compositional-isotopic trends in rejuvenated-stage magmas of Kauai, Hawaii, and implications for mantle melting processes: Geochimica et Cosmochimica Acta, v. 62, no. 13, p. 2347–2368, doi:10.1016/S0016-7037(98)00141-0.

Reiners, P.W., Nelson, B.K., and Izuka, S.K., 1999, Structural and petrologic evolution of the Lihue basin and eastern Kauai, Hawaii: Geological Society of America Bulletin, v. 111, no. 5, p. 674–685, doi:10.1130/0016-7606(1999)111<067.

Ren, Z.-Y., Takahashi, E., Orihashi, Y., and Johnson, K.T.M., 2004, Petrogenesis of tholeiitic lavas from the submarine Hana Ridge, Haleakala volcano, Hawaii: Journal of Petrology, v. 45, no. 10, p. 2067–2099, doi:10.1093/petrology/egh076.

Ren, Z.-Y., Shibata, T., Yoshikawa, M., Johnson, K.T.M., and Takahashi, E., 2006, Isotope compositions of submarine Hana Ridge lavas, Haleakala volcano, Hawaii; implications for source compositions, melting process and the structure of the Hawaiian plume: Journal of Petrology, v. 47, no. 2, p. 255–275, doi:10.1093/petrology/egi074.

Rhodes, J.M., 1996, Geochemical stratigraphy of lava flows sampled by the Hawaii Scientific Drilling Project: Journal of Geophysical Research, v. 101, no. B5, p. 11729–11746, doi:10.1029/95JB03704.

Rhodes, J.M., and Hart, S.R., 1995, Episodic trace element and isotopic variations in historical Mauna Loa lavas; implications for magma and plume dynamics, *in* Rhodes, J.M., and Lockwood, J.P., eds., Mauna Loa revealed; structure, composition, history, and hazards: American Geophysical Union Geophysical Monograph 92, p. 263–288, doi:10.1029/GM092p0263.

Ribe, N.M., and Christensen, U.R., 1999, The dynamical origin of Hawaiian volcanism: Earth and Planetary Science Letters, v. 171, no. 4, p. 517–531, doi:10.1016/S0012-821X(99)00179-X.

Riley, C.M., Diehl, J.F., Kirschvink, J.L., and Ripperdan, R.L., 1999, Paleomagnetic constraints on fault motion in the Hilina Fault System, south flank of Kilauea Volcano, Hawaii: Journal of Volcanology and Geothermal Research, v. 94, nos. 1–4, p. 233–249, doi:10.1016/S0377-0273(99)00105-5.

Robinson, J.E., and Eakins, B.W., 2006, Calculated volumes of individual shield volcanoes at the young end of the Hawaiian Ridge: Journal of Volcanology and Geothermal Research, v. 151, nos. 1–3, p. 309–317, doi:10.1016/j.jvolgeores.2005.07.033.

Rubin, K.H., Fletcher, C.H., III, and Sherman, C., 2000, Fossiliferous Lana'i deposits formed by multiple events rather than a single giant tsunami: Nature, v. 408, no. 6813, p. 675–681, doi:10.1038/35047008.

Ryan, M.P., 1987, Elasticity and contractancy of Hawaiian olivine tholeiite and its role in the stability and structural evolution of subcaldera magma reservoirs and rift systems, chap. 52 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 2, p. 1395–1447. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Sano, H., Sherrod, D.R., and Tagami, T., 2006, Youngest volcanism about 1 million years ago at Kahoolawe, Hawaii: Journal of Volcanology and Geothermal Research, v. 152, nos. 1–2, p. 91–96, doi:10.1016/j.jvolgeores.2005.10.001.

Schipper, C.I., White, J.D.L., Houghton, B.F., Shimizu, N., and Stewart, R.B., 2010a, “Poseidic” explosive eruptions at Loihi Seamount, Hawaii: Geology, v. 38, no. 4, p. 291–294, doi:10.1130/G30351.1.

Schipper, C.I., White, J.D.L., Houghton, B.F., Shimizu, N., and Stewart, R.B., 2010b, Explosive submarine eruptions driven by volatile-coupled degassing at Lōʻihi Seamount, Hawaiʻi: Earth and Planetary Science Letters, v. 295, nos. 3–4, p. 497–510, doi:10.1016/j.epsl.2010.04.031.

Shackleton, N.J., Sánchez-Goñi, M.F., Pailler, D., and Lancelot, Y., 2003, Marine isotope substage 5e and the Eemian Interglacial: Global and Planetary Change, v. 36, no. 3, p. 151–155, doi:10.1016/S0921-8181(02)00181-9.

Shamberger, P.J., and Hammer, J.E., 2006, Leucocratic and gabbroic xenoliths from Hualālai volcano, Hawaiʻi: Journal of Petrology, v. 47, no. 9, p. 1785–1808, doi:10.1093/petrology/egl027.

Sharp, W.D., and Clague, D.A., 2006, 50-Ma initiation of Hawaiian-Emperor bend records major change in Pacific Plate motion: Science, v. 313, no. 5791, p. 1281–1284, doi:10.1126/science.1128489.

Sharp, W.D., and Renne, P.R., 2005, The ^{40}Ar/^{39}Ar dating of core recovered by the Hawaii Scientific Drilling Project (phase 2), Hilo, Hawaii: Geochemistry, Geophysics, Geosystems (G^3), v. 6, no. 4, Q04G17, 18 p., doi:10.1029/2004GC000846.

Sharp, W.D., Turrin, B.D., Renne, P.R., and Lanphere, M.A., 1996, The ^{40}Ar/^{39}Ar and K/Ar dating of lavas from the Hilo 1-km core hole, Hawaii Scientific Drilling Project: Journal of Geophysical Research, v. 101, no. B5, p. 11607–11616, doi:10.1029/95JB03702.

Sherrod, D.R., and McGeehin, J.P., 1999, New radiocarbon ages from Haleakalā Crater, Island of Maui, Hawaiʻi: U.S. Geological Survey Open-File Report 99–143, 14 p. [Also available at http://pubs.usgs.gov/of/1999/0143/report.pdf.]

Sherrod, D.R., Nishimitsu, Y., and Tagami, T., 2003, New K-Ar ages and the geologic evidence against rejuvenated-stage volcanism at Haleakalā, East Maui, a postshield-stage volcano of the Hawaiian island chain: Geological Society of America Bulletin, v. 115, no. 6, p. 683–694, doi:10.1130/0016-7606(2003)115<0683:NKAATG>.

Sherrod, D.R., Murai, T., and Tagami, T., 2007a, New K-Ar ages for calculating the end-of-shield extrusion rates at West Maui volcano, Hawaiian island chain: Bulletin of Volcanology, v. 69, no. 6, p. 627–642, doi:10.1007/s00445-006-0099-9.

Sherrod, D.R., Sinton, J.M., Watkins, S.E., and Brunt, K.M., 2007b, Geologic map of the State of Hawaii (ver. 1): U.S. Geological Survey Open-File Report 2007–1089, 83 p., 8 map sheets, scales 1:100,000 and 1:250,000, with GIS database, accessed May 31, 2013, at http://pubs.usgs.gov/of/2007/1089/.

Simkin, T., Tilling, R.I., Vogt, P.R., Kirby, S.H., Kimberly, P., and Stewart, D.B., 2006, This dynamic planet; world map of volcanoes, earthquakes, impact craters, and plate tectonics (3d ed.): U.S. Geological Survey Geologic Investigations Map I–2800, scale 1:30,000,000. [Also available at http://pubs.usgs.gov/imap/2800/.]

Sinton, J.M., 1987, Revision of stratigraphic nomenclature of Waianae volcano, Oahu, Hawaii, *in* Stratigraphic notes, 1985–86: U.S. Geological Survey Bulletin 1775–A, chap. A, p. A9–A15. [Also available at http://pubs.usgs.gov/bul/1775a/report.pdf.]

Sinton, J.M., 2005, Geologic mapping, volcanic stages and magmatic processes in Hawaiian volcanoes [abs.]: American Geophysical Union, Fall Meeting 2005 Abstracts, abstract no. V51A–1471, accessed April 28, 2014, at http://abstractsearch.agu.org/meetings/2005/FM/sections/V/sessions/V51A/abstracts/V51A-1471.html.

Sisson, T.W., Lipman, P.W., and Naka, J., 2002, Submarine alkalic through tholeiitic shield-stage development of Kīlauea volcano, Hawai‘i, *in* Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., and Aramaki, S., eds., Hawaiian volcanoes; deep underwater perspectives: American Geophysical Union Geophysical Monograph 128, p. 193–219, doi:10.1029/GM128p0193.

Smith, J.R., 2002, The Kaena Ridge submarine rift zone off Oahu, Hawaii [abs.]: American Geophysical Union, Fall Meeting 2002 Abstracts, abstract no. T62A–1300, accessed April 28, 2014, at http://abstractsearch.agu.org/meetings/2002/FM/sections/T/sessions/T62A/abstracts/T62A-1300.html.

Staudigel, H., Zindler, A., Hart, S.R., Leslie, T., Chen, C.-Y., and Clague, D., 1984, The isotope systematics of a juvenile intraplate volcano; Pb, Nd, and Sr isotope ratios of basalts from Loihi Seamount, Hawaii: Earth and Planetary Science Letters, v. 69, no. 1, p. 13–29, doi:10.1016/0012-821X(84)90071-2.

Stearns, H.T., 1939, Geologic map and guide of the Island of Oahu, Hawaii: Hawaii (Terr.) Division of Hydrography Bulletin 2, 75 p., 1 folded map in pocket, scale 1:62,500.

Stearns, H.T., 1940, Geology and ground-water resources of the islands of Lanai and Kahoolawe, Hawaii: Hawaii (Terr.) Division of Hydrography Bulletin 6, pt. 2, p. 117–147, 1 folded map in pocket, scale 1:62,500. [Also available at http://pubs.usgs.gov/misc/stearns/Lanai_and_Kahoolawe.pdf.]

Stearns, H.T., 1946, Geology of the Hawaiian Islands: Hawaii (Terr.) Division of Hydrography Bulletin 8, 106 p.

Stearns, H.T., 1974, Submerged shorelines and shelves in the Hawaiian Islands and a revision of some of the eustatic emerged shorelines: Geological Society of America Bulletin, v. 85, no. 5, p. 795–804, doi:10.1130/0016-7606(1974).

Stearns, H.T., and Macdonald, G.A., 1942, Geology and ground-water resources of the island of Maui: Hawaii (Terr.) Division of Hydrography Bulletin 7, 344 p., 2 folded maps in pocket, scale, pl. 1, 1:62,500; pl. 2, 1:280,000. [Also available at http://pubs.usgs.gov/misc/stearns/Maui.pdf.]

Stearns, H.T., and Macdonald, G.A., 1946, Geology and ground-water resources of the island of Hawaii: Hawaii (Terr.) Division of Hydrography Bulletin 9, 363 p., 3 folded maps in pocket, scale, pl. 1, 1:125,000; pl. 2, 1:500,000; pl. 3, 1:90,000. [Also available at http://pubs.usgs.gov/misc/stearns/Hawaii.pdf.]

Stearns, H.T., and Macdonald, G.A., 1947, Geology and ground-water resources of the island of Molokai, Hawaii: Hawaii (Terr.) Division of Hydrography Bulletin 11, 113 p., 2 folded maps in pocket, scale, pl. 1, 1:62,500; pl. 2, ~1:240,000. [Also available at http://pubs.usgs.gov/misc/stearns/Molokai.pdf.]

Stearns, H.T., and Vaksvik, K.N., 1935, Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii (Terr.) Division of Hydrography Bulletin 1, 479 p. [Also available at http://pubs.usgs.gov/misc/stearns/Oahu.pdf.]

Strange, W.E., Machesky, L.F., and Woollard, G.P., 1965, A gravity survey of the Island of Oahu, Hawaii: Pacific Science, v. 19, no. 3, p. 350–353. [Also available at http://hdl.handle.net/10125/10759.]

Swanson, D.A., 1972, Magma supply rate at Kilauea volcano, 1952–1971: Science, v. 175, no. 4018, p. 169–170, doi:10.1126/science.175.4018.169.

Swanson, D.A., Duffield, W.A., and Fiske, R.S., 1976, Displacement of the south flank of Kilauea Volcano; the result of forceful intrusion of magma into the rift zones: U.S. Geological Survey Professional Paper 963, 39 p. [Also available at http://pubs.usgs.gov/pp/0963/report.pdf.]

Swanson, D.A., Rose, T.R., Fiske, R.S., and McGeehin, J.P., 2012, Keanakāko‘i Tephra produced by 300 years of explosive eruptions following collapse of Kīlauea’s caldera in about 1500 CE: Journal of Volcanology and Geothermal Research, v. 215–216, February 15, p. 8–25, doi:10.1016/j.jvolgeores.2011.11.009.

Tagami, T., Nishimitsu, Y., and Sherrod, D.R., 2003, Rejuvenated-stage volcanism after 0.6-m.y. quiescence at West Maui volcano, Hawaii; new evidence from K-Ar ages and chemistry of Lahaina Volcanics: Journal of Volcanology and Geothermal Research, v. 120, nos. 3–4, p. 207–214, doi:10.1016/S0377-0273(02)00385-2.

Tardona, M., Sinton, J.M., Pyle, D.G., Mahoney, J.J., Guillou, H., and Clague, D.A., 2011, Magmatic and structural evolution of Ka‘ena Ridge, NW O‘ahu, Hawai‘i [abs.]: American Geophysical Union, Fall Meeting 2011 Abstracts, abstract no. V41A–2477, accessed April 28, 2014, at http://abstractsearch.agu.org/meetings/2011/FM/sections/V/sessions/V41A/abstracts/V41A-2477.html.

Tatsumoto, M., 1966, Isotopic composition of lead in volcanic rocks from Hawaii, Iwo Jima, and Japan: Journal of Geophysical Research, v. 71, no. 6, p. 1721–1733, doi:10.1029/JZ071i006p01721.

Tatsumoto, M., 1978, Isotiopic compotisition of lead in oncanic basalt and its implications for mantle evolution: Earth and Planetary Science Letters, v. 38, no. 1, p. 63–87, doi:10.1016/0012-821X(78)90126-7.

Teanby, N., Laj, C., Gubbins, D., and Pringle, M., 2002, A detailed palaeointensity and inclination record from drill core SOH1 on Hawaii: Physics of the Earth and Planetary Interiors, v. 131, no. 2, p. 101–140, doi:10.1016/S0031-9201(02)00032-8.

Thornber, C.R., Rowe, M.C., Adams, D.B., and Orr, T.R., 2010, Application of microbeam techniques to identifying and assessing comagmatic mixing between summit and rift eruptions at Kilauea Volcano [abs.]: American Geophysical Union, Fall Meeting 2010 Abstracts, abstract no. V43F–01, accessed April 28, 2014, at http://abstractsearch.agu.org/meetings/2010/FM/sections/V/sessions/V43F/abstracts/V43F-01.html.

Trusdell, F.A., and Swannell, P., 2003, Explosive deposits on Mauna Loa [abs.]: Cities on Volcanoes 3 meeting, Hilo, Hawaii, July 14–18, 2003, Abstracts Volume, p. 135.

Trusdell, F.A., Novak, E., and Evans, S.R., 1992, Core lithology, State of Hawaii Scientific Observation Hole 4, Kilauea Volcano, Hawaii: U.S. Geological Survey Open-File Report 92–586, 72 p. [Also available at http://pubs.usgs.gov/of/1992/0586/report.pdf.]

Trusdell, F.A., Novak, E., Evans, S.R., and Okano, K., 1999, Core lithology from the State of Hawaii Scientific Observation Hole 1, Kilauea Volcano, Hawaii: U.S. Geological Survey Open-File Report 99–389, 67 p. [Also available at http://hdl.handle.net/10125/21548.]

Trusdell, F.A., Wolfe, E.W., and Morris, J., 2006, Digital database of the geologic map of the Island of Hawai‘i (ver. 1.0): U.S. Geological Survey Data Series 144 (supplement to I–2524A), 18 p., accessed April 2012, at http://pubs.usgs.gov/ds/2005/144/.

Umino, S., Obata, S., Lipman, P., Smith, J.R., Shibata, T., Naka, J., and Trusdell, F., 2002, Emplacement and inflation structures of submarine and subaerial pahoehoe lavas from Hawaii, *in* Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., and Aramaki, S., eds., Hawaiian volcanoes; deep underwater perspectives: American Geophysical Union Geophysical Monograph 128, p. 85–101, doi:10.1029/GM128p0085.

Van Ark, E., and Lin, J., 2004, Time variation in igneous volume flux of the Hawaii-Emperor hot spot seamount chain: Journal of Geophysical Research, v. 109, no. B11, B11401, 18 p., doi:10.1029/2003JB002949.

Walker, G.P.L., 1987, The dike complex of Koolau volcano, Oahu; internal structure of a Hawaiian rift zone, chap. 41 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 2, p. 961–993. [Also available at http://pubs.usgs.gov/pp/1987/1350/.]

Walker, G.P.L., 1988, Three Hawaiian calderas; an origin through loading by shallow intrusions?: Journal of Geophysical Research, v. 93, no. B12, p. 14773–14787, doi:10.1029/JB093iB12p14773.

Wallace, P.J., and Anderson, A.T., Jr., 1998, Effects of eruption and lava drainback on the H_2O contents of basaltic magmas at Kilauea Volcano: Bulletin of Volcanology, v. 59, no. 5, p. 327–344, doi:10.1007/s004450050195.

Wanless, V.D., Garcia, M.O., Rhodes, J.M., Weis, D., and Norman, M.D., 2006a, Shield-stage alkalic volcanism on Mauna Loa Volcano, Hawaii, *in* Coombs, M.L., Eakins, B.W., and Cervelli, P.F., eds., Growth and collapse of Hawaiian volcanoes: Journal of Volcanology and Geothermal Research, v. 151, nos. 1–3 (special issue), p. 141–155, doi:10.1016/j.jvolgeores.2005.07.027.

Wanless, V.D., Garcia, M.O., Trusdell, F.A., Rhodes, J.M., Norman, M.D., Weis, D., Fornari, D.J., Kurz, M.D., and Guillou, H., 2006b, Submarine radial vents on Mauna Loa Volcano, Hawai‘i: Geochemistry, Geophysics, Geosystems (G^3), v. 7, no. 5, Q05001, 28 p., doi:10.1029/2005GC001086.

Washington, H.S., and Keyes, M.G., 1926, Petrology of the Hawaiian Islands, V; The Leeward Islands: American Journal of Science, ser. 5, v. 12, no. 70, p. 336–352, doi:10.2475/ajs.s5-12.70.336.

Watson, S., and McKenzie, D., 1991, Melt generation by plumes; a study of Hawaiian volcanism: Journal of Petrology, v. 32, no. 3, p. 501–537, doi:10.1093/petrology/32.3.501.

Webster, J., Clague, D.A., Riker-Coleman, K., Gallup, C., Braga, J.C., Potts, D., Moore, J.G., Winterer, E.L., and Paull, C.K., 2004, Drowning of the –150 m reef off Hawaii; a casualty of global meltwater pulse 1A?: Geology, v. 32, no. 3, p. 249–252, doi:10.1130/G20170.1.

Webster, J.M., Clague, D.A., Braga, J.C., Spalding, H., Renema, W., Kelley, C., Applegate, B. [*sic*; Appelgate, B.], Smith, J.R., Paull, C.K., Moore, J.G., and Potts, D., 2006, Drowned coralline algal dominated deposits off Lanai, Hawaii; carbonate accretion and vertical tectonics over the last 30 ka: Marine Geology, v. 225, nos. 1–4, p. 223–246, doi:10.1016/j.margeo.2005.08.002.

Webster, J.M., Clague, D.A., and Braga, J.C., 2007, Support for the giant wave hypothesis; evidence from submerged terraces off Lanai, Hawaii: International Journal of Earth Sciences, v. 96, no. 3, p. 517–524, doi:10.1007/s00531-006-0107-5.

Webster, J.M., Braga, J.C., Clague, D.A., Gallup, C., Hein, J.R., Potts, D.C., Renema, W., Riding, R., Riker-Coleman, K., Silver, E., and Wallace, L.M., 2009, Coral reef evolution on rapidly subsiding margins: Global and Planetary Change, v. 66, nos. 1–2, p. 129–148, doi:10.1016/j.gloplacha.2008.07.010.

Webster, J.M., Clague, D.A., Faichney, I.D.E., Fullagar, P.D., Hein, J.R., Moore, J.G., and Paull, C.K., 2010, Early Pleistocene origin of reefs around Lanai, Hawaii: Earth and Planetary Science Letters, v. 290, nos. 3–4, p. 331–339, doi:10.1016/j.epsl.2009.12.029.

Weis, D., Garcia, M.O., Rhodes, J.M., Jellinek, M., and Scoates, J.S., 2011, Role of the deep mantle in generating the compositional asymmetry of the Hawaiian mantle plume: Nature Geoscience, v. 4, no. 12, p. 831–838, doi:10.1038/ngeo1328.

Wentworth, C.K., and Winchell, H., 1947, Koolau basalt series, Oahu, Hawaii: Geological Society of America Bulletin, v. 58, no. 1, p. 49–77, doi:10.1130/0016-7606(1947)58[49:KBSOH]2.0.CO;2.

Wessel, P., 1993, Observational constraints on models of the Hawaiian hot spot swell: Journal of Geophysical Research, v. 98, no. B9, p. 16095–16104, doi:10.1029/93JB01230.

West, H.B., 1988, The origin and evolution of lavas from Haleakala Crater, Hawaii: Houston, Texas, Rice University, Ph.D. dissertation, 351 p., accessed May 31, 2013, at http://hdl.handle.net/1911/16199.

West, H.B., and Leeman, W.P., 1987, Isotopic evolution of lavas from Haleakala Crater, Hawaii: Earth and Planetary Science Letters, v. 84, nos. 2–3, p. 211–225, doi:10.1016/0012-821X(87)90087-2.

West, H.B., and Leeman, W.P., 1994, The open-system geochemical evolution of alkalic cap lavas from Haleakala Crater, Hawaii, USA: Geochimica et Cosmochimica Acta, v. 58, no. 2, p. 773–796, doi:10.1016/0016-7037(94)90505-3.

Wilkinson, J.F.G., and Stolz, A.J., 1983, Low-pressure fractionation of strongly undersaturated alkaline ultrabasic magma; the olivine-melilite-nephelinite at Moiliili, Oahu, Hawaii: Contributions to Mineralogy and Petrology, v. 83, nos. 3–4, p. 363–374, doi:10.1007/BF00371205.

Wilson, J.T., 1963, A possible origin of the Hawaiian Islands: Canadian Journal of Physics, v. 41, no. 6, p. 863–870, doi:10.1038/1991052a0.

Winchell, H., 1947, Honolulu series, Oahu, Hawaii: Geological Society of America Bulletin, v. 58, no. 1, p. 1–48, doi:10.1130/0016-7606(1947)58[1:HSOH]2.0.CO;2.

Wolfe, E.W., and Morris, J., compilers, 1996a, Geologic map of the Island of Hawaii: U.S. Geological Survey Miscellaneous Investigations Series Map I–2524–A, 18 p., 3 map sheets, scale 1:100,000. [Also available at http://ngmdb.usgs.gov/Prodesc/proddesc_13033.htm.]

Wolfe, E.W., and Morris, J., compilers, 1996b, Sample data for the geologic map of the Island of Hawaii: U.S. Geological Survey Miscellaneous Investigations Series Map I–2524–B, 51 p. [Also available at http://pubs.usgs.gov/imap/2524b/report.pdf.]

Wolfe, E.W., Wise, W.S., and Dalrymple, G.B., 1997, The geology and petrology of Mauna Kea Volcano, Hawaii—a study of postshield volcanism: U.S. Geological Survey Professional Paper 1557, 129 p., 4 map sheets [in slipcase], scale 1:100,000 and 1:24,000. [Also available at http://pubs.usgs.gov/pp/1557/report.pdf.]

Xu, G., Frey, F.A., Clague, D.A., Weis, D., and Beeson, M.H., 2005, East Molokai and other Kea-trend volcanoes; magmatic processes and source as they migrate away from the Hawaiian hot spot: Geochemistry, Geophysics, Geosystems (G^3), v. 6, no. 5, Q05008, 28 p., doi:10.1029/2004GC000830.

Xu, G., Blichert-Toft, J., Clague, D.A., Cousens, B., Frey, F.A., and Moore, J.G., 2007a, Penguin Bank; a Loa-trend Hawaiian volcano [abs.]: American Geophysical Union, Fall Meeting 2007 Abstracts, abstract no. V33A–1174, accessed April 28, 2014, at http://abstractsearch.agu.org/meetings/2007/FM/sections/V/sessions/V33A/abstracts/V33A-1174.html.

Xu, G., Frey, F.A., Clague, D.A., Abouchami, W., Blichert-Toft, J., Cousens, B., and Weisler, M., 2007b, Geochemical characteristics of West Molokai shield- and postshield-stage lavas; constraints on Hawaiian plume models: Geochemistry, Geophysics, Geosystems (G^3), v. 8, Q08G21, 40 p., doi:10.1029/2006GC001554.

Yamasaki, S., Sawada, R., Ozawa, A., Tagami, T., Watanabe, Y., and Takahashi, E., 2011, Unspiked K-Ar dating of Koolau lavas, Hawaii; evaluation of the influence of weathering/alteration on age determinations: Chemical Geology, v. 287, nos. 1–2, p. 41–53, doi:10.1016/j.chemgeo.2011.05.003.

Yang, H.-J., Frey, F.A., and Clague, D.A., 2003, Constraints on the source components of lavas forming the Hawaiian North Arch and Honolulu Volcanics: Journal of Petrology, v. 44, no. 4, p. 603–627, doi:10.1093/petrology/44.4.603.

Yoder, H.S., Jr., and Tilley, C.E., 1962, Origin of basalt magmas; an experimental study of natural and synthetic rock systems: Journal of Petrology, v. 3, no. 3, p. 342–532, doi:10.1093/petrology/3.3.342.

Zbinden, E.A., and Sinton, J.M., 1988, Dikes and the petrology of Waianae volcano, Oahu: Journal of Geophysical Research, v. 93, no. B12, p. 14856–14866, doi:10.1029/JB093iB12p14856.

Appendix

Described here are the myriad source publications used to prepare the chemical variation diagrams. All data were compiled into a geochemical database, and geographical coordinates were assigned successfully to about 70 percent of those. The geochemical database originated from a compilation by Kevin Johnson while at the Bishop Museum in the mid-1990s[6]. Our database was probably current until about 2004, with only sparse additions since then. For the Island of Hawaiʻi we relied almost entirely upon an extant, major-element geochemical database of samples analyzed during a Big Island mapping project (Wolfe and Morris, 1996b). An electronic version of that database, including geographic coordinates, was published by Trusdell and others (2006).

Figure 3

Analyses for Kīlauea (456) and Mauna Loa (500) are from Wolfe and others (1996b). The total count of published analyses from Kīlauea and Mauna Loa is probably threefold greater, but the display of points shown is sufficient for the descriptive purposes of this chapter.

Late Shield-Stage Sequences (Fields)

[Asterisk indicates analyses provided originally as unpublished data to the Bishop Museum database]

Haleakalā, Honomanū Basalt, 41 analyses: West (1988); Chen and others (1991); Sherrod and others (2007b).
Mauna Kea, Hāmākua Volcanics, 196 analyses: Wolfe and Morris (1996b).
East Molokaʻi, lower member of East Moloka'i Volcanics, 87 analyses: Beeson (1976); Clague and Beeson (1980); Clague and Moore (2002); J.M. Sinton*; Xu and others (2005).
Kohala, Pololū Volcanics, 121 analyses: Wolfe and Morris (1996b).

Postshield-Stage Sequences

[Asterisk indicates analyses provided originally as unpublished data to the Bishop Museum database]

Waiʻanae volcano, Pālehua Member of Waiʻanae Volcanics, 43 analyses: Macdonald and Katsura (1964); Macdonald, (1968); Presley and others (1997); T.K. Presley*; J.M. Sinton and G.A. Macdonald.*
Kohala, Hāwī Volcanics, 114 analyses: Wolfe and Morris (1996b).
Mauna Kea, Laupāhoehoe Volcanics, 213 analyses: Wolfe and Morris (1996b).

[6]Bishop Museum geochemical database current through about 1995. [http://www.bishopmuseum.org/research/natsci/geology/geochem.html, accessed April 2012]

Figure 13

Panel *A*, Mauna Kea Volcano (449 Analyses)

[Outcrops and drill core from depths shallower than 420 m; thus late shield-stage and postshield-stage strata]

Rhodes (1996); Wolfe and Morris (1996b)

Panel *B*, Waiʻanae Volcano (196 Analyses)

[Asterisk indicates analyses provided originally as unpublished data to the Bishop Museum database]

J.M. Sinton and G.A. Macdonald*, Macdonald and Katsura (1964), T.K. Presley*, Presley and others (1997), Sinton (1987), Macdonald (1968), and Bauer and others (1973).

Panel *C*, Haleakalā Volcano (520 Analyses)

Macdonald and Powers (1946); Macdonald and Katsura (1964); Macdonald (1968); Macdonald and Powers (1968); Brill (1975); Horton (1977); Chen and others (1990); Chen and others (1991); West and Leeman (1994); Bergmanis (1998, with many appearing in Bergmanis and others, 2000); Sherrod and others (2003); D.R. Sherrod in Sherrod and others (2007b).

Figure 17

Shield-Stage Sequences (Fields)

[Asterisk indicates analyses provided originally as unpublished data to the Bishop Museum database]

Niʻihau, Pānīʻau Basalt, 20 analyses: D.A. Clague*.
Kauaʻi, Nāpali Member of Waimea Canyon Basalt, 8 analyses (exclusive of drill cuttings): Cross (1915); Macdonald and others (1960); Macdonald and Katsura (1964).
Koʻolau volcano, Koʻolau Basalt, 212 analyses: Wentworth and Winchell (1947), Yoder and Tilley (1962), Muir and Tilley (1963), Macdonald (1968), Jackson and Wright (1970), Frey and others (1994), Haskins and Garcia (2004), T.K. Presley*.

Postshield-Stage Sequences (Fields)

[Asterisk indicates analyses provided originally as unpublished data to the Bishop Museum database]

Niʻihau, Kaʻeo plug, 4 analyses: Washington and Keyes (1926); D.A. Clague*.
Kauaʻi, alkalic rocks in Olokele Member and Makaweli Member of Waimea Canyon Basalt, 15 analyses: Macdonald and Katsura (1964); Feigenson (1984); Clague and Dalrymple (1988).

Rejuvenated-Stage Data

[Asterisk indicates analyses provided originally as unpublished data to the Bishop Museum database]

Ni‘ihau volcano, Ki‘ei‘e Basalt, 30 analyses: Washington and Keyes (1926); Macdonald (1968); D.A. Clague*.
Kaua‘i volcano, Kōloa Volcanics (exclusive of Palikea Breccia Member), 183 analyses: Cross (1915); Washington and Keyes (1926); Macdonald and others (1960); Macdonald and Katsura (1964); Macdonald (1968); Kay and Gast (1973); Palmiter (1975); Feigenson (1984); Clague and Dalrymple (1988); Maaløe and others (1992); Reiners and Nelson (1998); Reiners and others (1999).
Ko‘olau volcano, Honolulu Volcanics, 142 analyses: Cross (1915), Winchell (1947), Tatsumoto (1966), Macdonald (1968), Macdonald and Powers (1968), Jackson and Wright (1970), Clague and Frey (1982), Wilkinson and Stolz (1983).