Geologic Map of the State of Hawaiʻi

By David R. Sherrod, John M. Sinton, Sarah E. Watkins, *and* Kelly M. Brunt

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About this map

This geologic map and its digital databases present the geology of the eight major islands of the State of Hawaiʻi. The map should serve as a useful guide to anyone studying the geologic setting and history of Hawaiʻi, including ground- and surface-water resources, economic deposits, and landslide or volcanic hazards. Its presentation in digital format allows the rapid application of geologic knowledge when conducting field work; analyzing land-use or engineering problems; studying onshore or nearshore biologic communities; or simply understanding the relation between the geology, scenery, and cultural history of the Hawaiian paradise.

The map includes eight map plates, one for each of the major islands. A Description of Map Units (at end of this pamphlet) describes the lithologic characteristics and distribution of the geologic deposits. A Correlation of Map Units (on each map plate) shows how the different geologic formations are related to each other stratigraphically. A fairly complete geospatial database of the radiometric ages and geochemical analyses has been compiled from findings published over the past 100 years by numerous Earth scientists working across the island chain. The digital map, analytical databases, and metadata may be downloaded online from the U.S. Geological Survey's publication Web site (http://pubs.usgs.gov/of/2007/1089).

Sources of mapping, methods of compilation, origin of stratigraphic names, and divisions of the geologic time scale

The geologic map of Hawaiʻi relies heavily on the seminal publications of Harold Stearns and Gordon Macdonald from the 1930s, 1940s, and 1950s for Niʻihau, Kauaʻi, Molokaʻi, Lānaʻi, Kahoʻolawe, much of Oʻahu, and West Maui (fig. 1). These publications have been out of print for decades and available only in a few libraries and private collections. Recently the text for each has been transferred into electronic document format and may be viewed and downloaded through the internet via the U.S. Geological Survey's publication website (specifically http://pubs.usgs.gov/misc_reports/stearns). Map plates that accompanied those publications have been scanned and made available electronically. We add to this map our own previously unpublished mapping for West Oʻahu and East Maui (J.M. Sinton and D.R. Sherrod, respectively).

The Island of Hawaiʻi has fared better in the past decade than the rest of the state with regards to readily available mapping, owing to a recently published map that brought a vast improvement in detail for the five subaerial volcanoes there (Wolfe and Morris, 1996a).

On our statewide map we utilize the Wolfe and Morris (1996a) geologic depiction of the Island of Hawai‘i as it was made available electronically (Trusdell and others, 2006). The Hawai‘i Island mapping is revised herein to show lava flows emplaced in the past 20 years on Kīlauea Volcano (unpub. data, Hawaiian Volcano Observatory, U.S. Geological Survey) and a few other minor changes discussed later.

The decision to use legacy mapping as our depiction for several of the islands instead of undertaking new field work stems partly from the lack of resources and the pressing need for a digital geologic map but also from the notable insight contained in the earlier geologic mapping for many areas. Those maps carry an inherent problem, however—the inaccuracy associated with their topographic base maps. Hawai‘i’s first topographic maps were produced early in the last century, prior to the advent of more precise tools like aerial photography and photogrammetry. Many parts of the state were remote or inaccessible when the first topographic base maps were made; consequently the maps were, in some areas, only generalized renditions. These shortcomings were recognized and described tersely on occasion. For example, H.T. Stearns (in Stearns and Macdonald, 1947, p. 19) described how “Detailed traverses were made up each tributary of Wailau and Pelekunu streams [on Moloka‘i], but the results could not be plotted on the topographic base map because the stream pattern shown on the map is seriously in error.” Such was the world when Harold Stearns began his phenomenal geologic march across the island chain in the 1930s, an effort that culminated when Gordon Macdonald and his team published the Kaua‘i geologic map in 1960.

Another source of discrepancy arises simply because the geographic setting of the Hawaiian island chain, as a map projection problem, was not as well known as now through modern geodesy. For example, an intracanyon lava flow, correctly depicted within its canyon on the older maps, may well be shifted geographically to a ridge top when digitized and recast unwittingly onto a modern topographic map. Therefore, when making this map, the boundary of every geologic unit shown on older maps had to be reinterpreted in order to display properly on modern 1:24,000-scale topographic quadrangle maps. Compilation was straightforward where newer geologic mapping was available, as was the case for West O‘ahu, East Maui, and the Island of Hawai‘i.

In some cases, we have modified the older geologic maps by showing a few geologic map units lacking on the legacy map plates but found on generalized figures within the monographs that described those maps. We have chosen to incorporate as much of that geologic knowledge as possible, especially where the geologic interpretation has been borne out by subsequent chemical analyses and where the old map figures were prepared so carefully that contacts may be traced accurately. Examples include the distribution of younger (postshield?) strata on the West Moloka‘i volcano (Moloka‘i) and some lava flows of the Hāna Volcanics on Haleakalā’s north slope (East Maui). We view our map as a guide to future research and have attempted to include as much substantive information as available to us.

The stratigraphic names of nearly all major volcanic units were formalized long ago by the early publications. A revision of those names was undertaken

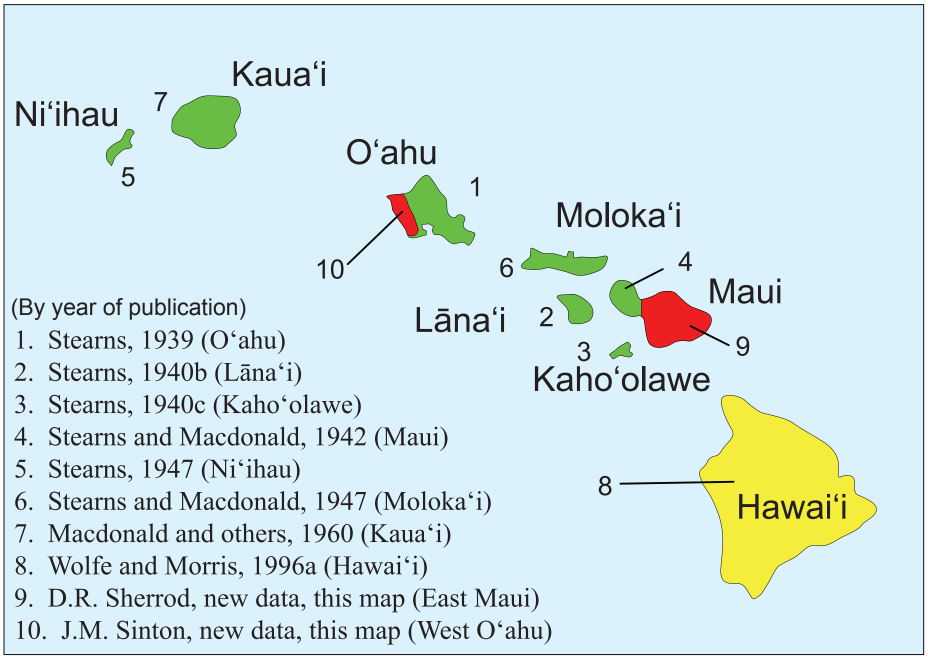

Figure 1. Chief sources of mapping used in compilation of digital geologic map of State of Hawai‘i. See References Cited for full bibliographic citation.

by Langenheim and Clague (1987), in order to meet changing national standards and to keep the naming straightforward. We follow the Langenheim and Clague usage explicitly. For West Oʻahu, we rely upon a revision to the stratigraphic nomenclature of the Waiʻanae volcano (Sinton, 1987; Presley and others, 1997), which reflects new mapping in the past two decades. Volcanic formations on the Island of Hawaiʻi are unchanged from their representation by Wolfe and Morris (1996a), which modified the Langenheim and Clague usage only by using the more inclusive name Pololū Volcanics for the oldest strata at Kohala volcano, which are slightly more diverse than basalt.

The time scale used herein is that published recently by the International Commission on Stratigraphy (Gradstein and others, 2004). A prominent change pertinent to our discussion of Hawaiian geology is the revision of the Pleistocene- Holocene boundary to 11, 500 yr before present (yr before A.D. 1950). This change results from calibrating to sidereal years the long-established 10,000-yr radiocarbon age (Gibbard and Van Kolfschoten, 2004). The Pliocene-Pleistocene boundary is 1.81 Ma, and the Miocene-Pliocene boundary is 5.33 Ma. Minor revisions to chron boundaries in the geomagnetic-polarity time scale are also incorporated (Ogg and Smith, 2004).

Map accuracy

Accuracy ranges widely across the map. For most of the islands, contacts should be considered “approximately located,” with standard error of 100 m (plus or minus 50 m). This estimate allows for the vagaries associated with the change from an antiquated topographic base to a modern base for most of the islands. It also has some basis in the old saying, “accuracy is commonly a millimeter at the presentation scale of the map,” from which a 100-m error estimate corresponds to the 1:100,000 scale of the Island of Hawaiʻi geologic map (Wolfe and Morris, 1996a). We found during limited field testing on Kauaʻi and West Maui that the accuracy is generally well within that limit, commonly better than 50 m—perhaps surprising in view of the geographic fitting undertaken for the legacy maps, the locally forbidding nature of the Hawaiian landscape faced by any field worker, and the commonly poor geologic exposure encountered during field work then and now. The geology for the Island of Hawaiʻi (from Wolfe and Morris, 1996a) retains an accuracy of plus-or-minus 50 m overall. The new mapping from West Oʻahu and East Maui ranges in accuracy from 15 to 50 m. No effort has been made to further classify the accuracy or precision of linework.

One other caveat is offered. We adapted the older published maps, originally published at scale 1:62,500, to portray suitably at 1:24,000 scale, the only series of topographic maps for entire-state coverage at large or intermediate scale when we began our work. (The U.S. Geological Survey’s 100,000-scale topographic maps are unfinished for some islands, and the 1:250,000-scale maps are too generalized for many purposes.) By fitting contacts to large-scale topographic depictions, we have added an apparent precision perhaps unwarranted by the accuracy available in the published data.

No estimate of accuracy is assigned to the presentation of the numerous dikes and sparse sills shown for several of the islands. Dikes in the State of Hawaiʻi typically lack topographic expression. Consequently we had few clues to aid in fitting the older geologic rendition to modern base maps. The dike coverage should be considered a schematic representation derived from the published depictions, useful for studying dike trends and abundance and their relation to rift zones on eroded volcanoes.

Radiometric ages and geochemistry

As part of our map depiction we compiled GIS layers showing radiometric ages and whole-rock geochemical analyses from the published literature and a few unpublished sources for all the islands except Hawaiʻi. For the Island of Hawaiʻi, the substantial presentation by Wolfe and Morris (1996b), with its 1,786 major-element analyses, proved sufficient for our purposes. Potassium-argon ages obtained prior to 1977 were recalculated to conform to a change in international standards for the isotopic abundance and decay rates (Steiger and Jäger, 1977). For consistency, all ages are reported herein with their two-sigma (95 percent) confidence interval, the method adopted increasingly as new ages are reported. Analytical error was not reported directly for some seminal ages reported by McDougall (1964), but his text was sufficiently detailed to allow for their calculation, the results of which are included herein. The digital database for ages includes one- and two-sigma error for all the K–Ar and ^{40}Ar/^{39}Ar ages, as well as an indication of how the data were reported originally. See appendix 1 for additional comments about the radiometric dating database.

Radiocarbon ages representing volcanic events are an important part of the geochronologic record for East Maui (Haleakalā) and most of the volcanoes on the Island of Hawaiʻi. These ages are customarily reported as “raw data”; that is, in radiocarbon years before present (before A.D. 1950) and with one-sigma confidence interval, and so they are shown in the digital database. However, for purposes of discussion in our explanatory text and description of map units, we calibrate the ages to sidereal years using the CALIB radiocarbon calibration program, version 5.0.1 (after Stuiver and Reimer, 1993; see URL in References Cited) in conjunction with a recent decadal atmospheric ^{14}C database (Reimer and others, 2004). We chose the option of two-sigma confidence for the analytical uncertainty of the calibrated ages.

The whole-rock geochemical database originates from a compilation undertaken by Kevin Johnson while at the Bishop Museum in the mid-1990s. We have built upon Johnson's database to incorporate analyses published since 1996 and some previously unpublished data that have been made available to us. No attempt was made to assess geochemical data quality or reliability except by verifying from the original published accounts.

Nearly 90 percent of the dated samples and 70 percent of geochemical analyses in the database have geographic coordinates assigned by us from written sample descriptions or sample location maps that accompanied many publications. This step was necessary to verify stratigraphic setting but also to grasp the sporadic spatial distribution of samples collected over the years. Through written correspondence, nearly 40 percent of the locations have been rechecked by the numerous scientists who made the original field collections, heightening the accuracy and precision of the geospatial data. Hidden in the convenience of this geochemical database is a huge blessing of aloha to those contributors for a debt we can never fully repay.

About spelling

Spelling of Hawaiian words follows the usage in the *Hawaiian Dictionary* (Pukui and Elbert, 1986). Geographic place names are written as found in the *Atlas of Hawai'i* (Juvik and others, 1998) and the online Geographic Names Information System managed by the U.S. Geological Survey (http://geonames.usgs.gov). We use a Hawaiian glottal stop, or ʻokina, when writing State of Hawaiʻi, in keeping with the University of Hawaiʻi's style guide and the State's constitution, which declares Hawaiian and English as the two official languages. (*Hawaiian* is a fully anglicized word and requires no diacritical marks.)

We favor the parsimonious use of capital letters or "down" style advocated by the Chicago Manual of Style (University of Chicago Press, 2003) when referring to informally named features such as the major volcanoes along the island chain (for example, Koʻolau volcano, lower-case v). In contrast is the formally named Kīlauea Volcano; therefore both its given name and generic term are capitalized. Most of the stratigraphic names applied to rock units have been formalized by past workers, but a few retain informal status. The use of upper- and lower-case typography aids in making that distinction, too.

Titles in the References Cited section are written as found in the original publications. The Earth sciences literature is slowly accepting modern Hawaiian orthography. Thus, titles published before 1996 typically lack any diacritical marks; the ʻokina occurs sporadically after 1996; and the Hawaiian macron, the kahakō, has crept into a few Earth science publications since 1999.

A final note on spelling may be helpful to users who avail themselves of the electronic databases that support this map. No diacritical marks are used therein, owing to the lack of conformity among the differing computer software for interpreting uncommon character encodings.

Island growth in review

An island's growth and demise along the Hawaiian–Emperor chain is a history of volcanism, extinction, and erosion. Geologic mapping investigations led to a synoptic model in which the volcanoes grow through several volcanic stages, defined chiefly on the basis of gross lithologic, petrographic, and geomorphic changes (for example, Stearns, 1946). Subsequent advances in submarine geology and geophysics, the advent of radiometric dating, and ready availability of multi-element geochemical analyses have substantiated many aspects of these growth stages, including the timing of events.

Volcanic evolution

Popular today is an idealized model of Hawaiian volcano evolution that involves four eruptive stages: preshield, shield, postshield, and rejuvenated stages (Clague, 1987b; Clague and Dalrymple, 1987; Peterson and Moore, 1987). These stages likely reflect variation in the amount and rate of heat supplied to the lithosphere as the Pacific plate overrides the Hawaiian hot spot (Moore and others, 1982; Wolfe and Morris, 1996a). Volcanic extinction follows as a volcano moves away from the hot spot. Dissection by large landslides may occur any time in the growth or quiescence of a volcano, and subaerial erosion is ongoing whenever the volcano is emergent.

The geologic map units or groups of units on this map typically correspond closely to idealized stages of a volcano's growth—hardly surprising since the interpretive stages are rooted in geologic mapping. An illustrative example is West Maui volcano (Stearns and Macdonald, 1942). There, the Wailuku Basalt comprises tholeiitic basalt of the shield stage. Preshield lava, if present, is buried deeply in the core of the volcano. Analyses from the Wailuku Basalt indicate a spotty transition to more alkalic lava as shield growth ends. Overlying the Wailuku is the Honolua Volcanics, a postshield-stage sequence that contains distinctly more fractionated alkalic lava flows of benmoreite and trachyte; rocks of tholeiitic composition are lacking. Rejuvenated-stage volcanic rocks, the Lahaina Volcanics, are represented by four cinder and spatter cones and associated basanitic lava flows found on the west, southwest, and southeast sides of the West Maui volcano. The map units are based on field criteria, however, and not the interpretation of a volcanic episode. The assignment of growth-stage characteristics is an interpretation imposed after a geologic map is completed.

The transition from shield- to postshield-stage volcanism may be abbreviated or may not occur at all. In the abbreviated case, some of the stratigraphic units characteristic of shield-stage episodes may include, in their upper part, alkalic basalt interbedded among the tholeiitic lava flows. In the case of Kaua‘i, sporadically distributed flows of even more evolved lava such as hawaiite or mugearite are found at the top of the shield-stage Nāpali Member or caldera-filling Olokele Member, both of the Waimea Canyon Basalt. No separate formation corresponding to these lava flows was mapped because of limited exposure or insufficient time available for mapping (Macdonald and others, 1960). Similarly, Kohala volcano (Island of Hawai‘i) has sparse hawaiite among the strata of the Pololū Volcanics, thought to characterize the shield stage there. Examples in which a volcano possesses no transitional or postshield lava are limited to Ko‘olau and Lāna‘i volcanoes (for example, Clague and Dalrymple, 1987), as well as the still-robust shield-stage volcanoes Mauna Loa and Kīlauea that may someday exult in the final stages of volcanic evolution.

The peppering of alkalic basalt lava flows in the upper part of some shield-stage sequences leads to a petrologic interpretation that the shield-to-postshield

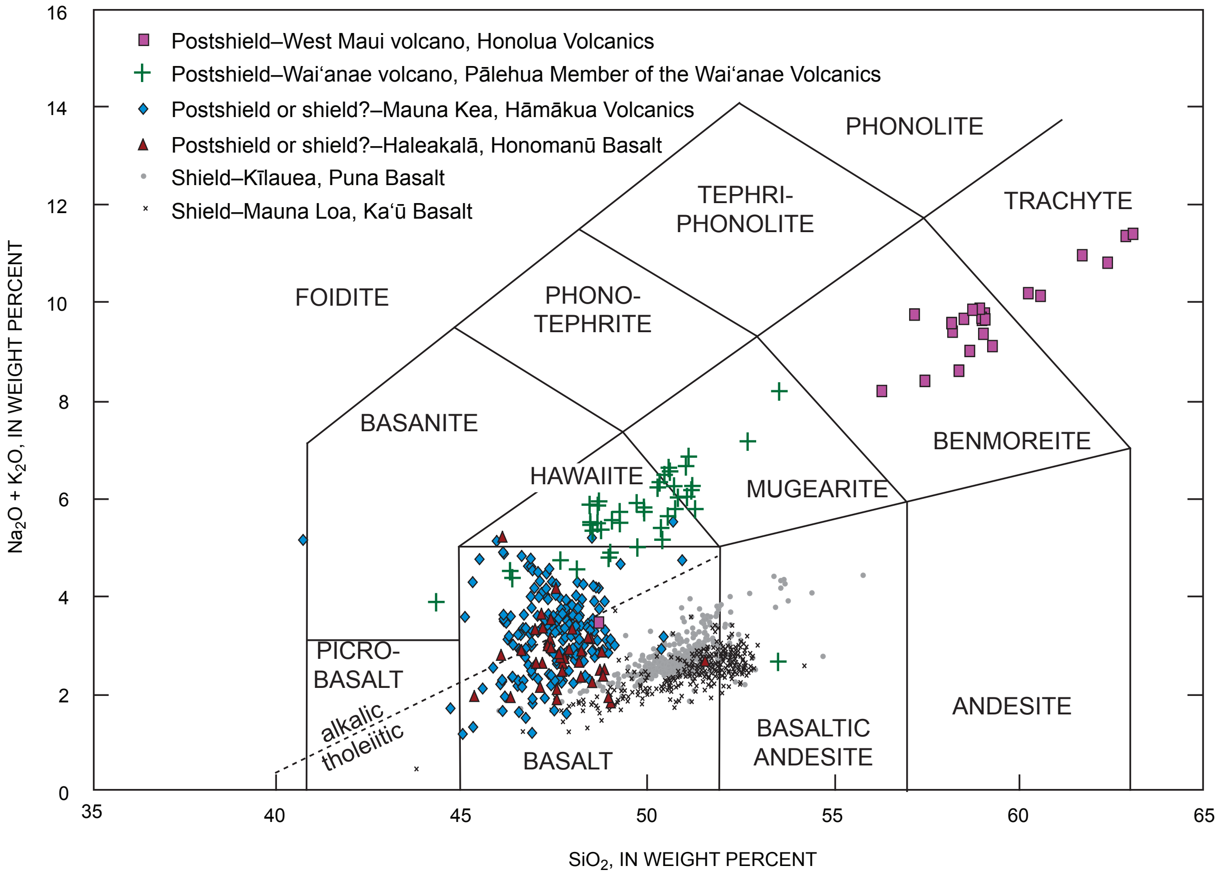

Figure 2. Alkali-silica diagram (Na_2O+K_2O versus SiO_2) composited from several volcanoes. Rock classification grid labeled (from Le Bas and others, 1986, with tephrite-basanite field shown specifically as the olivine-bearing occurrence, basanite, as found commonly in Hawai‘i). Shown dashed is boundary separating tholeiitic and alkalic basalt (Macdonald and Katsura 1964). Data for Kīlauea and Mauna Loa on this and subsequent alkali-silica diagrams from Wolfe and Morris (1996b). Data sources for the other volcanoes are listed in captions to figures 11, 23, 25, and 32.

transition at some volcanoes begins prior to the onset of readily mapped postshield stratigraphic units (Sinton, 2005). Consider a chemical variation diagram showing total alkalis versus silica (fig. 2), in which we create a composite picture showing the key volcanic stages from several well-known stratigraphic sequences. Few would argue against the shield-stage assignment for wholly tholeiitic lava from Kīlauea or Mauna Loa; nor is there quarrel that the benmoreite and trachyte of West Maui's Honolua Volcanics or the hawaiite and mugearite of Waiʻanae's Pālehua Member of the Waiʻanae Volcanics are postshield. But compositions annotated as stratigraphically transitional basalt on figure 2, in this case from the Honomanū Basalt of Haleakalā and the Hāmākua Volcanics of Mauna Kea, lead to varying interpretation. The Hāmākua, the lowest stratigraphic sequence exposed at Mauna Kea, was considered shield-stage volcanism by Stearns and Macdonald (1946) but was redefined as a basaltic substage of postshield volcanism by Wolfe and others (1997). Are shield-stage strata exposed at Mauna Kea? The answer hinges on the interpretation of the geochemical data, a story we revisit in our discussion of Mauna Kea's history.

Structure

Geologic structures such as faults and folds are sparse on the geologic map. Except for caldera-bounding structures, few faults are mapped among the older volcanoes of the Hawaiian Islands. Kauaʻi is notable as the one older volcano with substantial structural complexity at the present level of subaerial exposure. This general lack of subaerial structure along the island chain is surprising, inasmuch as seismicity and active faulting are rampant during the shield-building stage, as may be judged from the historical record of the active volcanoes Kīlauea and Mauna Loa. Kīlauea, with its Hilina and Koaʻe fault systems, is blessed with the best-developed subaerial fault system in the islands, at least for exposed offset. Presumably many of the structural zones are lost from view owing to large submarine landslides and slumps. What scarps might remain probably become mantled by later shield lava flows or, less commonly, by postshield lava.

Nonvolcanic deposits

Erosion at volcanoes is constantly taking place, but its subaerial depositional products are mostly unremarkable during the shield and postshield stages of volcanism. Stream courses have moderate to high topographic gradients, so alluvium is transported to the sea, and only trifling amounts are left sandwiched thinly between lava flows. Some detritus is captured in structural traps such as calderas and graben, but typically these depressions are inundated and filled quickly by lava flows. Thus, little sediment is stored on the volcano, and that found is difficult to show at most map scales. As volcanism wanes, however, the balance is tipped toward more extensive alluvial deposits. Canyon floors of the windward drainages broaden and hold the sand and silt of meander belts (unit Qa). Large alluvial fans, shown as older alluvium (unit QTao) on the geologic map, mantle valley walls. In a few cases, younger lava flows have draped part of the older alluvium; examples are found on West and East Maui. On Kauaʻi, some older alluvium is mapped as the Palikea Breccia Member of the Kōloa Volcanics. On Oʻahu, similar beds are included locally in the Kolekole Member of the Waiʻanae Volcanics.

Sedimentation also occurs at all volcanoes by the wind-driven redistribution of beach sand inland, where it forms dune deposits. Substantial calcareous dunes, however, develop only at volcanoes that have ended their shield- and postshield-stage volcanism, when rapid island subsidence ceases. In interpretations prior to 1980, these deposits were thought to have formed during Pleistocene low sea-level stands, when broad sand-covered flats might have been intermittently emergent and subject to ablation. Most modern workers disagree, favoring formation during interglacial high stands of the sea (for example, Fletcher and others, 1999; Blay and Longman, 2001). Subsequent diagenetic cementation and recrystallization lithifies the deposits into eolianite.

Episodic deposition has created some features specific to a particular volcano. For example, glaciation of Mauna Kea has crowned it with moraines and outwash, deposits unique along the island chain. A large debris-flow sequence, the Kaupō Mud Flow on Haleakalā's south slope, probably stands alone among the archipelago's subaerial exposures by virtue of its preserved extent, thickness, and coarse, poorly sorted aspect. Smaller landslide deposits are mapped sporadically; the most extensive of these is the A.D. 1868 Wood Valley landslide on the southeast side of Mauna Loa. Landslides happen frequently, but most are small enough that their deposits are reworked downslope relatively quickly and lost from the geologic record. So, too, for the onshore deposits of conventional tsunami, which invariably are far too thin to show on most geologic maps.

Megatsunami deposits

Disagreement still surrounds the origin for poorly sorted, coralline-bearing breccia found at widely ranging altitudes on the leeward sides of Kohala, West Maui, Lānaʻi, and East Molokaʻi volcanoes. These deposits are shown on our map as calcareous breccia and conglomerate (unit Qcbc) where sufficiently extensive to map separately. Many smaller sites are compiled as a separate layer in the GIS database. Although Stearns (1978) generally attributed these deposits to glacioeustatic marine high sea-level stands, substantial uplift of Lāna‘i and Moloka‘i is required to explain the deposits at these altitudes by this mechanism.

A hypothesis that has gained a wide level of acceptance explains these deposits as the consequence of catastrophic, giant waves (megatsunami) generated by several prehistoric large submarine landslides (J.G. Moore and Moore, 1984; G.W. Moore and Moore, 1988). The interpretation stems partly from the landward fining of the Lāna‘i deposits (Moore and Moore, 1984) and landward fining in the carbonate-clast component of the Moloka‘i deposits (A.L. Moore, 2000). The Lāna‘i deposits were specifically attributed to the ‘Ālika 2 Slide on the west side of Hawai‘i Island (Moore and others, 1989). The ‘Ālika 2 was emplaced about 125 ka on the basis of several lines of analysis (McMurtry and others, 1999).

The outstanding challenges to a giant-wave origin are three fold. One geochronologic study found a moderately high level of internal stratigraphic order for coral clasts within some of the deposits, on the basis of radiometric ages of the fragments (Rubin and others, 2000), results not in accord with chaotic deposition during a single megatsunami event. Some detailed sedimentologic analyses describe the Lāna‘i deposits as not exclusively tsunamigenic in origin (Felton and others, 2000). And interpretations that wave-cut notches are exposed above sea level on Moloka‘i and Lāna‘i and that terraces lie at several altitudes on Moloka‘i (Grigg and Jones, 1997) call into question the amount of uplift that Lāna‘i and Moloka‘i might have experienced in the past several hundred thousand years.

Recent estimates for uplift of O‘ahu suggest rates of 0.020–0.024 m per 1,000 yr for the past 400,000 yr (Hearty, 2002). The result has been to expose calcareous reef rock and marine sediment (unit Qcrs), which is found only on O‘ahu. The lack of these emerged reefs and lagoonal limestone beds elsewhere along the island chain suggests that uplift is the exception, not the rule. Although rates are less precisely defined for Lāna‘i, during the past 30,000 yr that island has been relatively stable, with uplift or subsidence bracketed between +0.1 and -0.4 m per 1,000 yr, on the basis of a sedimentary facies model for carbonate deposits on submerged terraces adjacent to the island (Webster and others, 2006). Clearly, a better understanding of vertical motions of all the Hawaiian islands remains an important area of future research.

Compelling evidence in favor of the giant-wave hypothesis comes from deposits on Kohala volcano, Island of Hawai‘i, where the question of uplift is made moot by the ongoing subsidence that has characterized Hawai‘i Island since its emergence. The calcareous breccia of Kohala, found today at altitudes ranging from sea level to 100 m, must have been deposited originally at altitude 350 to 390 m higher if corrected for modern rates of subsidence and age of the deposits (McMurtry and others, 2004).

Summary of Island Geology

We describe in the following sections the salient geologic features of each island, with an emphasis on new stratigraphic findings and unresolved problems of research in the past two decades. Numerous stratigraphic and lithologic details, omitted here, are available in most cases from the original reports that led to the sources of mapping used here. Readers should seek out those sources, both for the authoritative descriptions therein but also for an illuminating historical view of Hawai‘i and ocean-island science during the 1930s, ‘40s, and ‘50s. We also highly recommend the island-by-island descriptions presented as the story of Hawai‘i’s geology by Gordon Macdonald and colleagues, a book which through its first two editions has provided the fundamental introduction and reference work for generations of laypeople and scientists alike (Macdonald and others, 1983). Throughout our research we referred frequently to the stratigraphic summary of Langenheim and Clague (1987) and the geochronology summary by Clague and Dalrymple (1987, their appendix 1.1) for statewide topics reported here. Our discussion for volcanic stratigraphy on the Island of Hawai‘i is shortened relative to the other islands because past summaries by Moore and Clague (1992) and Wolfe and Morris (1996a) cover so much of the ground in exemplary style.

Herein we shy away from much discussion of the petrologic details of each volcano. Those studies have created an immense body of work, owing in part to the importance of the Hawaiian Islands in understanding basaltic volcanism worldwide. To present them fairly and comprehensively would double or triple the scope of our undertaking. Another harsh decision was the limited presentation of the submarine geology of the island chain, except as needed to better explain some of the subaerially exposed features.

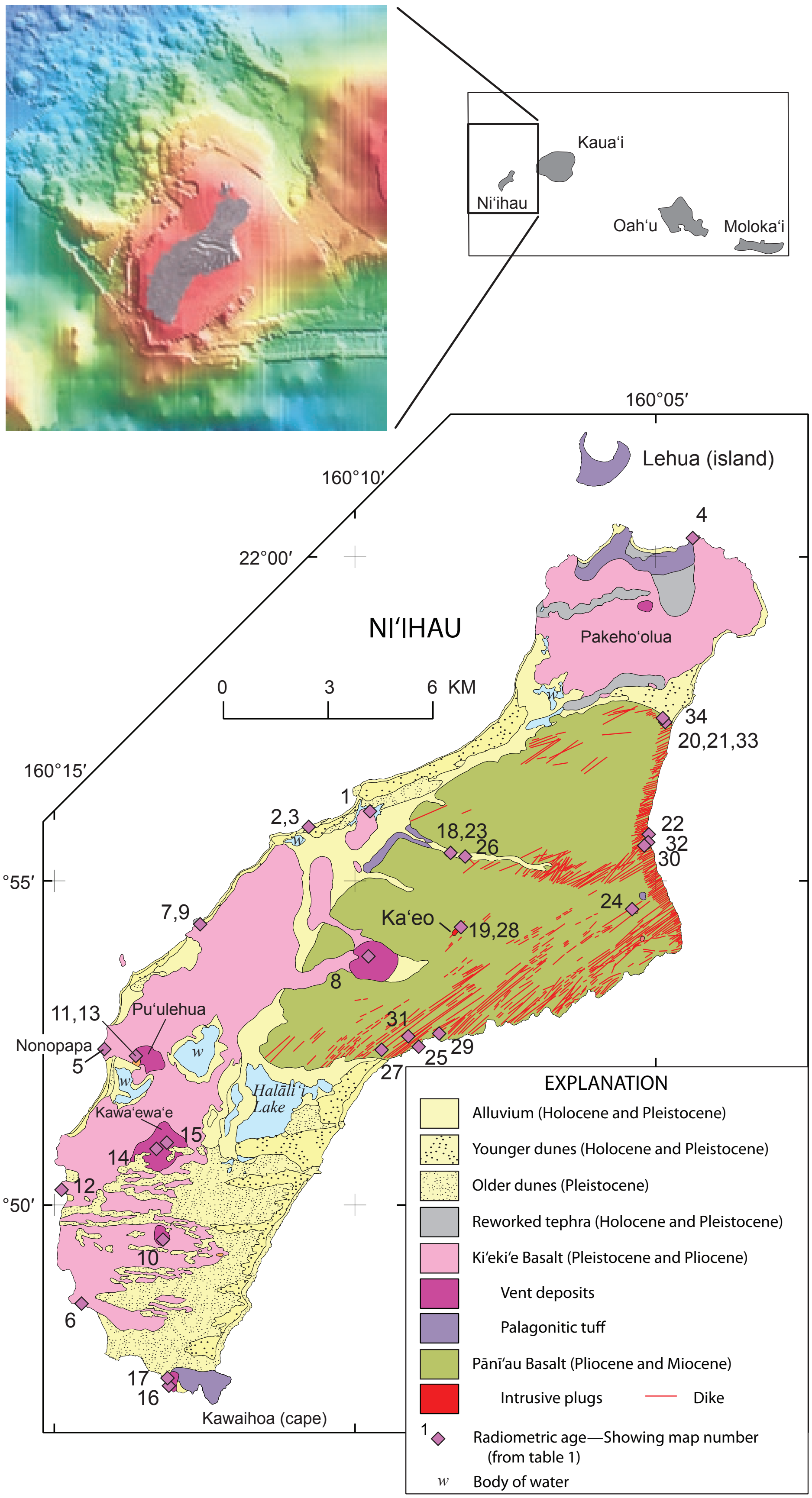

Figure 3. Geologic map of Ni'ihau, generalized from this publication's digital map database. Geology from Stearns (1947). Radiometric ages in table 1. Inset bathymetric map from Eakins and others (2003).

Niʻihau

Setting and stratigraphic notes

Niʻihau, covering 187 km^2, is third smallest of the major Hawaiian islands, larger only than Kahoʻolawe and Lānaʻi. Its land is held privately, and access is controlled; consequently it is one of the least visited and least studied of the Hawaiian islands. Our geologic knowledge of the island's surface is limited almost entirely to the seminal study by Stearns (1947) and investigations in the 1970s by David A. Clague, G. Brent Dalrymple, and Richard R. Doell (for example, Doell, 1972).

Niʻihau is the eroded remnant of a single shield volcano (fig. 3). Topographically it comprises a central highland built almost entirely of shield-stage pāhoehoe lava flows (Pānīʻau Basalt). A late vent, Kaʻeo, stands about 60 m above the surrounding surface. Possibly a product of postshield-stage activity (Langenheim and Clague, 1987), Kaʻeo is eroded to show mostly intrusive basalt. A surrounding coastal platform is underlain by lava flows (Kiʻekiʻe Basalt) assigned to rejuvenated-stage volcanism. More than 23 percent of this platform's area is mantled by alluvium and dune deposits. Offshore, a fringing wave-cut shelf extends out 5–10 km, beyond which the slopes plunge steeply to abyssal depth (fig. 3).

Radiometric ages were described only summarily by Langenheim and Clague (1987). The complete set of radiometric data, kindly provided by G. Brent Dalrymple (written commun., 2004), is presented here as table 1. Shield-stage lava, mapped as the Pānīʻau Basalt, ranges in age from about 6.3 to 4.3 million years (mega-annums, Ma) (table 1; fig. 4), a span of time similar to that represented by the exposed shield-stage lava flows of nearby Kauaʻi Island. The only available paleomagnetic data indicate that at least some of the dated lava flows possess reversed-polarity magnetization, and no normal-polarity findings were reported (Doell, 1972). As known today, the paleomagnetic time scale has a reversed-polarity epoch occurring from 4.799 to 4.631 Ma (Ogg and Smith, 2004), possibly the chief emplacement age of the exposed lava flows. Only about 400 m of shield-stage strata are found in the island's eastern sea cliffs. A duration as lengthy as 3 million years (m.y.) is allowed by the radiometric ages at 68 percent analytical confidence, but the actual span likely is less than 1 m.y. on the basis of accumulation rates known for other late-shield sequences along the island chain (Sharp and others, 1996; Guillou and others, 2000).

Published chemical analyses for Niʻihau are sparse, so we rely heavily on unpublished data provided by D.A. Clague (written commun., 2004). The Pānīʻau Basalt is

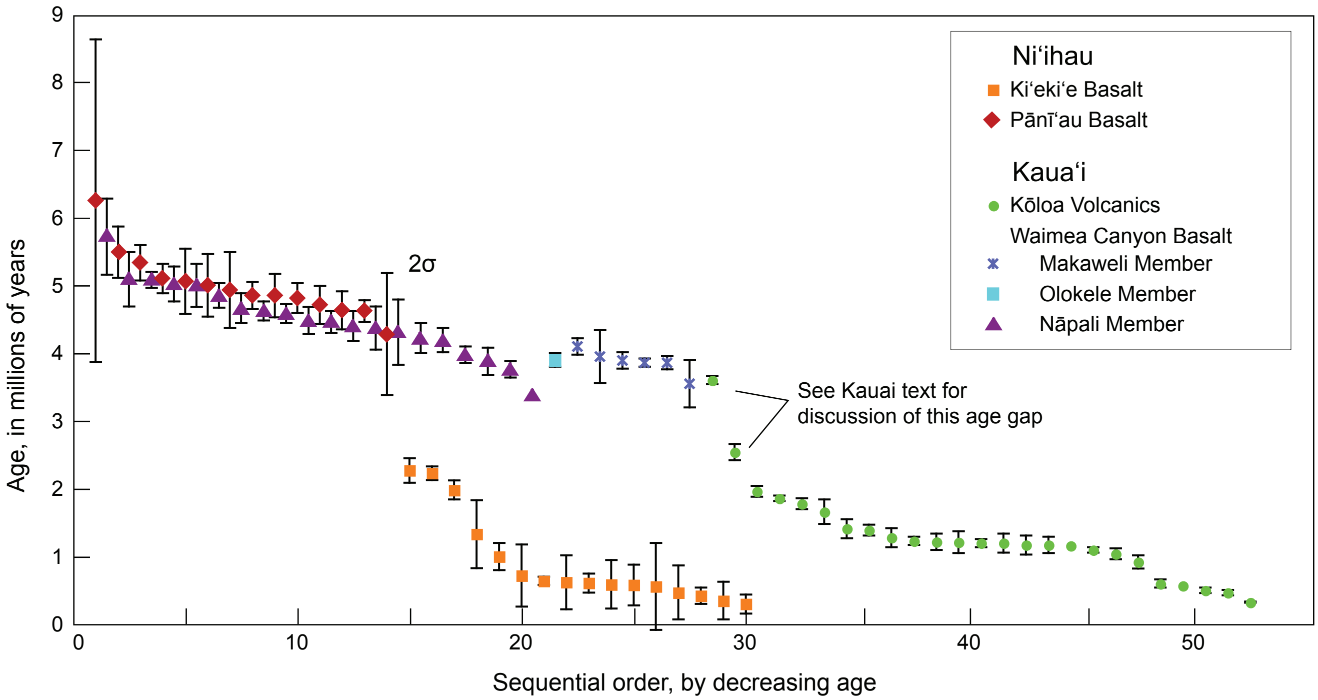

Figure 4. Radiometric ages, Niʻihau and Kauaʻi. Data for Niihau courtesy of G.B. Dalrymple (table 1). For Kauaʻi, one Nāpali Member age reported without analytical error (Evernden and others ,1964). Other ages from McDougall (1964, 1979), Clague and Dalrymple (1988), and Hearty and others (2005).

Table 1. Potassium-argon ages for Pānīʻau and Kiʻekiʻe Basalts, Island of Niʻihau, Hawaiʻi.

[Data courtesy of G. Brent Dalrymple. Sample locations in GIS data that accompany this map.]

Map No.	Sample No.	K_2O (wt. percent)	±S.D. (for n>2)	Weight (g)	${}^{40}Ar_{rad}$ [†] (10^{-12} mol/g)	${}^{40}Ar_{rad}$ (percent)	Age±1σ error [§] (Ma)	Rock type
Ki‘eki‘e Basalt								
1	69NII-8	0.326	±0.002 (4)	26.450	0.1650	4.9	0.35±0.07	
2	69NII-7	0.288	±0.007 (7)	19.989	0.1677	4.1	0.40±0.14	Alkalic lava flow
3	69NII-7	0.311	±0.003 (4)	28.420	0.2114	7.6	0.47±0.06	
4	70X121	0.248	±0.005 (8)	17.905	0.1983	3.2	0.52±0.20	
				17.943	0.1490	1.7		
5	69NII-4	0.243	±0.005 (6)	15.645	0.2137	2.1	0.61±0.32	Alkalic lava flow
6	70NII-7	0.295	±0.003 (4)	20.091	0.2540	7.3	0.63±0.15	Alkalic lava flow
				20.047	0.3805	4.1		
7	69NII-3	0.208	±0.003 (4)	23.983	0.1911	3.5	0.64±0.18	Alkalic lava flow
8	70NII-18	0.453	±0.007 (8)	16.939	0.3697	5.8	0.66±0.07	Alkalic lava flow
				17.102	0.5163	8.1		
9	69NII-3	0.222	±0.011 (8)	19.982	0.2156	3.4	0.67±0.20	
10	75NII-13	0.486	±0.004 (4)	24.889	0.553	16.5	0.69±0.03	Alkalic lava flow, Mau‘uloa
				25.125	0.404	12.4		
11	69NII-6	0.310	±0.003 (4)	25.607	0.3444	3.3	0.77±0.23	Alkalic lava flow
12	70NII-11	0.291	±0.004 (7)	19.965	0.4082	5.4	1.05±0.10	Alkalic lava flow
				19.761	0.4617	7.6		
13	69NII-6	0.274	±0.002 (4)	19.975	0.5465	5.3	1.38±0.25	
14	70NII-21	0.376	±0.004 (4)	18.877	1.0730	18.0	2.03±0.07	Alkalic lava flow, Kāwa‘ewa‘e
				18.826	1.1370	18.5		
15	75NII-14	0.304	±0.005 (4)	25.272	0.937	21.9	2.28±0.05	Alkalic lava flow, Kāwa‘ewa‘e
				25.406	1.048	33.8		
16	70NII-4	0.222	±0.001 (4)	18.748	0.8066	21.2	2.32±0.09	Alkalic lava flow
				19.192	0.6971	18.5		
17	75NII-69	0.286	±0.006 (4)	18.151	1.100	5.4	2.68±0.30	
				23.438	1.061	5.0		
				21.923	(1.350)	5.7		
				17.426	1.168	4.7		

Table 1. Continued.

Map No.	Sample No.	K_2O (wt. percent)	±S.D. (for n>2)	Weight (g)	$^{40}Ar_{rad}$† (10^{-12} mol/g)	$^{40}Ar_{rad}$ (percent)	Age±1σ error § (Ma)	Rock type
Pānīʻau Basalt								
18	70NII-15	0.479	±0.005 (8)	19.169	3.129	7.7	4.33±0.45	Tholeiitic lava flow(?)
				19.387	2.837	6.7		
19	75NII-1	0.636	±0.003 (4)	24.806	4.067	45.7	4.67±0.08	Alkalic lava flow, Kaʻeo
				24.637	(3.699)	43.7		
				25.508	4.436	49.9		
				25.441	4.384	46.0		
20	69X019	0.263	±0.005 (8)	14.999	1.791	24.4	4.68±0.14	Tholeiitic lava flow
				15.001	1.753	21.5		
21	69X018	0.264	(2)	26.384	1.811	24.9	4.76±0.14	Tholeiitic lava flow
22	70NII-23	0.536	±0.003 (4)	18.558	3.753	42.3	4.86±0.11	Alkalic dike
				18.535	3.763	44.7		
23	70NII-14	0.275	±0.007 (8)	20.134	1.978	21.5	4.90±0.16	Tholeiitic lava dike
				20.030	1.914	22.5		
24	75NII-10	0.713	±0.005 (4)	24.686	4.882	55.8	4.90±0.10	Alkalic dike
				24.667	5.217	61.2		
25	75NII-61	0.281	±0.003 (4)	24.731	1.999	14.4	4.98±0.28	Tholeiitic lava flow
				24.662	(2.496)	18.7		
				10.624	2.061	9.8		
26	70NII-17	0.536	±0.005 (8)	19.004	3.866	45.5	5.05±0.23	Tholeiitic dike(?)
				19.234	4.232	36.2		
27	75NII-65	0.340	±0.004 (4)	24.984	2.404	12.1	5.11±0.24	Tholeiitic lava flow
				23.012	2.584	14.5		
28	75NII-2	0.617	±0.002 (4)	23.827	4.803	60.6	5.15±0.11	Alkalic lava flow, Kaʻeo
				23.852	4.386	59.5		
29	75NII-57	0.327	±0.004 (4)	24.619	2.550	22.7	5.38±0.13	Tholeiitic lava flow
				24.344	2.528	23.0		
30	70NII-24	0.193	±0.003 (4)	15.952	1.549	20.1	5.54±0.19	Tholeiitic dike
				17.059	1.554	18.8		
31	75NII-67	0.314	±0.004 (4)	19.893	2.279	10.9	5.56±0.24	Tholeiitic lava flow
				20.616	2.418	12.9		
				20.011	2.916	13.0		
				14.893	(5.187)	17.0		

Table 1. Continued.

Map No.	Sample No.	K_2O (wt. percent)	±S.D. (for n>2)	Weight (g)	$^{40}Ar_{rad}$ † (10^{-12} mol/g)	$^{40}Ar_{rad}$ (percent)	Age±1σ error § (Ma)	Rock type
32	70NII-25	0.181	±0.015 (4)	18.764	1.494	3.5	6.30±1.19	Tholeiitic lava flow
				9.348	1.830	3.9		
33	69X020	0.299	±0.017 (4)	22.961	1.161	16.4	(2.69±0.34)	Tholeiitic lava flow
34	69X028	0.367	(2)	20.953	1.550	14.0	(3.05±0.13)	Tholeiitic lava flow

† Values shown parenthetically not used in final age calculation.

§ Values shown parenthetically rejected for stratigraphic reasons.

almost entirely tholeiitic basalt, with the exception of a transitional basalt plug at Ka‘eo hill, which straddles the boundary between tholeiitic and alkalic basalt (fig. 5). Langenheim and Clague (1987) described this lava as belonging to a postshield stage of volcanism but retained it within the Pānī‘au Basalt. Two samples from that plug yielded ages of 5.15±0.11 Ma and 4.67±0.08 Ma (table 1), indistinguishable from ages obtained elsewhere in the Pānī‘au Basalt.

Ni‘ihau’s rejuvenated-stage lava ranges in age from about 2.32 to 0.35 Ma, with most of the lava flows younger than 1 Ma (fig. 4). These lava flows and associated vent deposits form the Ki‘eki‘e Basalt. They are chiefly alkalic basalt with lesser tholeiitic basalt (fig. 5). Reversed-polarity Ki‘eki‘e lava was sampled at the southern tip of the island (Doell, 1972), from the site that yielded K–Ar ages of 2.68 Ma and 2.32 Ma (table 1). The combination of the paleomagnetic polarity and radiometric age data suggest that the southern site is younger than 2.60 Ma. Normal-polarity magnetization characterizes most other sampled Ki‘eki‘e lava flows. Those sites are entirely within lava-flow units whose radiometric ages are younger than 0.78 Ma, in agreement with their emplacement during the Brunhes Normal-Polarity Chron.

Lehua island is a tiny Ki‘eki‘e Basalt tuff cone, only 1.1 km^2 in area, that lies 1 km north of Ni‘ihau (fig. 3). Undated, it is fairly youthful, to judge from its landform. Ash from its eruptions carried across much of Ni‘ihau, forming weakly consolidated dunes on the northern part of the island. These deposits are 1–5 m thick where mapped on Pakeho‘olua[1] cone, a small Ki‘eki‘e shield vent emplaced about 0.52 Ma that now forms the northern quarter of Ni‘ihau. Stearns (1947) thought that Pakeho‘olua was the youngest subaerial feature on Ni‘ihau itself (nearby Lehua island would be even younger.) Ages slightly younger than the 0.52-Ma Pakeho‘olua age were obtained by G.B. Dalrymple (table 1) for some lava flows farther south along the west shore, but the stratigraphic relation of those units to Pakeho‘olua and Lehua island cone is unknown.

Stearns (1947) describes sparse shoreline features at 8 and 60 m altitude on cinder cones of the Ki‘eki‘e Basalt that may warrant reevaluation in light of megatsunami deposits found elsewhere along the island chain. Black mud, possibly of marine origin, fills the crater of Pu‘ulehua cone, and a ledge of rock he thought had been swept bare by the sea crops out on the northwestern side of the cone at about 30 m altitude.

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[1] The geographic term “Pakeho‘olua” was used by Stearns (1947) in his text but does not appear on the 1926 topographic base map or subsequent maps of Ni‘ihau. The term is absent from modern geographic lexicons.

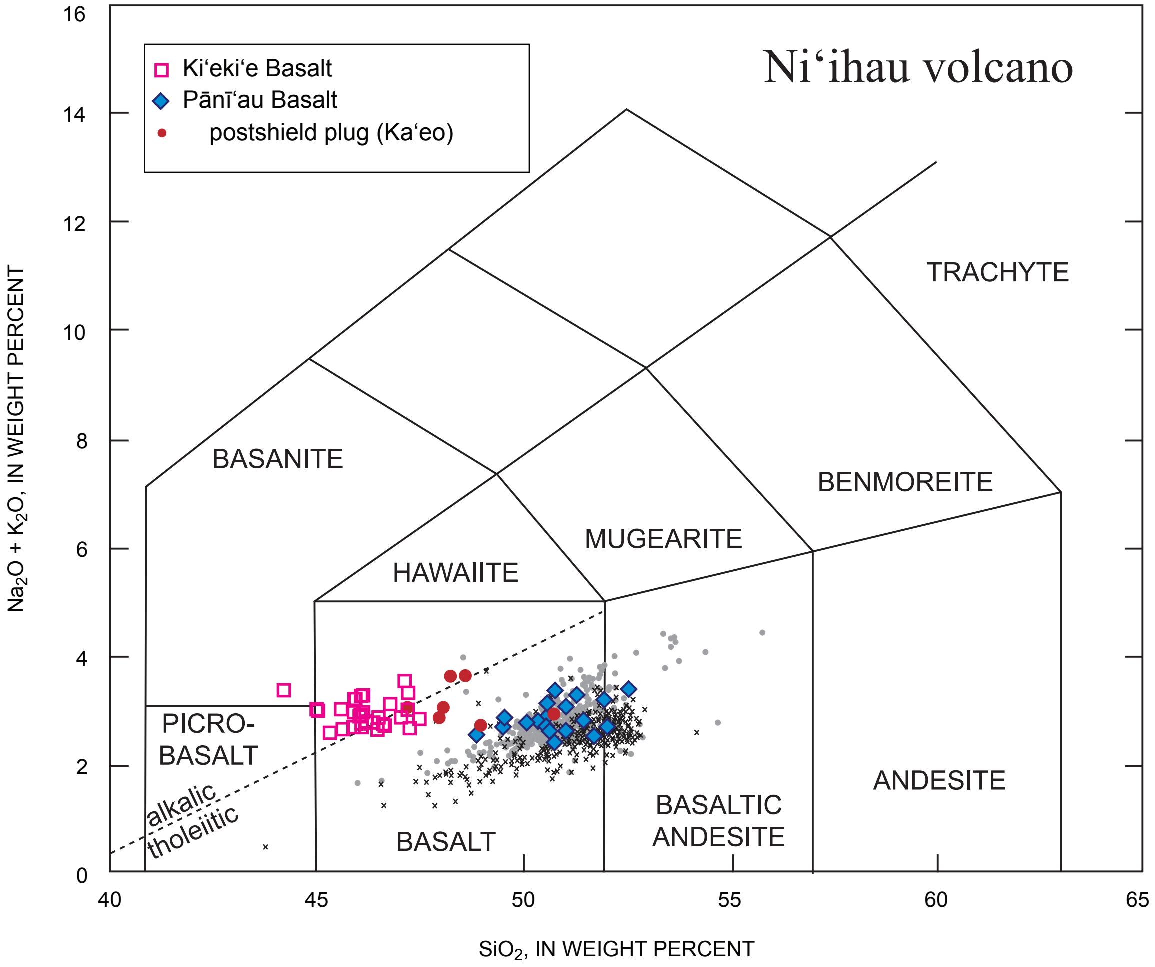


Figure 5. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Ni‘ihau. Grid fields labeled for those compositional types commonly recognized in Hawaiian islands; grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Ni‘ihau chemical data from D.A. Clague (unpub. data, 50 analyses), Washington and Keyes (1926, 5 analyses), and Macdonald (1968, 1 analysis).

Stearns also describes a well-preserved shoreline found farther south, at Kawa‘ewa‘e cone, where fossiliferous limestone at about 8 m altitude can be traced around the cone’s northwest slope. At the southern tip of the island, he found a ledge of reef limestone perched at 30 m altitude on Kawaihoa cone. The Kawa‘ewa‘e and Kawaihoa limestone occurrences are each shown by an × on his map (Stearns, 1947), which suggests their extent was limited. (An × marks the spots on our rendition, too.) Deposits mapped and described in a similar manner on Lāna‘i and Maui (Stearns, 1940c; Stearns and Macdonald, 1942) are thought by many modern researchers to be onshore evidence of megatsunami.

Kaua‘i

Setting and stratigraphic notes

Kaua‘i, one of the older islands in the chain, is also the most complex structurally. Generally thought of as a single-volcano island, some isotopic data challenge that interpretation. Consequently, Kaua‘i provides many opportunities to substantially broaden our understanding of how ocean-island volcanoes develop.

Strata forming the main mass of the Kaua‘i volcanic complex are assigned to the Waimea Canyon Basalt, a formation containing separate members that record the growth of the shield and the late structural development of a central caldera and adjacent graben (fig. 6). Radiometric ages indicate that the subaerial part of the Kaua‘i volcanic complex grew mainly between 5.5 and 4 Ma (fig. 4); these strata form the Nāpali Member of the Waimea Canyon Basalt. A caldera was probably present throughout much of Waimea time, ultimately expanding to encompass a roughly circular area 18–19 km across. The caldera-filling deposits, assigned to the Olokele Member, are chiefly thick lava flows that ponded within the caldera depression about 4 Ma, on the basis of a single radiometric age. Talus breccia accumulated

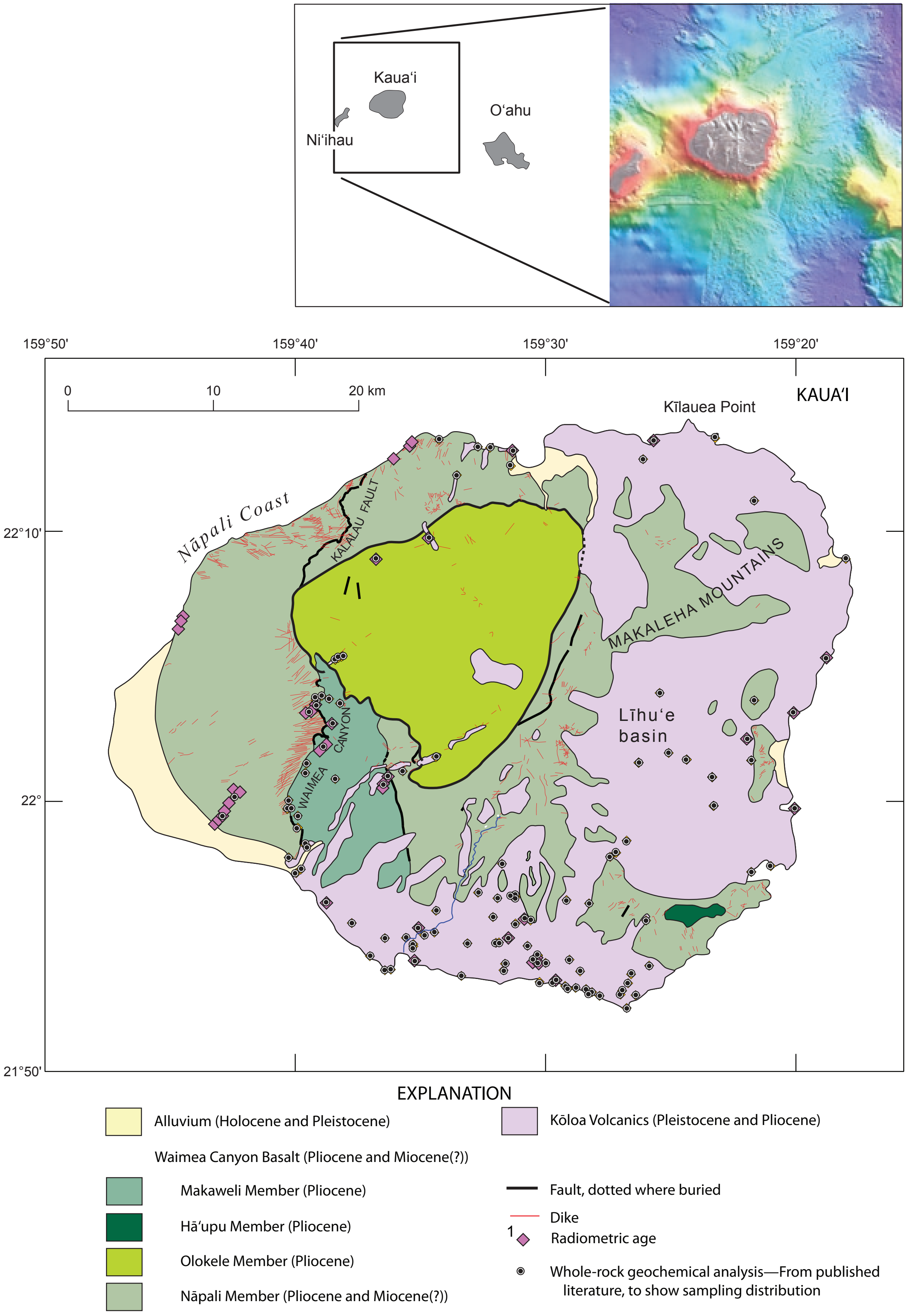


Figure 6. Geologic map of Kaua'i, generalized from this publication's digital map database. Geology from Macdonald and others (1960). Inset bathymetric map from Eakins and others (2003).

near the caldera walls and is exposed locally along the present-day mapped boundary. Mapping of the caldera boundary was based on the finding of thick lava flows (of the Olokele Member) juxtaposed against thin lava flows (of the Nāpali Member) and, where exposures were suitable, the presence of colluvial breccia deposits preserved on the paleoslopes of the caldera walls (Macdonald and others, 1960).The geologic map shows the Kalalau fault, of highly irregular trace, north of the Olokele caldera. Macdonald and others (1960) thought this fault formed at about the same time and in same manner as the caldera-bounding fault. When viewed in detail on topographic base, it is seen to range from nearly vertical to nearly horizontal. Little is known in detail of the Kalalau fault, which may be a composite of features found in the cliffy exposures of northeast Kaua‘i.

Eruptions filled the summit caldera, and lava spilled outward in some areas. Once free of the ponding effect of the caldera depression, these lava flows formed thin pāhoehoe and ‘a‘ā, similar to lava flows of the Nāpali Member. These spill-over flows were necessarily included with the Nāpali Member, owing to their similar aspect and the limited amount of time available for the original mapping project (Macdonald and others, 1960). Thus the Nāpali is a time-transgressive stratigraphic unit whose upper part is coeval with the Olokele Member.

A more restrictive view of the Nāpali–Olokele relation was suggested by Bogue and Coe (1984) on the basis of paleomagnetic directions measured at four sites across the island. In their interpretation, the upper part of the Nāpali contains the reversed-polarity chronozone 3n.1.r and overlying normal-polarity chronozone 3n.1.n, the boundary of which is about 4.30 Ma in age (Ogg and Smith, 2004). The caldera-filling Olokele Member preserves another polarity reversal interpreted by Bogue and Coe (1984, their Kāhililoa site) as normal-polarity chronozone 3n.1.n overlain by reversed-polarity chronozone 2Ar. This latter polarity boundary formed about 4.187 Ma (Ogg and Smith, 2004). Applied broadly, this interpretation suggests that the Olokele caldera never overflowed extensively, because the capping reversed-polarity lava flows of the Olokele Member are lacking from the upper part of the Nāpali Member. In our view, the number of paleomagnetic sampling sites is too sparse, but the application of paleomagnetism for refining the stratigraphic understanding of Kaua‘i remains tantalizing. Indeed, future detailed mapping may resolve chemical or magnetostratigraphic characteristics that permit a finer-scale delineation across the mapped breadth of the Nāpali and Olokele Members.

Late in Olokele time, a flanking structural trough, the Makaweli graben, developed southward from the Olokele caldera to become another site of lava deposition. Lava flows in the graben are assigned to the Makaweli Member of the Waimea Canyon Basalt. A volumetrically minor part of the Makaweli Member is the Mokuone Breccia Beds, which comprises a few layers of conglomerate and breccia found at the base of the graben-filling sequence and interbedded in its lower part. Radiometric ages indicate that lava was emplaced in the Makaweli graben from about 4 to 3.5 Ma.

Another stratigraphic unit, the Hā‘upu Member of the Waimea Canyon Basalt, was thought to have originated in a small caldera on the southeast flank of the Kaua‘i volcanic complex, 20 km from the summit area. The Hā‘upu Member contains nearly flat-lying, thick lava flows and coarse breccia described as sitting concordantly and discordantly on the underlying Nāpali Member (Macdonald and others, 1960). No faults are shown in the area on the original geologic map, but a small page-size figure showed the Hā‘upu caldera as fault bounded (Macdonald and others, 1960, compare their plate 1 and their fig. 18). Doubtless the Hā‘upu Member is a record of volcanic fill, but whether it is a separate caldera 4 km in diameter, the remnant of a valley wall, or the edge of the much larger Līhu‘e basin (discussed later) seems open to speculation. The Hā‘upu Member lacks radiometric ages and geochemical or isotopic analyses.

Rift zones on Kaua‘i are poorly developed, judging from the symmetrical form of the Kaua‘i shield compared to the typical Hawaiian shield volcano. This distinction may result from Kaua‘i’s distance from its nearest neighbor, Ni‘ihau, which allowed it to grow in a nearly symmetrical stress field (Fiske and Jackson, 1972). The shield-stage lava flows assigned to the Nāpali Member of the Waimea Canyon Basalt typically dip outward away from the main volcanic center defined by the island’s summit area. Bouguer gravity contours (Krivoy and others, 1965) show an elongate gravity high extending northwestward from a maximum in the Līhu‘e basin, the basis for some depictions showing a rift zone in a northwest-southeast orientation (Fiske and Jackson, 1972). The density of gravity stations is sparse, however, and enhanced station coverage in the mountainous region southwest and west of the Līhu‘e basin could change the sense of elongation or weaken it greatly. Alternative interpretations of two rift zones oriented northeast and west-southwest arise from the geologic source map itself (Macdonald and others, 1960): the northeast trend is inferred from the gentle dip of lava flows in the Makaleha Mountains in the northeastern part of the island and a submarine bathymetric bulge off the northeast shore (fig. 6, inset). The west-southwest trend is inferred from the numerous dikes exposed in the west wall of Waimea Canyon (Macdonald and others, 1960; Macdonald and others, 1983).

Kaua‘i geologic maps lack a stratigraphic unit that corresponds directly to the postshield volcanic stage found at several Hawaiian volcanoes. However, some lava flows in the compositional range hawaiite to mugearite, characteristic of postshield strata in other volcanoes, are scattered among the upper part of the Olokele and Makaweli Members and were encountered in drill holes that penetrate the Līhu‘e basin (Reiners and others, 1999) (fig. 7). The drill-hole analyses, obtained from bulk cuttings thought to represent lava flows in the Nāpali Member, are compositionally distinct from analyses of Nāpali basaltic rocks from outcrops (fig. 7).

What Kaua‘i may lack in readily mapped postshield strata seems more than compensated for by an extensive field of rejuvenated-stage volcanic rocks, the Kōloa Volcanics. The Kōloa includes all the lava flows and vent deposits lying largely in a post-erosional setting and were erupted long after the main stage of shield growth ended. The rejuvenated-stage lava flows, chiefly basanite, were emplaced mainly between 2.6 and 0.15 Ma (Clague and Dalrymple, 1988). A single age of 3.65±0.06 Ma was reported by Clague and Dalrymple (1988; reported here as 2σ error) from a basanitic lava flow that they interpreted as a rejuvenated-stage product on the basis of its alkalic chemistry. This age, more than 1 myr older than other Kōloa ages, overlaps with ages from the underlying Makaweli Member (fig. 4) and raises skepticism about the sample’s stratigraphic assignment to the younger unit, the Kōloa. But the 3.65-Ma sample has a $^{87}Sr/^{86}Sr$ isotopic ratio characteristic of the Kōloa (Clague and Dalrymple, 1988). These arguments have proponents on both sides of the debate: those who side with “rejuvenated stage” as a geochemical distinction marked by the occurrence of

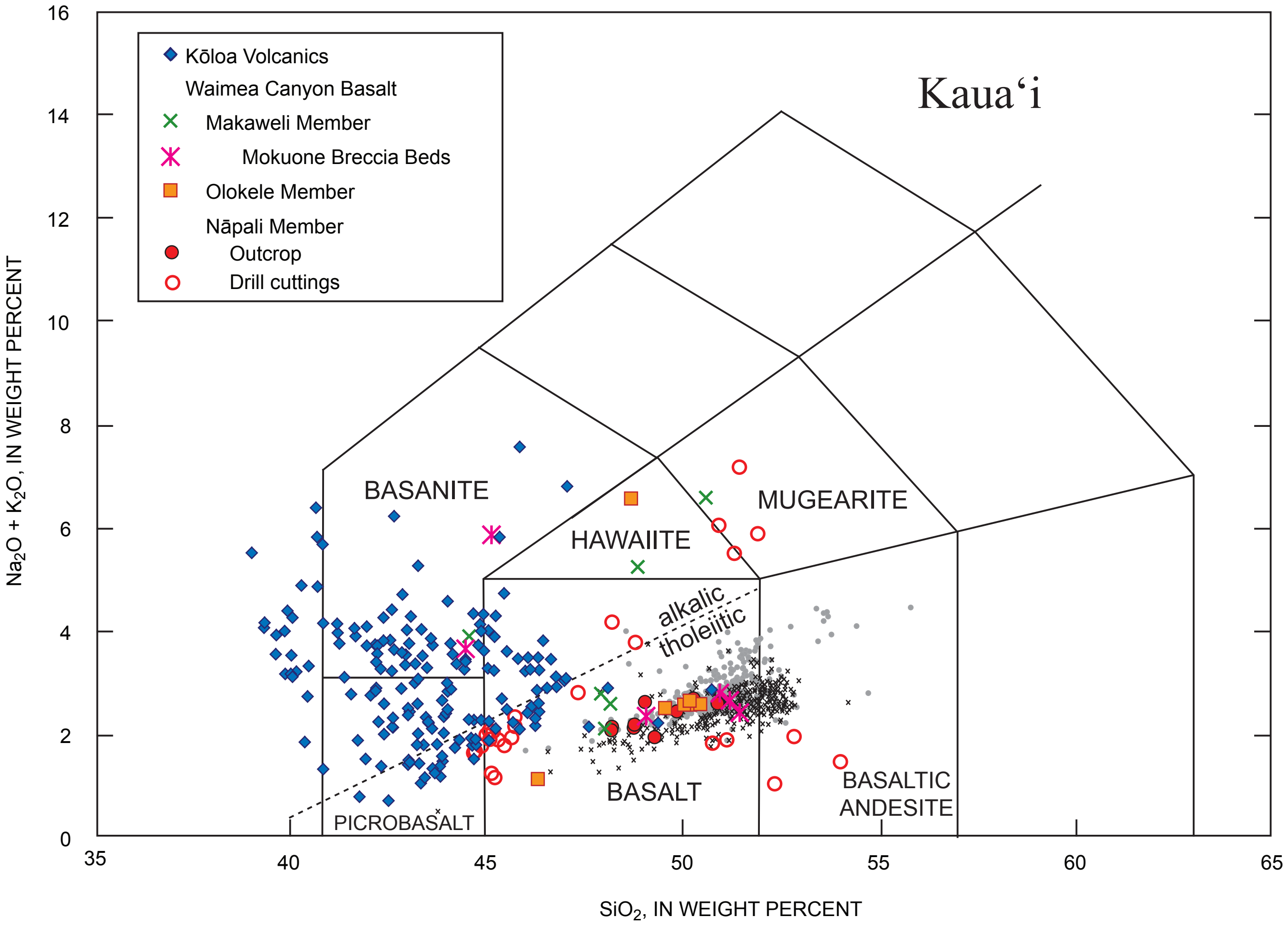


Figure 7. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Kaua‘i. Grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Kaua‘i chemical data from Clague and Dalrymple (1988, 55 analyses), Reiners and others (1999, 54 analyses), Reiners and Nelson (1998, 46 analyses), Palmiter (1975, 29 analyses), Washington and Keyes (1926, 1 analysis), Maaløe and others (1992, 18 analyses), Macdonald and others (1960, 14 analyses), Garcia (1993, 14 analyses), Macdonald and Katsura (1964, 12 analyses), Macdonald (1968, 11 analyses), Feigenson (1984, 11 analyses), Cross (1915, 3 analyses), and Kay and Gast (1973, 3 analyses).

undersaturated alkalic lava versus those who desire geologic or geochronologic evidence for a significant break in eruptive activity prior to rejuvenation.

Līhuʻe basin

The Līhuʻe basin is an elongate lowland on the east-central side of Kauaʻi. It is fully drained by east-flowing streams mostly tributary to the Wailua River and Hanamāʻulu and Hulēʻia Streams. A north-trending ridge of shield-stage lava flows (Nāpali Member of Waimea Canyon Basalt) forms the east side of the basin, poking through a pervasive veneer of Kōloa Volcanics as thick as 225 m (Reiners and others, 1999). In the basin, fossiliferous marine mudstone was penetrated in drill holes at depths below modern sea level, minus 125 m to minus 175 m (Izuka and Gingerich, 1997a, b, c, d; Gingerich and Izuka, 1997).

A structure-contour map (fig. 8) shows the breadth and depth of the basin, the altitude at the base of the Kōloa Volcanics within the basin, and the abrupt thickening of the Kōloa Volcanics at the foot of the east-

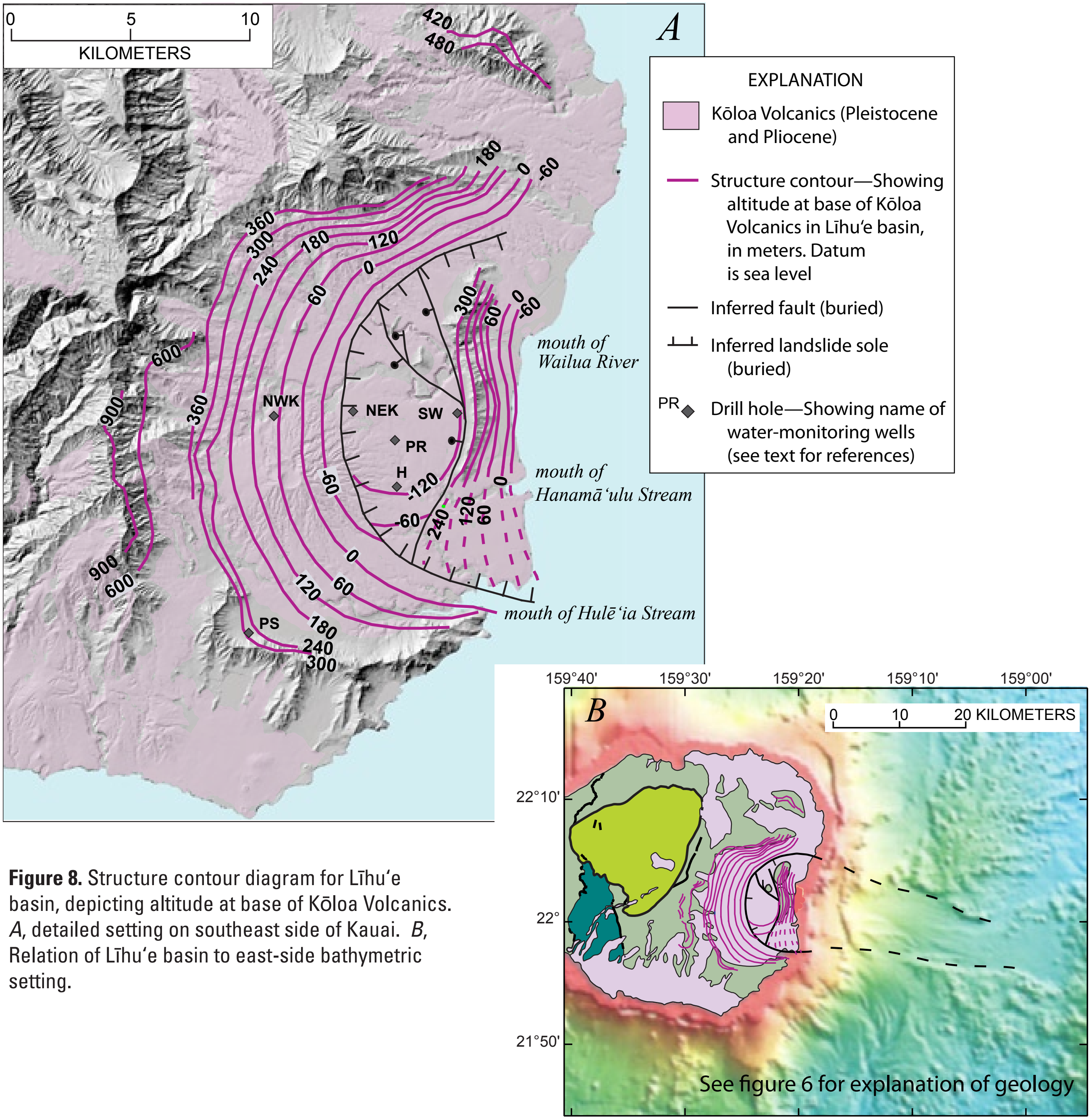


Figure 8. Structure contour diagram for Līhuʻe basin, depicting altitude at base of Kōloa Volcanics. *A*, detailed setting on southeast side of Kauai. *B*, Relation of Līhuʻe basin to east-side bathymetric setting.

side ridge. Contours along the west side of the basin show minimum altitude for the base of the Kōloa on the basis of modern-day exposures of the underlying Nāpali Member bedrock. A fault boundary is required only on the east side of the basin; whereas elsewhere the Nāpali–Kōloa contact dips gently into the basin's flattish floor. The structure-contour map and adjacent bathymetric setting (fig. 8) lead us to favor a landslide-based origin for the Līhuʻe basin. The hypotheses for erosional and caldera-collapse origins for the basin were summarized by Macdonald and others (1960), who concluded that evidence was sparse but that a caldera-collapse origin might be favored because it was the simpler of the two choices considered by them. A landslide hypothesis was suggested recently (Reiners and others, 1999).

Two shields or one?

As offered by Macdonald and others (1960), the depiction of Kauaʻi as a single-shield volcano is the best-known interpretation of volcanic history for the island. An alternative interpretation has been suggested on the basis of strontium isotopic analyses from late-shield strata of the Waimea Canyon Basalt on the west and east sides of the island, which differ sufficiently to suggest that two magma-supply systems were erupting during the growth of Kauaʻi (Holcomb and others, 1997). An additional rationale offered in support of a two-volcano hypothesis is the possibility of numerous rift zones radiating outward in as many as five directions (Holcomb and others, 1997). The suggestion that numerous weakly developed Kauaʻi rift zones may coincide with small elongate submarine ridges was noted earlier by Clague (1990). Most Hawaiian volcanoes have three or fewer rift zones (for example, Fiske and Jackson, 1972); hence the inference that more than one volcano is present on a multi-rift zone island. A two-volcano, five-zone rift system was depicted in a simplified map figure by Clague (1996), but no discussion ensued.

Another explanation for the Sr isotopic spatial pattern is that it results from sampling across disparate parts of a single volcano's stratigraphic sequence. Thus, the across-island isotopic variation could mark the volcanic expression of changing mantle source as the Pacific plate was transported over a radially or vertically zoned hotspot plume, as suggested by Mukhopadhyay and others (2003) from their more detailed study of isotopic variations within Nāpali Member strata. A zoned plume was invoked by previous workers to explain contrasts within volcanoes like West Maui, Haleakalā, and Mauna Loa.

To diminish the effect of stratigraphic variation, Holcomb and others (1997) based their sampling on the position of a magnetostratigraphic polarity boundary thought correlative across Kauai, on the basis of similar paleomagnetic directions measured at sites on the west and east sides of the island (Bogue and Coe, 1984). This correlation has never been tested rigorously, however, insofar as no radiometric ages have been reported from the Waimea Canyon Basalt on the east half of the island. Most of the ages obtained from the Waimea Canyon Basalt span the time from about 5 to 4 Ma, a period when the Earth's magnetic polarity switched from reversed to normal and back no fewer than four times. Thus the sampled strata, if mismatched, may differ in age by as little as 0.26 myr or as much as 0.91 myr. The two-volcano hypothesis remains a topic worthy of pursuit. Its resolution will depend on some closely linked, detailed magnetostratigraphic observations, radiometric dating, and analytical chemistry.

Oʻahu

Oʻahu was built by two volcanoes, the older Waiʻanae volcano and the more easterly Koʻolau volcano. Each volcano has been truncated by massive submarine slides, the Waiʻanae Slump to the southwest and Nuʻuanu Slide to the northeast. Walker (1995) noted the general dearth of plant molds in lava flows of Oʻahu volcanoes and suggested that the exposed lava sequences represent the arid, upper 1,000-m remnants of mountains that once projected above the altitude of trade winds (~3000 m above present sea level). This interpretation is consistent with the argument that most of the older Hawaiian islands have subsided several thousand meters since formation (Moore, 1987) by their imposition on the underlying oceanic crust.

Waiʻanae volcano—setting and stratigraphic notes

Waiʻanae volcano, older of the two Oʻahu volcanoes, is built of the Waiʻanae Volcanics, whose four members (Lualualei, Kamaileʻunu, Pālehua, and Kolekole Members) encompass (1) shield-building tholeiitic basalt, (2) a late-shield or transitional phase that includes caldera-filling lava, (3) a dominantly hawaiitic postshield-stage phase, and (4) a later post-erosional, dominantly basaltic postshield phase (fig. 9). The first systematic geologic map of Oʻahu (Stearns, 1939) grouped the Waiʻanae Volcanics into a single map unit, although informal members were described earlier (Stearns and Vaksvik, 1935) and an upper member (Pālehua and Kolekole Members on our

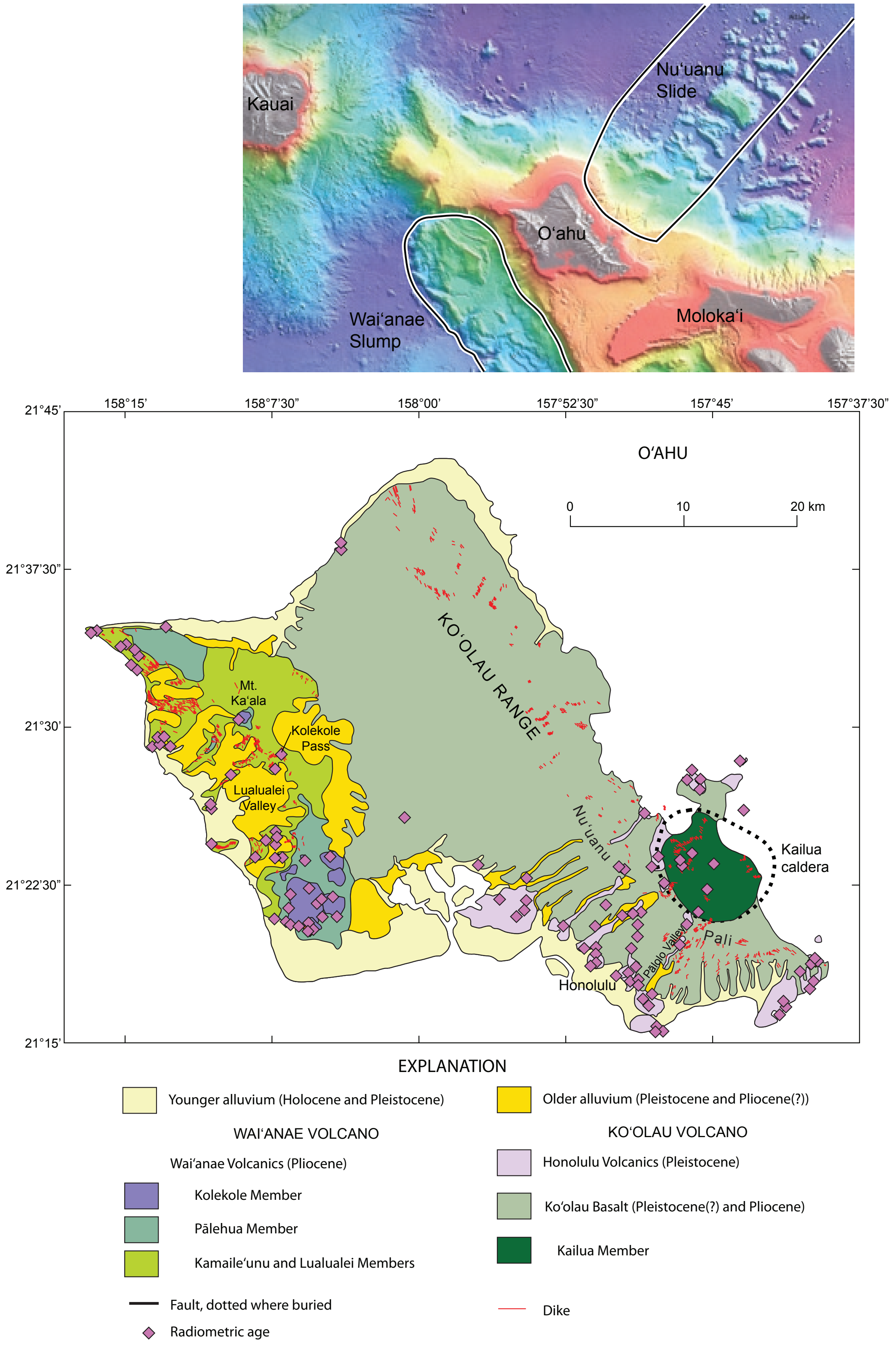


Figure 9. Geologic map of O‘ahu, generalized from this publication’s digital map database. Geology from Stearns (1939) and J.M. Sinton (this map). Inset bathymetric map from Eakins and others (2003).

map) was later shown separately on a small-scale map figure (Macdonald, 1940a). In addition, Stearns (1939) recognized the post-erosional character of a lava flow at Kolekole Pass, which he later named as a formal stratigraphic unit (Stearns, 1946).

Sinton (1987) revised the stratigraphic nomenclature for the Wai‘anae Volcanics, replacing the former lower, middle and upper members with newly defined Lualualei, Kamaile‘unu and Pālehua Members. The Kolekole Volcanics was extended to include several lava flows and cinder cones on the southeastern and south flanks of the Wai‘anae Range, on the basis of chemical and stratigraphic similarity to the type section at Kolekole Pass (Sinton, 1987). Subsequently it was determined that the age of Kolekole eruptions is barely distinguishable from that of the earlier Pālehua lavas, with the transition occurring about 3 Ma, and that the intervening unconformity marked a short-lived event perhaps related to the massive submarine slumping of the west side of the Wai‘anae Volcano (Presley and others, 1997). As a consequence, the Kolekole Volcanics unit is now thought to represent a continuation of postshield volcanism that began with the eruptions of the Pālehua Member, and not the product of a separate, rejuvenated-stage volcanic episode. For these reasons, Presley and others (1997) chose to reduce the rank of the Kolekole Volcanics from formation to member and to include it in the encompassing Wai‘anae Volcanics.

More recent mapping has further clarified the outcrop areas of Pālehua and Kolekole Members of the Wai‘anae Volcanics (this map). The combined outcrop area of these postshield members is more areally restricted on our map than in the depiction of the upper member of Stearns (1939) and Macdonald (1940a), with most of the difference lying along the range crest northwest of Mount Ka‘ala.

The Wai‘anae Volcanics have radiometric ages ranging from about 4.0 Ma to as young as about 2.9 Ma. A few younger ages were reported by Doell and Dalrymple (1973), but we interpret those ages as too young, in view of the more complete dating and stratigraphic information available today (fig. 10). The period between 3 and 4 Ma was one of frequent magnetic polarity reversals spanning parts of the Gilbert and Gauss Chrons, including the Mammoth and Ka‘ena Reversed-Polarity Subchrons within the Gauss Normal-Polarity Chron (Ogg and Smith, 2004). The combination of relatively easy access, numerous magnetic reversals, 80 radiometric ages (McDougall, 1963; 1964; Funkhouser and others, 1966; 1968; Doell and Dalrymple, 1973; Presley and others, 1997; Laj and others, 1999; Guillou and others, 2000), and advanced

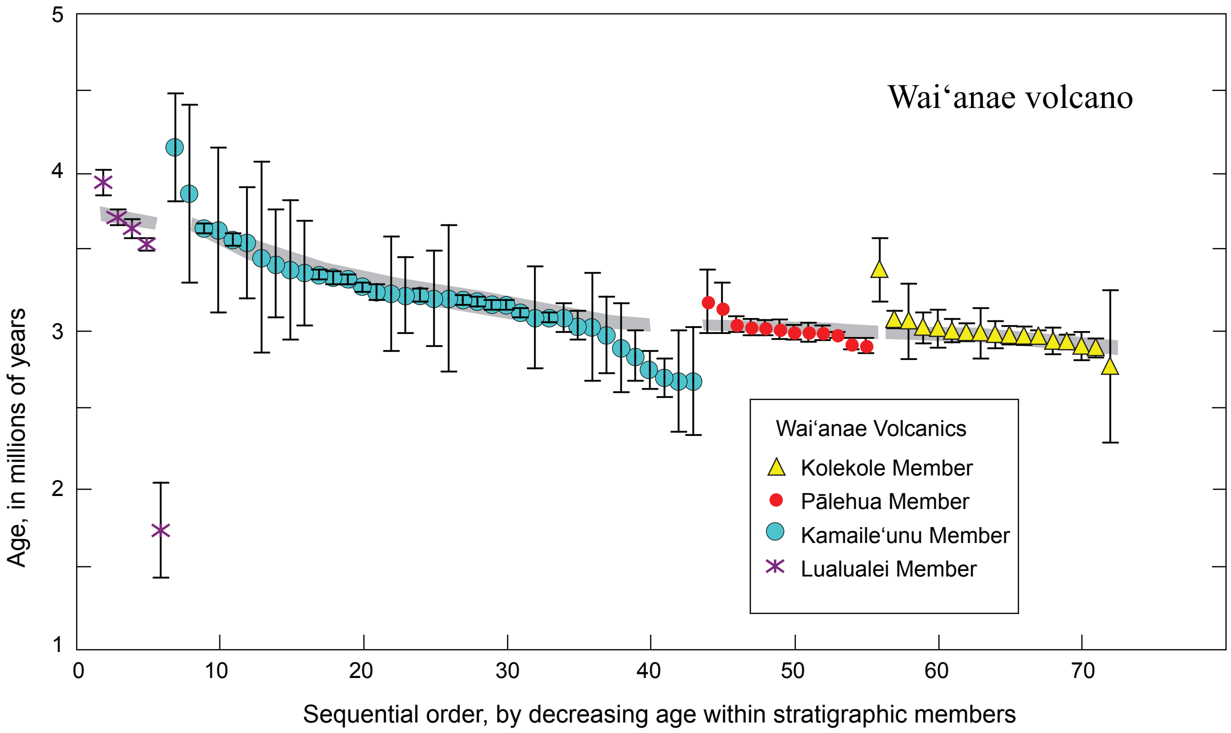


Figure 10. Radiometric ages from Wai‘anae volcano. Gray bands indicate likely range of stratigraphically valid ages, as a guide to recognizing ages too old or too young. Data from McDougall (1964), McDougall and Aziz-ur-Rahman (1972), Doell and Dalrymple (1973), Presley and others (1997), Laj and others (1999), and Guillou and others (2000).

stage of erosion on the leeward (dry) side of O‘ahu has allowed a fairly precise stratigraphic resolution of the volcano.

The oldest exposed lava flows, in the Lualualei Member, are tholeiitic olivine basalt with reversed polarity magnetization and radiometric ages ranging from slightly older than about 3.9 to as young as 3.55 Ma. A well-developed caldera in the vicinity of Lualualei Valley was present throughout Lualualei time, as was a well-developed rift zone trending approximately N. 60° W. from near Kolekole Pass. Another lesser rift zone runs southeast from the head of Lualualei Valley, which marks the volcano’s center, but its dikes trend along a more radial pattern as they swing around the south side of the caldera, perhaps in response to the stress field created by caldera growth (Zbinden and Sinton, 1988). A poorly developed third rift zone trends approximately N. 65° E. from the volcanic center (Stearns and Vaksvik, 1935).

The Kamaile‘unu Member, erupted during a later shield-building stage lasting from 3.55 to 3.06 Ma, is characterized by increasing variability of lava composition, including plagioclase-phyric tholeiitic basalt, alkali olivine basalt, and alkalic, plagioclase-phyric hawaiite (composition on the basalt–hawaiite boundary, fig. 11). Eruptions of Kamaile‘unu lava flows occurred within the caldera and along rift zones outside the caldera. The caldera eventually was filled by Kamaile‘unu lava flows, so this period can be viewed as a caldera-filling episode. Alkalic lava flows become increasingly abundant in Kamaile‘unu sections younger than about 3.207 Ma, the upper boundary of the Mammoth Reversed-Polarity Subchron (Ogg and Smith, 2004). Silicic lava, including icelandite (Al-poor,

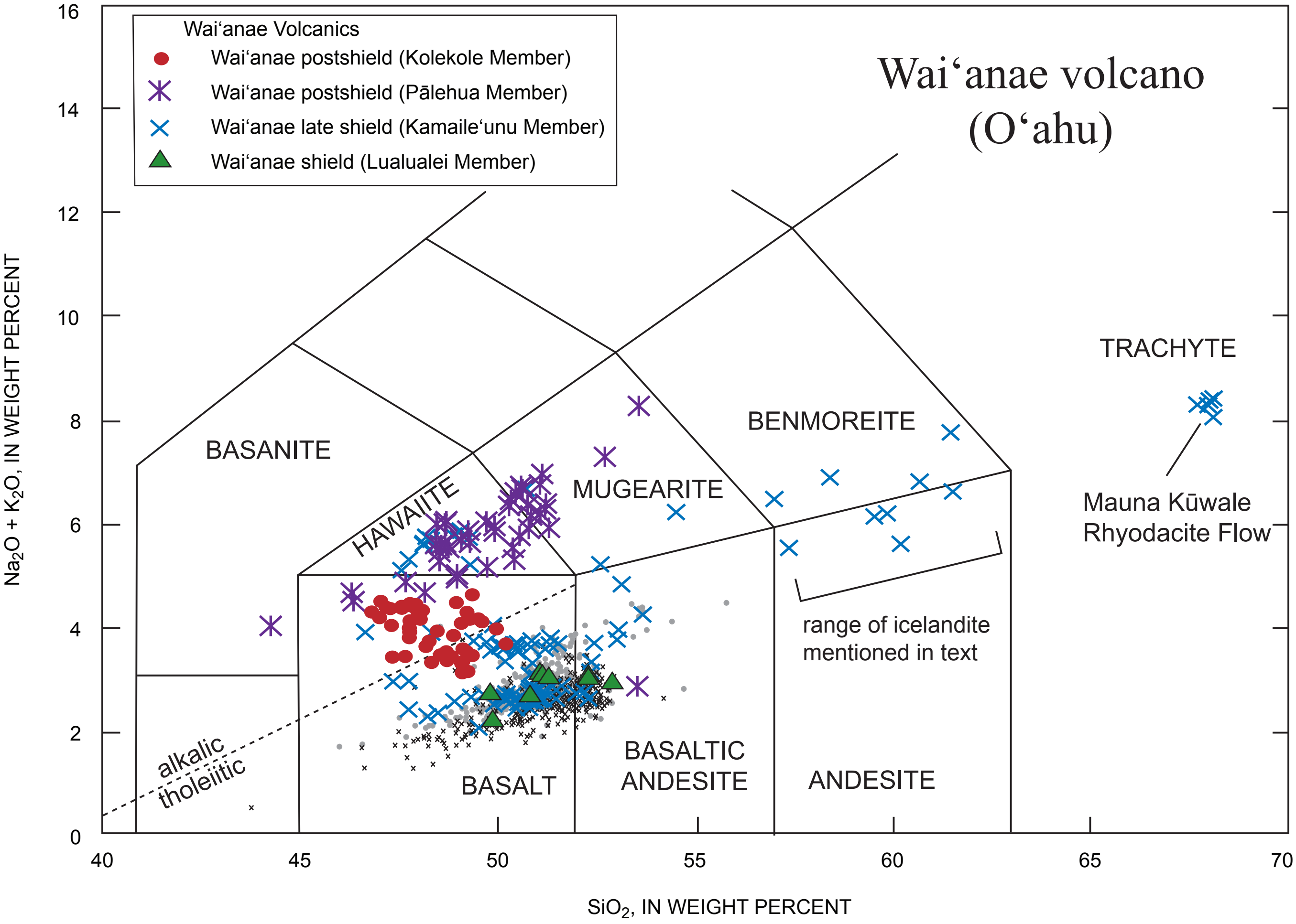


Figure 11. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Wai‘anae volcano, O‘ahu. Grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Wai‘anae chemical data from J.M Sinton and G.A. Macdonald (Bishop Museum’s online database, 72 analyses), Macdonald and Katsura (1964, 50 analyses), T.K. Presley (Bishop Museum’s online database, 48 analyses), Presley and others (1997, 18 analyses), Sinton (1987, 4 analyses), Macdonald (1968, 2 analyses), and Bauer and others (1973, 2 analyses).

Fe-rich andesite) and rhyodacite (fig. 11), is exposed as intracaldera dikes and flows. Radiometric ages for the Mauna Kūwale Rhyodacite Flow range from 2.4±0.3 Ma (Funkhouser and others, 1966, 1968) to about 8.4 Ma (McDougall, 1964), but the eruption of this unit is now known to have occurred close to the lower Mammoth boundary, about 3.3 Ma (Guillou and others, 2000). The Mauna Kūwale Rhyodacite Flow, which contains 68 percent SiO_2, is the most silicic lava composition reported from the Hawaiian island chain, and the Wai‘anae volcano is remarkable for its eruptions of highly evolved lava emplaced during the shield stage.

The postshield cap of the volcano comprises the Pālehua and Kolekole Members. They possess mainly normal-polarity magnetization younger than the Ka‘ena subchron's younger boundary, about 3.04 Ma, although rare reversed-polarity Pālehua lavas have been found near the base of the postshield section. The Pālehua includes hawaiite and mugearite. The overlying Kolekole Member, the "last gasp" of the Wai‘anae volcano, marks a return to basaltic eruptions (fig. 11); it also commonly contains xenoliths of lower crustal dunite, pyroxenite, and gabbro. The Kolekole is separated from the Pālehua by a substantial erosional disconformity; but their difference in age is barely distinguishable, the transition occurring about 2.98 Ma (Presley and others, 1997). Thus, the profound erosional event separating Pālehua and Kolekole Members, although short-lived, correlates with a substantial decrease in the amount of magmatic differentiation.

A huge landsliding event has been suggested as a mechanism to precipitate the major erosional episode prior to Kolekole time, with the evidence preserved as the Wai‘anae Slump (Presley and others, 1997). Covering roughly 5,500 km^2, the Wai‘anae Slump is one of the larger submarine landslides associated with the Hawaiian Islands (inset, fig. 9). It contains features thought typical of a slumplike landslide with a complicated and possibly prolonged history (Moore and others, 1989; Coombs and others, 2004). By one interpretation, the Wai‘anae Slump occurred prior to Pālehua time (before about 3.06 Ma), inasmuch as no alkalic rocks have been collected from the slump (Coombs and others, 2004). The slump is sparsely sampled, however, owing to the ominous plexus of telecommunication cables that traverse the region. Also, the volcano's capping alkalic strata likely are thin, and most of the slump is derived from the submarine flanks of the volcano, which is broadly tholeiitic in composition. Thus, an age estimate derived on the basis of recovered rock types might be judged cautiously. But in view of the arguments for multiple events contributing to the Wai‘anae Slump (Coombs and others, 2004), the Kolekole-related, subaerial erosion and deposition about 2.98 Ma might be one in a series of mass-wasting events that affected the Wai‘anae volcano.

Ko‘olau volcano—setting and stratigraphic notes

The Ko‘olau Range is the western dip slope and core of Ko‘olau volcano (fig. 9). About 10 percent of the east half of the volcano has been carved away by large submarine landslides—specifically, 2–4 $x10^3$ km^3 from a volcano originally containing about 34 $x10^3$ km^3 (Satake and others, 2002; Robinson and Eakins, 2006, respectively).

Volcanic strata of the shield stage are assigned to the Ko‘olau Basalt, a sequence of tholeiitic basalt lava flows (fig. 12). They dip 3–10° west and southwest from the summit of the Ko‘olau Range; thus the east face of the range is an anti-dip slope exposing about 850 m of the Ko‘olau Basalt. A prominent northwest-trending rift zone is defined by a dike complex on the east side of the range (Stearns, 1939). Ease of access and good exposures make it the best studied dike complex in the Hawaiian Islands. Comparable zones on West Maui and East Moloka‘i lie in rugged terrain lacking roads or trails. The dike complex, containing over 7,400 subparallel dikes in a zone 3–5 km wide, is mapped as a separate part of the Ko‘olau Basalt, owing to the abundance of dikes (greater than 50 percent) in much of the area it covers (Walker, 1987). The boundary between dike complex and the main mass of the Ko‘olau Basalt, although shown by a distinct line on the map, is a gradational zone in which the number of dikes diminishes outward from the core of the dike complex.

A caldera complex, the Kailua caldera, also formed during shield-stage volcanism. Its rocks are assigned to the Kailua Member of the Ko‘olau Basalt, demarcating a roughly equant caldera 9–10 km in diameter (fig. 9) (Stearns, 1939; Walker, 1987).

The oldest ages for subaerially emplaced Ko‘olau Basalt are about 3 Ma, from surface exposures and from samples obtained by drilling (Ozawa and others, 2005, and Haskins and Garcia, 2004, respectively) (fig. 13). The youngest age from the Ko‘olau Basalt is 1.78±0.26 Ma (Doell and Dalrymple, 1973), although Ozawa and others (2005) argued that Ko‘olau volcanism ended ~2.0–2.1 Ma, on the basis of the analytical error associated with their newly obtained ages. An age of 1.59±0.13 Ma from one of several flows sampled near the southeast end of the Ko‘olau Range was reported by Doell and Dalrymple (1973), who regarded it skeptically. Other samples gathered from that sample set range in age from 1.75 to 2.30 Ma, and of those, only two lava

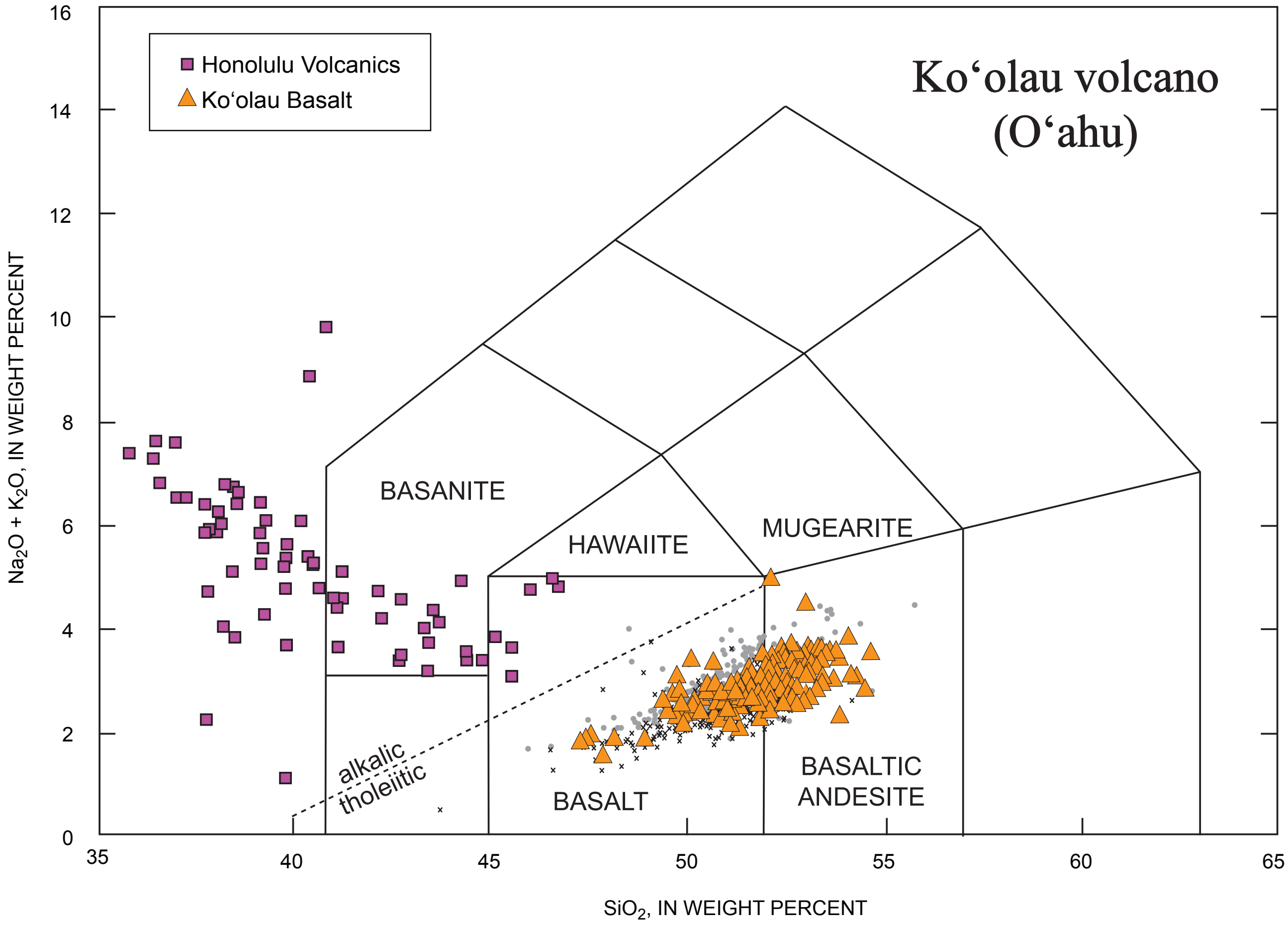


Figure 12. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Koʻolau volcano, Oʻahu. Grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Koʻolau chemical data from Haskins and Garcia (2004, 118 analyses), Frey and others (1994, 71 analyses), Clague and Frey (1982, 41 analyses), Jackson and Wright (1970, 13 analyses), Roden and others (1984, 12 analyses), Macdonald (1968, 10 analyses), Wentworth and Winchell (1947, 9 analyses), Winchell (1947, 8 analyses), Wilkinson and Stolz (1983, 8 analyses), Yoder and Tilley (1962, 4 analyses), Muir and Tilley (1963, 2 analyses), T.K. Presley (Bishop Museum's online database, 2 analyses), Cross (1915, 1 analysis), and Macdonald and Katsura (1964, 1 analysis).

flows had ages that could be repeated satisfactorily through several experimental determinations (Doell and Dalrymple, 1973).

Scattered sporadically above the Ko‘olau Basalt are lava flows and vent deposits of the Honolulu Volcanics (fig. 9). Interpreted as products of rejuvenated-stage volcanism, the Honolulu Volcanics contains several of Hawai‘i's best known vents, such as Diamond Head, Punchbowl Crater, Salt Lake Crater, and Koko Head. The individual eruptive units have had names applied to them in the past, and we carry those into the geologic map digital database, treating them as informally named parts of the Honolulu Volcanics, as recommended by Langenheim and Clague (1987). Some vents of the Honolulu Volcanics form alignments transverse to the rift zone that built the Ko‘olau shield (for example, Stearns and Vaksvik, 1935; Winchell, 1947).

The Honolulu Volcanics have K–Ar ages that range from about 0.80 to somewhat younger than 0.1 Ma, according to a recent, detailed analysis of the unit's emplacement history (Ozawa and others, 2005) (fig. 13). Previously determined ages indicated a similar span of time, although two ages were slightly older, about 1.1–1.0 Ma (Lanphere and Dalrymple, 1980), and two other ages were much too old to make sense stratigraphically (Lanphere and Dalrymple, 1980). As can be seen in the inset for figure 13, some of the youngest reported radiometric ages (Gramlich and others, 1971) are unrealistically precise for the methods available when the work was done.

In keeping with the mapping of Stearns (1939), this geologic map subdivides the Honolulu Volcanics to show separately its youngest deposits, those from the Tantalus Peak–Sugar Loaf vent system and the Koko fissure system. As dated by Ozawa and others (2005), these volcanic deposits are distinctly younger than earlier parts of the Honolulu Volcanics. Their ages form a suite chiefly about 0.1 Ma but perhaps as young as 0.04 Ma when analytical error is considered. The older part of the Honolulu Volcanics is chiefly older than about 0.4 Ma (Ozawa and others, 2005).

Reports that the Honolulu Volcanics includes volcanic rocks with ages younger than 30,000 years probably arise from misinterpretations of the data. For example, eruptions from craters in the Koko fissure system were assigned an age between 32,000 and 7,000 years by Hazlett and Hyndman (1996). As best we can tell, the 32,000-yr age originated from the radiocarbon dating of coral fragments within the ash deposits. The result was an age *greater than* 32,000 years (Rubin and Suess, 1956), by which was meant a sample too old to date by radiocarbon methods at that time. The 7,000-yr age results from radiocarbon dating of reef growing on the Koko fissure deposits (Easton and Olson, 1976); thus, it is a minimum age that provides no better constraint than the 32,000-yr minimum age already mentioned.

An age younger than 10,000 yr was reported for the Sugarloaf flow, a Honolulu Volcanics lava that spread out across the mouth of Mānoa Valley (Hazlett and Hyndman, 1996). This age is an interpretation that hinges on a string of assumptions by Ferrall (1981) about the age of interbedded alluvium and ash deposits that fill an ancestral Mānoa stream channel now flooded by the lava flow; no radiometric data were forthcoming. The Sugarloaf flow has been dated by K–Ar methods. In one case it produced a weighted mean age of about 0.069±0.004 Ma (Gramlich and others, 1971); in the other, a weighted mean age of 0.11±0.13 Ma (Ozawa and others, 2005).

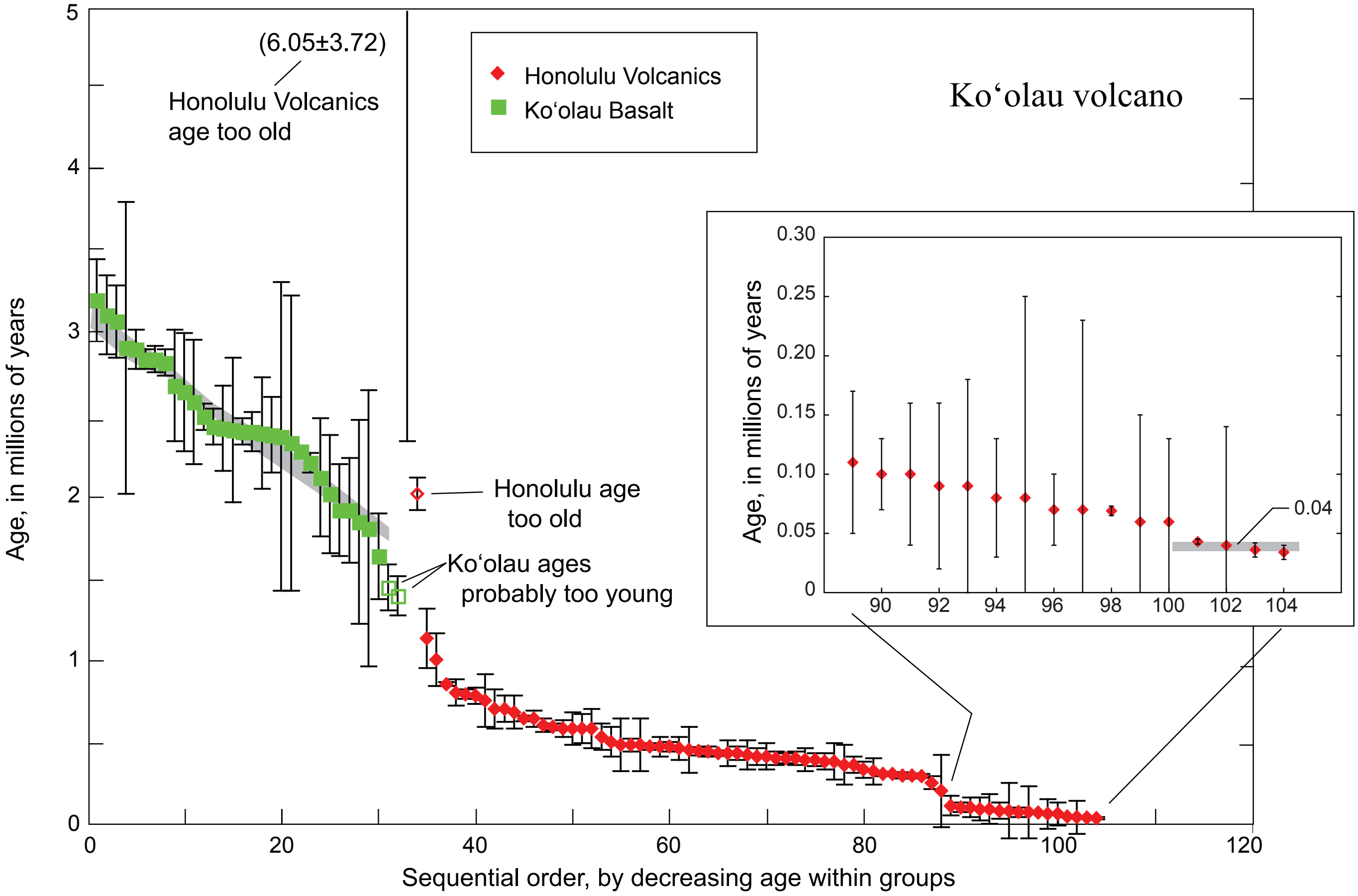


Figure 13. Radiometric ages from Ko‘olau volcano. Open symbols, ages likely too old or too young; see text for discussion. Labeled parenthetically is exceptionally old age from Honolulu Volcanics, for which only the lower part of the error bar shows on range of this graph. Inset is enlargement showing 16 youngest ages from Honolulu Volcanics. Data from McDougall (1964), Gramlich and others (1971), McDougall and Aziz-ur-Rahman (1972), Doell and Dalrymple (1973), Stearns and Dalrymple (1978), Lanphere and Dalrymple (1980), Haskins and Garcia (2004), and Ozawa and others (2005).

Nuʻuanu Pali

One of the most striking geomorphologic features in the Hawaiian Islands is the great northeast-facing cliff that extends for more than 40 km along the present-day crest of the Koʻolau volcano. This sheer precipice ranges in height from about 150 to 800 m above the surrounding terrain. The pali originated mainly by subaerial fluvial erosion (Stearns and Vaksvik, 1935; Macdonald and others, 1983). Structural origins have been proposed (for example, Dana, 1890) but refuted because stratigraphic units exposed at the foot of the pali extend eastward across the abruptly lower terrain. Also, the Koʻolau dike complex (Walker, 1987) is undisturbed. The missing eastern part of the volcano, mentioned in our introduction to Koʻolau, is now marked by the Nuʻuanu Debris Avalanche. This great debris avalanche has a landslide head thought to coincide with an arcuate embayment in the submarine bathymetric contours 15 km northeast of the present shoreline (inset, fig. 9) (Moore and Clague, 2002).

As recognized by Stearns and Vaksvik (1935), it is an oversimplification to say that faulting and caldera structures played no role whatsoever in the formation of the pali. Fluvial erosion may have been enhanced by caldera-related structures, and hydrothermally altered rocks near the ancient caldera may have been highly susceptible to removal by erosion. Nevertheless, the pali extends far beyond the western edge of the Koʻolau caldera, and it is characterized along its entire length by a pattern of scallops that resemble coalesced amphitheater heads of a Hawaiian stream valley. The coincidence of the pali and the main Koʻolau rift zone suggests the numerous dikes influenced the pattern of erosion, perhaps by controlling the volcano's permeability to ground water on its windward side.

Molokaʻi

Molokaʻi is built by lava flows assigned to two major volcanoes, East Molokaʻi and West Molokaʻi. The island today is elongate, roughly 60 km long and only 15 km wide, but it was probably somewhat more equant earlier in its history, before the Wailau Slide chopped off the north half of the island (fig. 14).

West Molokaʻi volcano

West Molokaʻi is a low-lying volcano whose highest point is only about 430 m altitude. Most exposures are of thin-bedded basaltic lava flows typical of shield-stage volcanism. As summarized by Stearns and Macdonald (1947), southwest and northwest rift zones are inferred from the 2–10° dip of lava flows away from the rift zone axes. The northwest rift zone's trace is further defined by northwest-striking dikes exposed in sea cliffs along the northwest shore of the island. The southwest rift zone is customarily drawn to coincide with a broad ridge trending west-southwest away from the summit area, where a few west-southwest-striking dikes have been mapped, to Lāʻau Point. Across much of the volcano, the lava flows have weathered so deeply that little original structure can be recognized. Given the low topographic relief, gentle dips of lava, and shallow incision of the volcano, it is unlikely that more than 100 m of stratigraphic sequence is exposed in the gulches and coastal cliffs of West Molokaʻi.

All volcanic rocks from West Molokaʻi were grouped into the West Molokaʻi Volcanics stratigraphic unit by Stearns and Macdonald (1947). They depicted the distribution of late lava flows in a small-scale figure (Stearns and Macdonald, 1947, their fig. 18), which forms the basis for our informally named map unit "Waiʻeli and other late lava flows" (fig. 14). Some of these flows (Waiʻeli, Kaʻa) are hawaiite and mugearite (fig. 15), a composition typical of postshield formations on other volcanoes, whereas others are tholeiitic. No rejuvenated-stage deposits are known from West Molokaʻi.

Radiometric ages from the West Molokaʻi Volcanics are limited. Two ages from presumed postshield strata, about 1.80 and 1.73 Ma (Clague, 1987a), probably provide the best control on the minimum age of the underlying shield lava (fig. 16). An age of 1.84 Ma from near the shield's summit (McDougall, 1964) may be a reasonable estimate for the end of shield activity. Another suite of six ages, which range from about 1.3 to 2.8 Ma (Naughton and others, 1980), include some ages with large analytical error and ages that create apparent stratigraphic inversion—in which the older age is from the stratigraphically higher lava at some localities.

The eastern edge of the West Molokaʻi volcano is terminated by a fault zone with displacement of at least 150 m. The lava from East Molokaʻi volcano has filled in the downdropped area, banked against the fault zone, and lapped across it onto the West Molokaʻi lava flows.

In compiling this geologic map, we found a substantial southern expansion of the coastline in the area west of Kaunakakai during the past 60 years. Areas shown as tidal flats and open ocean on the 1922 topographic base map have been filled in by mud eroded from upland sites. The progression was already well established by 1935, when H.T. Stearns first started the Molokaʻi geologic mapping. In their text, Stearns and Macdonald (1947) describe the burial of the shoreward part of a fringing reef along the island's south coast, the result of red mud carried seaward as a result of

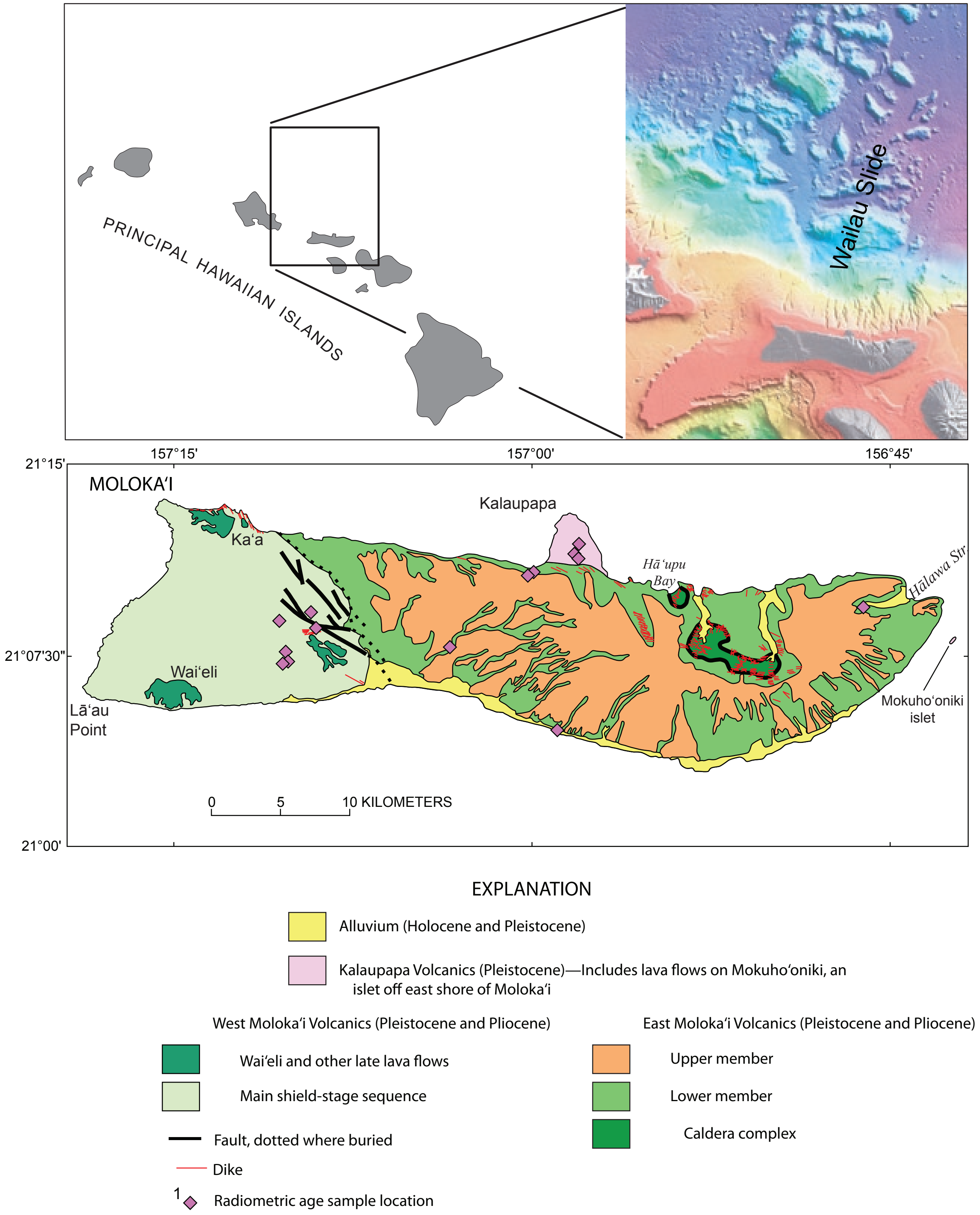


Figure 14. Geologic map of Molokaʻi, generalized from this publication's digital map database. Geology from Stearns and Macdonald (1947). Inset bathymetric map from Eakins and others (2003).

overgrazing in the 150 years previously. Many of the ancient Hawaiian fishponds were partly filled with mud during that time. Today, our map shows 4 km^2 of subaerial mudflats not found on the original geologic map, a new-land area nearly twice that created on the Island of Hawaiʻi during the past 15 years by lava entering the sea from Kīlauea volcano.

East Molokaʻi volcano

East Molokaʻi volcano is the larger of the two volcanoes that form the island of Molokaʻi, covering two-thirds of the island (fig. 14). The north half of the volcano is missing, but its remainder suggests that the volcano likely had an east–west elongation, perhaps the basis for the suggestion that rift zones extend away west-northwest and east-northeast from the summit area (Fiske and Jackson, 1972). The west-northwest rift zone may have additional basis arising from a few dikes mapped in sea cliffs along its trend. Neither rift zone was postulated by Stearns and Macdonald (1947).

A caldera complex high in the shield-stage lava flows was interpreted on the basis of anomalously thick lava flows, talus breccia, and intrusive stocks and plugs (Stearns and Macdonald, 1947). A subsequent investigation into the paleomagnetic stratigraphy of the East Molokaʻi volcano led to the interpretation that the caldera may have been substantially larger, 11 km in diameter (Holcomb, 1985). The western margin of this larger caldera coincides with a late-shield pit crater mapped by Stearns and Macdonald (1947) at Hāʻupu Bay. We view Holcomb's (1985) caldera skeptically and retain the structural depiction by Stearns and Macdonald (1947) until a more rigorous examination of north-slope

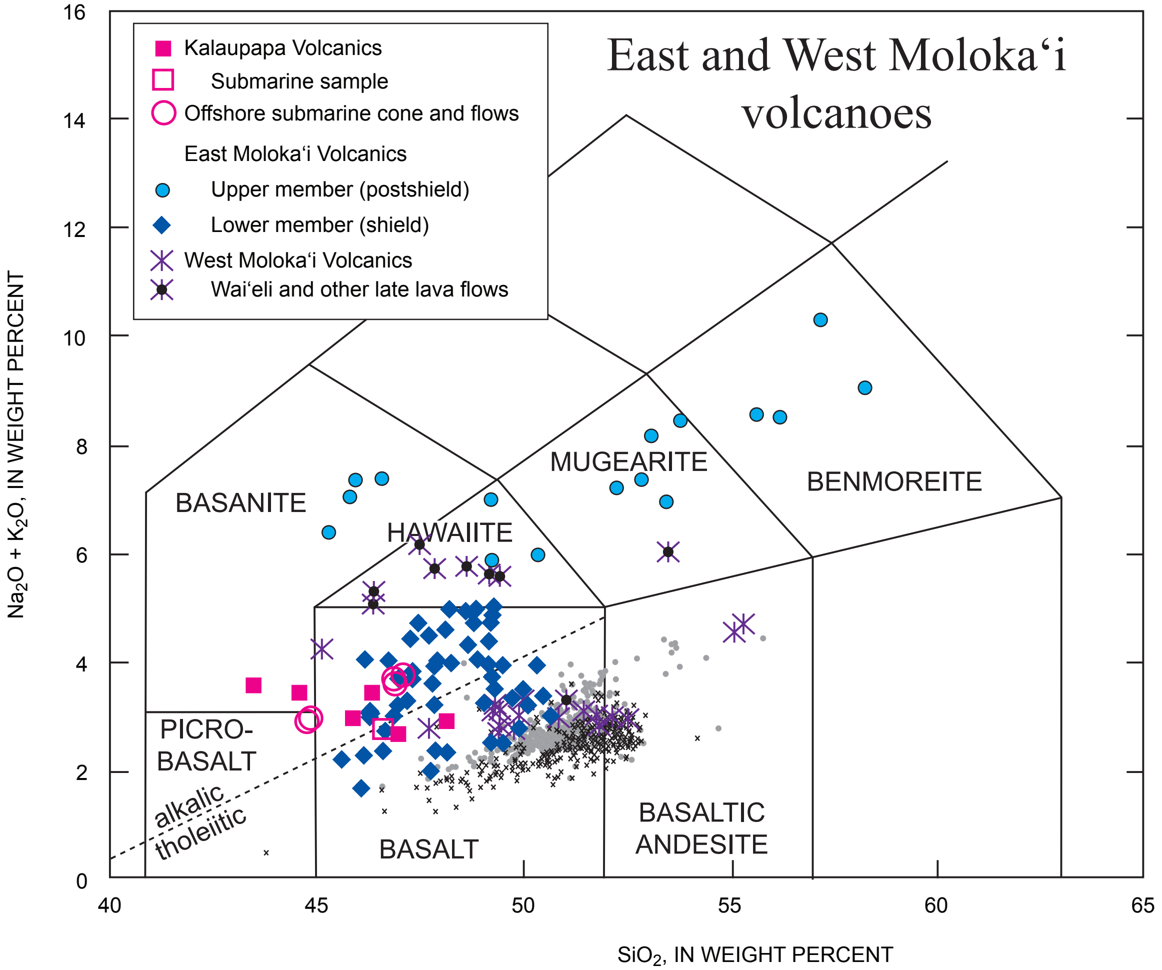


Figure 15. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Molokaʻi. Grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Molokaʻi chemical data from Guangping Xu and others (2005, 39 analyses) Beeson (1976, repeated in Clague and Beeson, 1980, 26 analyses), Potter (1976, 20 analyses), Clague and Moore (2002, 10 analyses), J.M. Sinton (unpub., 9 analyses), Macdonald (1968, 5 analyses), Clague and others (1982, 5 analyses), Macdonald and Katsura (1964, 2 analyses), Sinton and Sinoto (1997, 2 analyses), and Stearns and Macdonald (1947, 1 analysis).

stratigraphy is undertaken.

The East Moloka‘i Volcanics was divided into lower and upper members by Stearns and Macdonald (1947). In our opinion these designations were formal in status, inasmuch as a type section was named and the units were described thoroughly and depicted on a published map with topographic base at suitable scale—meeting far more requirements than is characteristic of many stratigraphic units formalized later in the 20th and into the 21st centuries. Modern usage, however, considers the members as informally named features (for example, Langenheim and Clague, 1987, or USGS online GEOLEX database, http://ngmdb.usgs.gov/Geolex/geolex_home.html). Perhaps the confusion arises from the lack of a geographic term in the stratigraphic name. Regardless, we hew to the modern use of informally named members when describing the East Moloka‘i Volcanics.

The lower member consists of tholeiitic, transitional, and alkalic basalt (fig. 15). Its oldest reported age is 1.75±0.14 Ma, from a sample collected about 250 m below the shield–postshield contact along Hālawa Stream at the east end of the island (fig. 14) (Naughton and others, 1980). Radiometric ages of about 1.52 Ma were obtained from two closely spaced samples near the top of the lower member along the trail to Kalaupapa, and an age from postshield strata upslope just above the contact was only slightly younger, about 1.49 Ma (McDougall, 1964; ages recalculated using modern decay constants). These latter ages provide a good estimate for the age of the boundary between the lower and upper members. Two other samples higher in the postshield sequence on the southwest flank yielded ages of 1.39 and 1.35 Ma (McDougall, 1964).

Upper member postshield strata as thick as 520 m are preserved on the summit and flanks of the East Moloka‘i volcano. The lava flows are ‘a‘ā, ranging from basanite to benmoreite (fig. 15). They were erupted from cinder

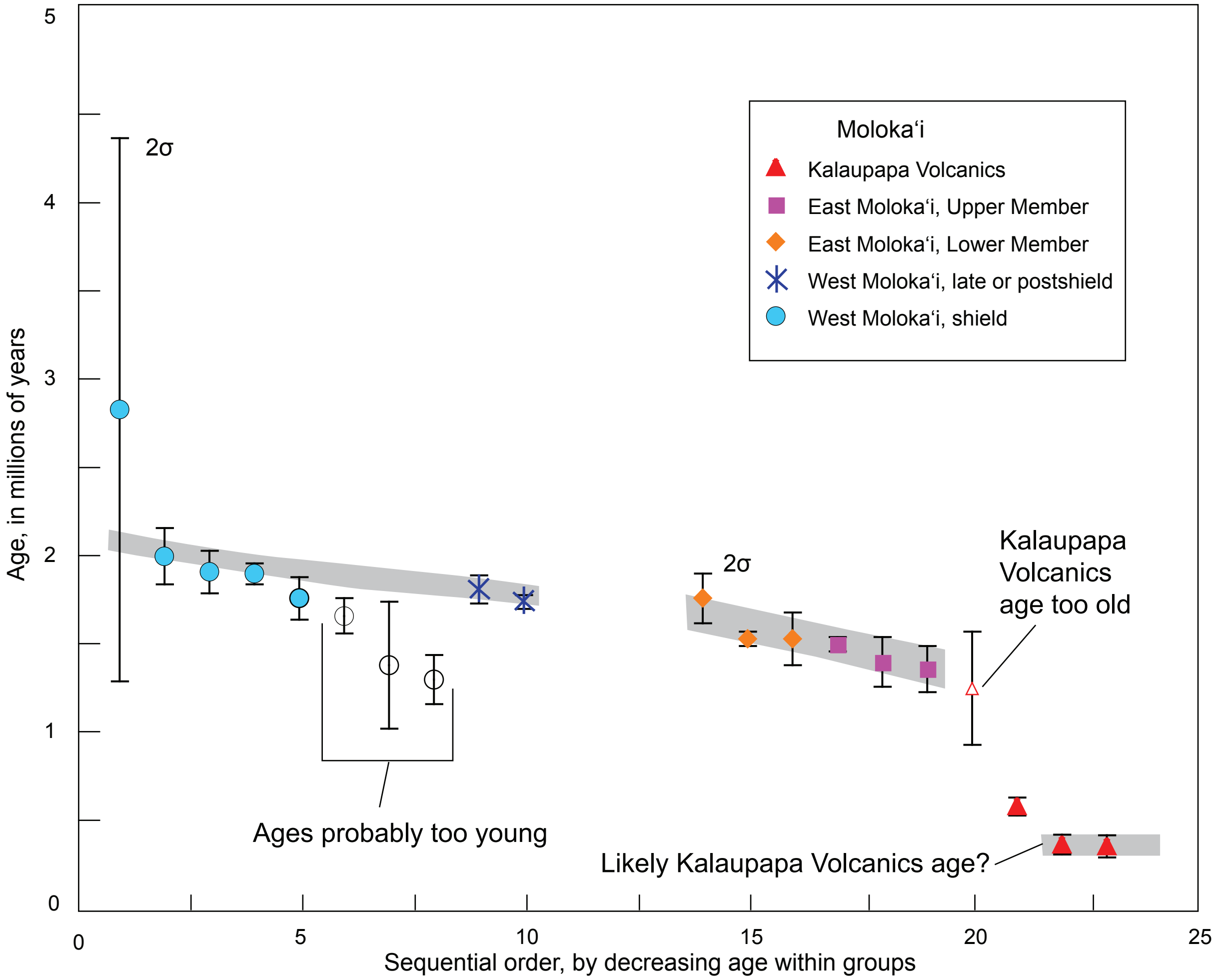


Figure 16. Radiometric ages from Moloka‘i. Open symbols show ages likely too old (Kalaupapa Volcanics) or too young (West Moloka‘i Volcanics). Gray bands show likely range of ages. Data from McDougall (1964), Naughton and others (1980), Clague and others (1982), and Clague (1987a).

cones and thick bulbous domes.

Perhaps the best-known single volcanic feature of East Moloka‘i is the small shield vent of Kalaupapa that grew along the northern sea cliffs after the island’s last major landslide (fig. 14). The peninsula’s lava flows, the Kalaupapa Volcanics, are thought to represent a single, monogenetic lava shield erupted from a vent now marked by a small prominent crater, Kauhakō (Stearns and Macdonald, 1947; Walker, 1990). Another vent about 1.6 km southwest was described by Coombs and others (1990). Its deposits, included here with the Kalaupapa Volcanics, lie plastered on the base of East Molokai’s prominent cliff at about the 200-m altitude. They lack obvious topographic expression, have not been mapped except by a mark on a sketch figure, and have not been seen by us, so their depiction on our digital geologic map should be considered schematic. A recently discovered small submarine cone and associated lava flows lie about 15 km northeast of Kalaupapa (Clague and Moore, 2002). It, too, is likely part of rejuvenated-stage eruptions. Compositionally the Kalaupapa Volcanics ranges from tholeiitic basalt to basanite (SiO_2 ranges from 43.5 to 48 weight percent; fig. 15).

The hypothesis of a short-lived, monogenetic eruption is slightly at odds with the radiometric dating, as acknowledged by Clague and Moore (2002). Three K–Ar ages range from about 0.34 to 0.57 Ma (fig. 16). A preference toward the younger ages is indicated on figure 16, but there is no statistical basis for discarding the 0.57-Ma age. A substantially older age, about 1.24 Ma (Naughton and others, 1980) is too old, in light of only slightly older ages from the upper member of the East Moloka‘i Volcanics.

Off the east shore of Moloka‘i is one other small vent that forms Mokuho‘oniki and Kanahā islets. Interpreted by Stearns and Macdonald (1947) as part of the rejuvenated-stage sequence, it is shown separately on our map as the informally named tuff of Mokuho‘oniki cone.

Lāna‘i

Setting and stratigraphic notes

Lāna‘i is a one-volcano island, built up by shield-stage volcanic rocks assigned to the Lāna‘i Basalt stratigraphic unit (fig. 17). Rift zones radiating away from the summit to the northwest, southwest, and south have long been inferred on the basis of topography and dike concentrations (Stearns, 1940b). A partly infilled caldera about 5 km in diameter supposedly occupies the south-central part of the island, coincident with the topographic Pālāwai Basin. Lāna‘i became extinct while still in the shield stage of activity. All chemical analyses from Lāna‘i are characteristic of shield-building volcanic rocks (fig. 18).

A large undersea landslide deposit, the Clark debris avalanche, can be traced back to the outer slope of Lāna‘i (inset, fig. 17; Eakins and others, 2003). Its

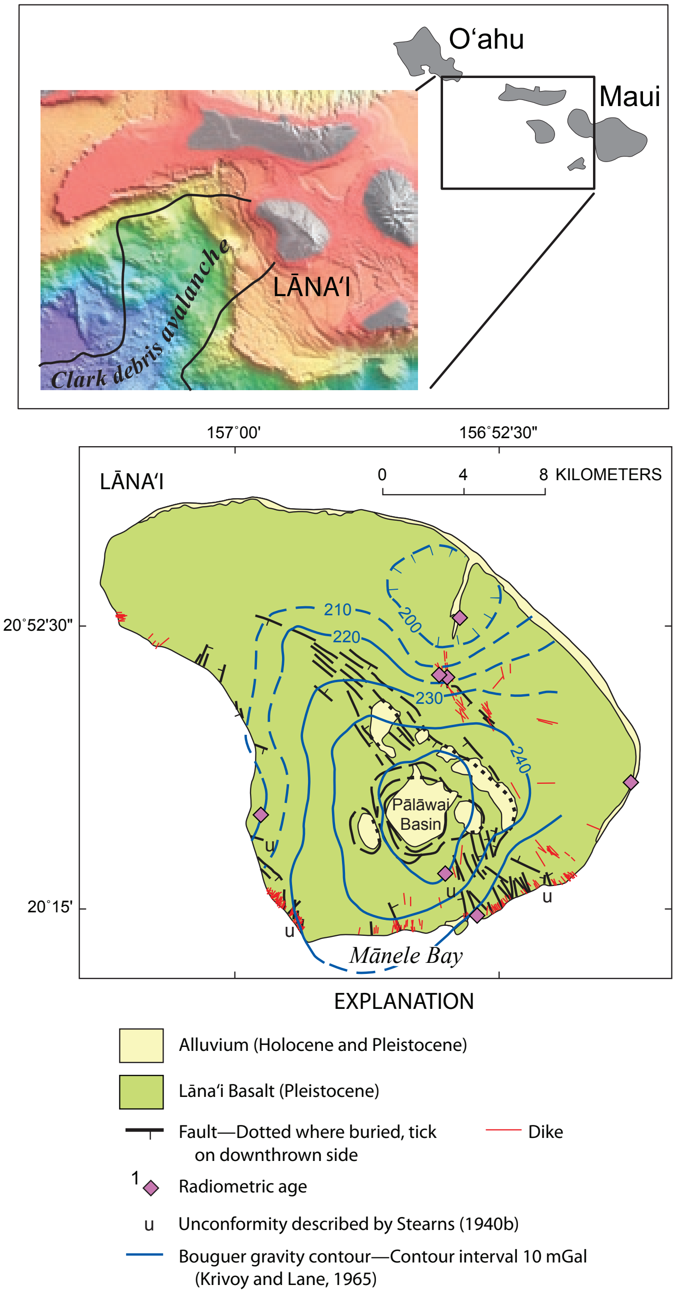


Figure 17. Geologic map of Lāna‘i, generalized from this publication’s digital map database. Geology from Stearns (1940b); gravity contours from Krivoy and Lane (1965). Inset bathymetric map from Eakins and others (2003). Clark debris avalanche outlined from Moore and others (1989).

upper limit of failure may be marked by the northwest-striking faults that nearly bisect the island (Moore and others, 1989). Indeed, when that origin for the faults is considered, then we might also question the caldera origin for the faults encircling the Pālāwai Basin, the basin having formed instead as a shallow sag when the island was weakly extended during Clark time. However, a 40–60-mGal Bouguer gravity anomaly centered over the Pālāwai Basin suggests that a magma chamber, if not a caldera, may have been positioned in that area (fig. 17; Krivoy and Lane, 1965). The Clark debris avalanche is thought to be older than 0.65 Ma, on the basis of an estimated age for the deepest reef that originally grew on the shallow submarine shore of Lāna‘i during oxygen isotope stage 18 and has subsequently subsided (Moore and Campbell, 1987).

The Lāna‘i volcano is one of the lesser-studied volcanoes among the Hawaiian island chain. At this writing it has the fewest radiometric ages of any of the emergent volcanoes. Six samples collected by Bonhommet and others (1977) from around the southern third of the island yielded ages ranging from about 1.51 to 1.24 Ma (fig. 19). No description was offered of the stratigraphic relations among the various sampled sites. As noted by Bonhommet and others (1977), the ages are indistinguishable at the 95-percent confidence level; therefore the ages were grouped to obtain a weighted mean age of 1.30±0.06 Ma. An alternative interpretation by isochron analysis yielded an age of 1.32±0.04 Ma, the age thought most representative of the top of the Lāna‘i volcanic shield (Bonhommet and others, 1977; recalculated by method of Dalrymple, 1979). Three other ages reported by Naughton and others (1980) had such large analytical error that they could correspond to eruptive events occurring anytime between 1.4 and 0.3 Ma.

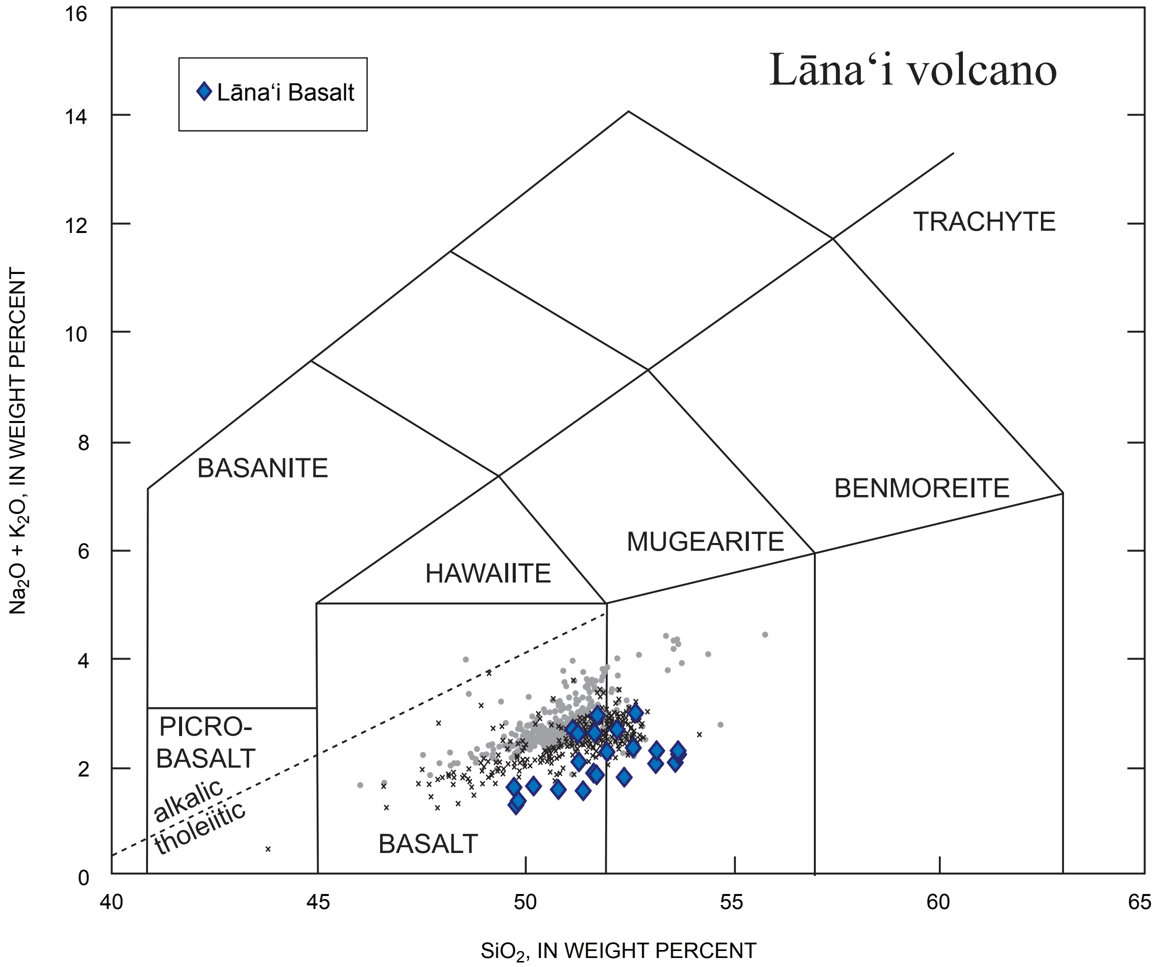


Figure 18. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Lāna‘i. Grid fields labeled for those compositional types commonly recognized in Hawaiian islands; grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Lāna‘i chemical data from West and others (1992, 21 analyses) and from Bonhommet and others (1977, 4 analyses).

Stearns's original map was marked to indicate four sites where disconformities (erosional unconformities) were found in the stratigraphic sequence (Stearns, 1940b). The evidence in support of a disconformable relation was the interbedding of talus, hillwash colluvium, or mudflow deposits within the lava-flow sequence. It remains to be seen whether a dedicated effort to date the shield lava above and below the disconformities would yield ages that indicate a longer record of volcanism than is generally assigned to the top-of-shield stratigraphic sequence at Lāna‘i. Reconnaissance paleomagnetic sampling found only reversed-polarity lava flows (Herrero–Bervera and others, 2000), but a more detailed study of a single 250-m-thick sequence of lava flows suggests that as many as three normal-polarity subchronozones are present, corresponding to the Cobb Mountain, Jaramillo, and Kamikatsura Normal-Polarity Subchrons (Herrero–Bervera and Valet, 2003). If borne out (and details remain too vaguely reported to gauge), then Lāna‘i volcanism may have continued until at least as recently as about 0.85 Ma.

Coarse calcareous breccia crops out at several localities on the south slope of Lāna‘i (Stearns, 1940b). Today, most lies at altitudes lower than 70 m, with isolated outcrops as high as ~170 m. The deposits contain lava blocks, pebbles, and cobbles in a matrix of coral, coralline algae, and shells. As noted by Stearns (1940b), the lava clasts are chiefly angular to subangular. In addition there are calcite-filled veins ranging to ~375 m altitude. The origin of these deposits, perhaps the most accessible of the coralline breccia found on four islands, has been at the center of a controversy—either landslide-generated megatsunami or as storm beaches or uplifted shorelines—discussed in an earlier section entitled *Island Growth in Review*.

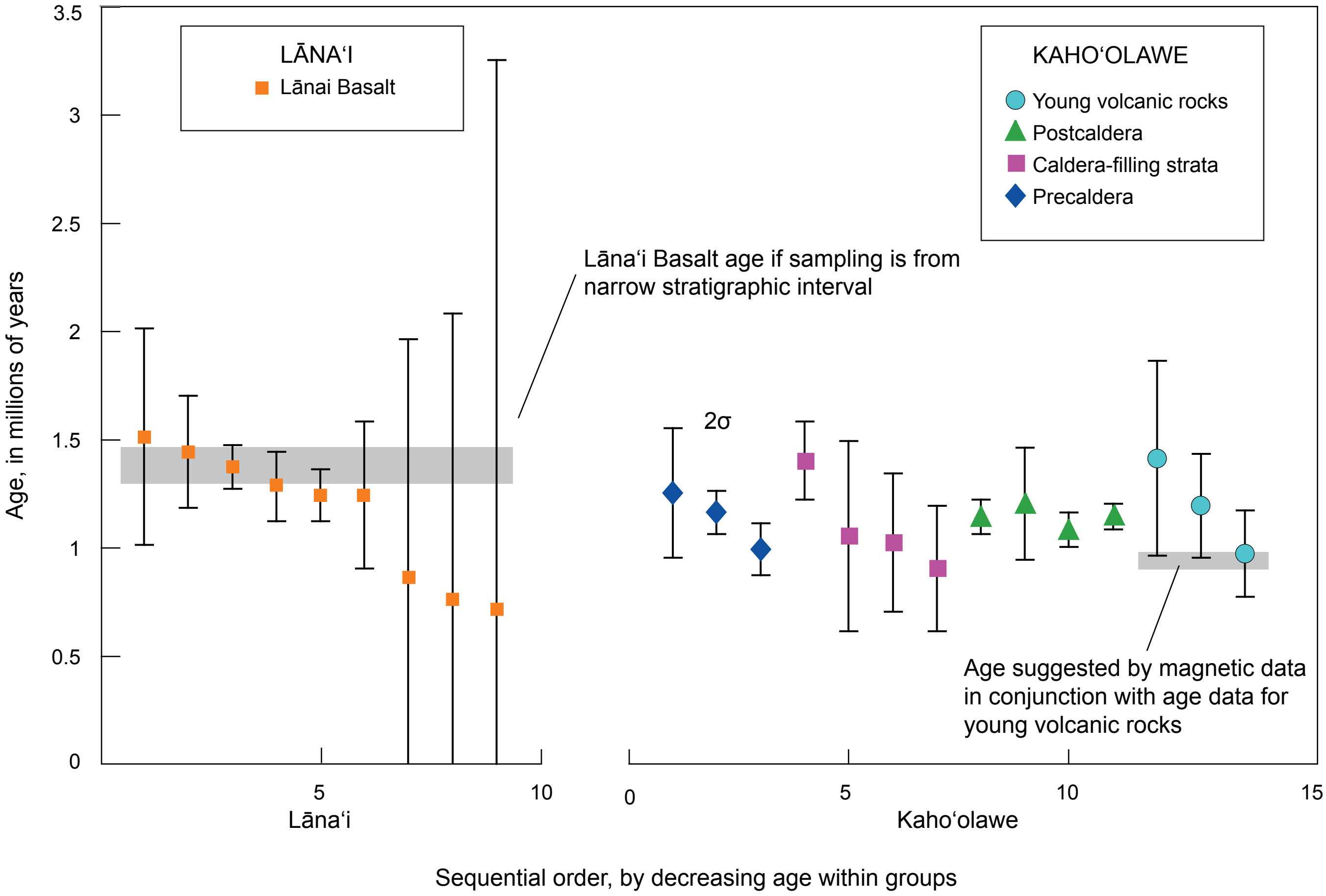


Figure 19. Radiometric ages from Lāna‘i and Kaho‘olawe. Gray bar across Lāna‘i data shows age if sampling is from narrow stratigraphic interval, as suggested by Bonhommet and others (1977). For Kaho‘olawe data, gray bar shows age range indicated by magnetic and age data. Data from Bonhommet and others (1977), Naughton and others (1980), Fodor and others (1992), and Sano and others (2006).

Kahoʻolawe

Setting and stratigraphic notes

Kahoʻolawe is the smallest of the emergent volcanoes among the eight major islands. Its geologic history is known mainly from the early work by Harold Stearns (Stearns, 1940c). Subsequent studies have concentrated on geochemistry and radiometric ages of the island's lava flows.

The Kahoʻolawe volcanic complex exposes the youngest part of shield-building strata, including a late-forming caldera and its infilling lava flows and thin tuff beds (fig. 20). Stearns (1940c) included the entire sequence and overlying postcaldera strata in a single stratigraphic unit, the Kanapou Volcanics. Geochemical analyses suggest that the postcaldera lava flows, which range from tholeiitic basalt to hawaiite, correspond to a transition into the postshield volcanic stage (fig. 21) (Fodor and others, 1992; Leeman and others, 1994).

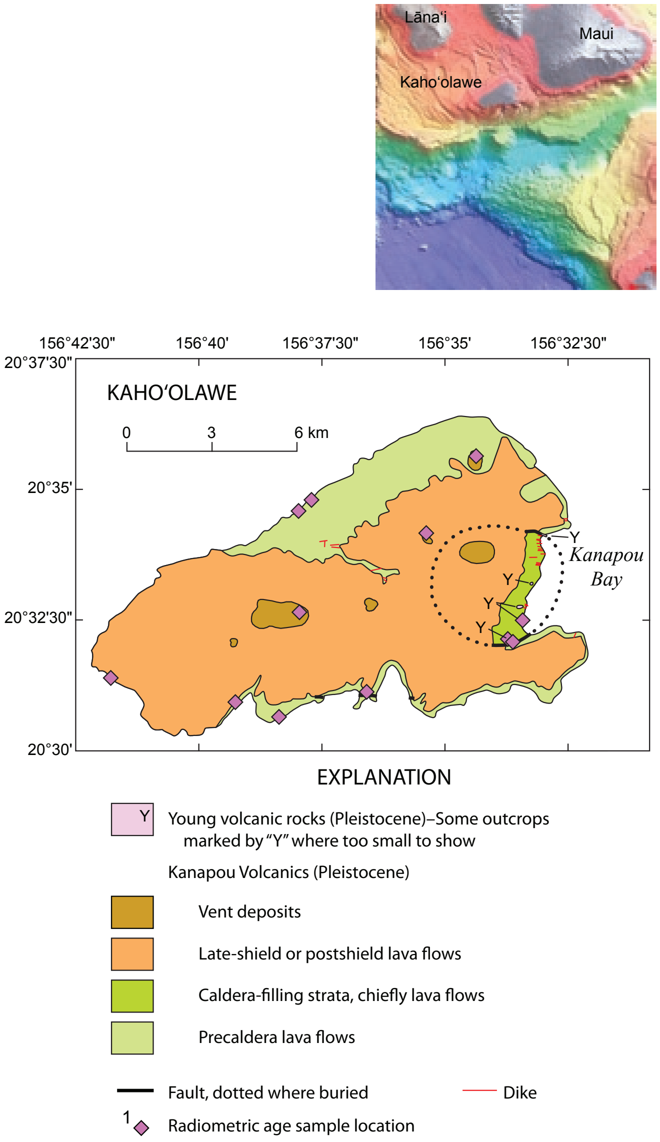


Figure 20. Geologic map of Kahoʻolawe, generalized from this publication's digital map database. Geology chiefly from Stearns (1940c) and a manuscript map (H.T. Stearns, unpub. data). Inset bathymetric map from Eakins and others (2003).

According to Langenheim and Clague (1987), the lava of Kahoʻolawe volcano was erupted along a prominent rift zone trending west-southwest (azimuth 245). Stearns (1940c) made clear that the southwest rift zone was an assumption drawn from analogy with other Hawaiian volcanoes. No cliffs run transverse to the rift zone, so only a few of its dikes are exposed (Stearns, 1940c). Three cones lie along the zone. An east rift zone was presumed to extend eastward from the island's summit, on the basis of a dike swarm exposed along the northern part of Kanapou Bay (Stearns, 1940c). Stearns also suspected that a rift zone trended northward, thereby explaining the slight topographic elongation of the island in that direction.

Geologic map data for Kahoʻolawe have always been sparse, mainly because the U.S. Navy condemned the island to a bombing range in the 1940s. Even today, as the island is returned to the State of Hawaiʻi, the hazard of unexploded ordnance creates nearly insurmountable obstacles for free-ranging map traverses. Stearns' published geologic map was a generalized, small-scale (1:130,000), page-size figure appearing in the Kahoʻolawe monograph (Stearns, 1940c, fig. 25). Indeed, among the major islands portrayed geologically in the Hawaiʻi Hydrography series, only Kahoʻolawe lacked a depiction on a separate map plate at 1:62,500 scale. We were able to obtain a copy of Stearns's hand-drafted, prepublication 1:62,500 portrayal of Kahoʻolawe's geology to use for digitizing this map, courtesy of M.O. Garcia (written commun., 2003). This map showed Stearns' preliminary depiction of an approximate separation between shield- and postshield-stage lava on Kahoʻolawe, which we have incorporated on our map (fig. 20). The contact also appeared as part of a previously published sketch geologic map (Leeman and others, 1994).

Mapped separately from the Kanapou Volcanics are the deposits of a final volcanic episode, preceded by the slope collapse that carved out Kanapou Bay (Stearns, 1940c). Alluvial deposits accumulated on the west wall of Kanapou Bay after the collapse. Dikes then cut through the alluvial deposits at five(?) locations, erupting cinders and sparse lava flows that mantle the alluvial deposits. These dikes, cinders, and lava flows are tholeiitic in composition where sampled from two sites at the south end of Kanapou Bay (fig. 21) (Fodor and others, 1992).

Overall, the radiometric ages indicate an age of about 1.25 Ma for the shield-forming lava flows (fig. 19). The individual ages are difficult to reconcile internally and probably suffer from the problems characteristic in dating the older Hawaiian shield volcanoes, namely low K content among tholeiitic rocks and weathering and mobility of K and Ar in some samples (Fodor and others, 1992). For example, a lava flow collected near the top of the shield-stage Kanapou strata directly beneath a thick postshield lava has an age of 1.25±0.14 Ma (Fodor and others, 1992). Another sample was assigned to the shield stage by Fodor and others (1992), apparently on the basis of its age, 1.40±0.09 Ma. However, according to Stearns's unpublished mapping, the 1.40-Ma sample is part of the postcaldera suite, hence of postshield stratigraphic position. These two ages were combined by Fodor and colleagues to suggest an average age for the shield of 1.34±0.08 Ma, but only the 1.25-Ma age may be pertinent if Stearns's mapping is correct. Two other ages from precaldera shield strata were viewed skeptically by Fodor and colleagues: an age of 0.99±0.06 Ma from precaldera shield tholeiite and an age of 1.08±0.04 Ma from the Keālialuna vent, which Stearns considered also of precaldera stratigraphic position. The ages seem too young in view of ages from postshield strata.

Several "postshield" lava ages range from about 1.20 to 1.14 Ma (Naughton and others, 1980; Fodor and others, 1992). These lava flows, chiefly alkali basalt, tend to be fresher and have higher K content, so their ages may be more accurate than those from the shield-stage lava flows. Two other ages, each about 1 Ma and presumably from postshield strata, were collected by H.S. Palmer in 1925 and dated in the 1970s (Naughton and others, 1980; their "upper member" of Kaho'olawe volcanic strata). The published site descriptions are

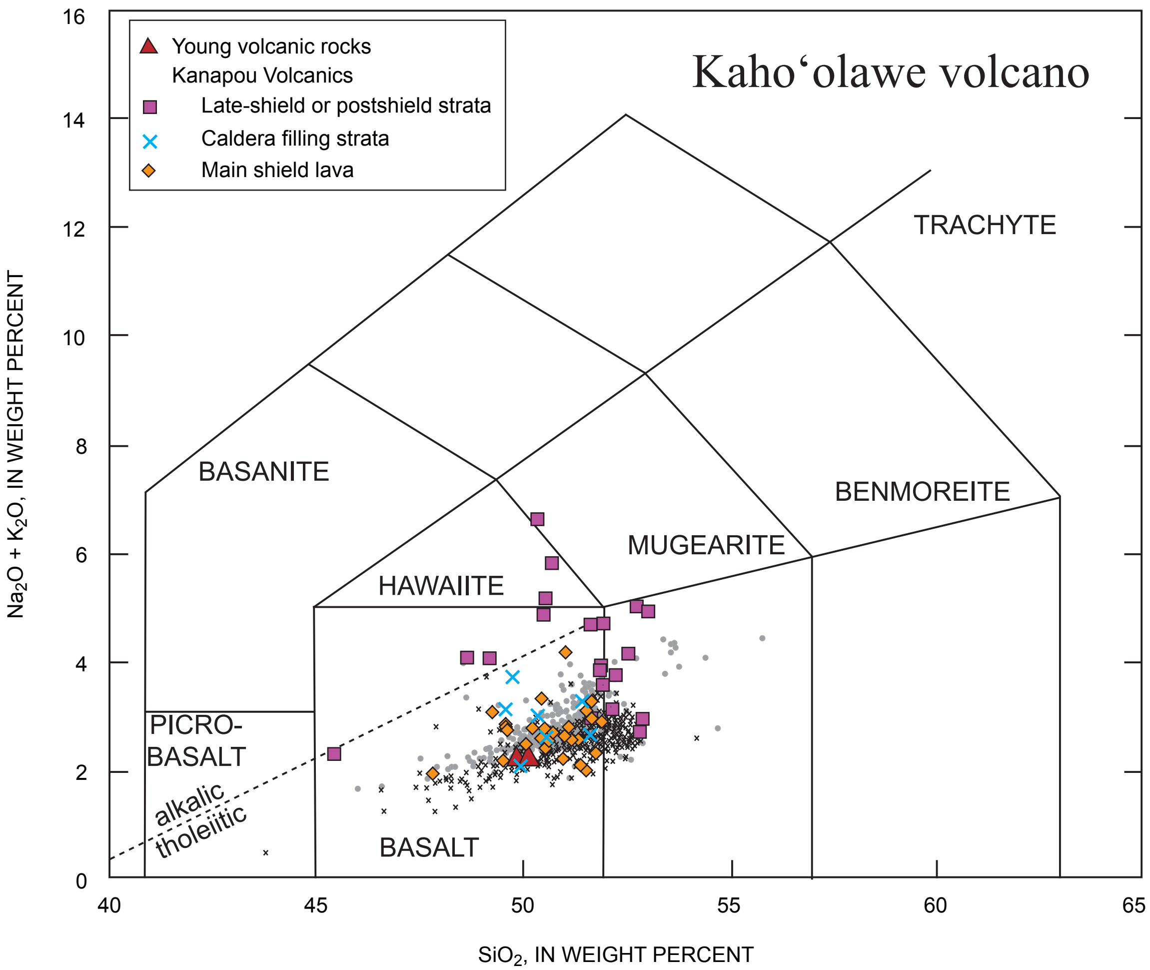


Figure 21. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Kaho'olawe. Grid fields labeled for those commonly used in Hawaiian islands; grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Kaho'olawe chemical data from Fodor and others (1992, 43 analyses), Leeman and others (1994, 13 analyses), Washington (1923, 1 analysis), Rudek and others (1992, 1 analysis), and Fodor and others (1993, 1 analysis).

inadequate to determine stratigraphic setting, although one of the samples is from a thick platy flow that likely is of postcaldera emplacement age. The analytical error reported for these two samples is sufficiently large that they overlap other postcaldera ages (fig. 19). Thus, broadly viewed, postshield volcanism might have been active from about 1.2 to 1.1 Ma.

As part of this map project, we collected three samples for dating the youngest volcanic deposits, those that drape the wall of Kanapou Bay. The southerly cinders and lava are from a dike with normal-polarity magnetization, as measured in the field with a portable fluxgate magnetometer. The other sample is from a dike found 0.8 km north along the coast; its polarity was indeterminate owing to surprisingly weak magnetization. Both produced K–Ar ages of about 1 Ma, which, in conjunction with the magnetization, suggests emplacement during the Jaramillo Normal-Polarity Subchron, about 0.98 Ma (Sano and others, 2006). The implication is that the steep slopes of Kanapou Bay formed during Kanapou time as the volcano was ending its postshield activity, another example of how volcanic deposits in a post-erosional physiographic setting needn't be evidence for rejuvenated stage volcanism. The island has not witnessed volcanic activity in roughly 1 million years.

Maui

Maui is a two-volcano island. By one interpretation, its nickname, the Valley isle, originates from the broad lowland that lies between West Maui volcano and, to the east, Haleakalā volcano.

West Maui volcano

The relation between stratigraphic units and interpreted volcanic stages is so clearcut on West Maui that it formed the basis for the example we used in this explanatory text in the section, *Island Growth*. West Maui's oldest strata are assigned to the Wailuku Basalt (fig. 22). A caldera-filling sequence and dike complex are mapped separately within the Wailuku. The caldera sequence, defining a roughly circular area about 3 km across, coincides approximately with the southern half of the ʻĪao Valley headwall amphitheater. Rift zones that trend northward and south-southeastward from the volcano's central area are delineated on the basis of mapped dike complexes, other dikes mapped separately, and the topographic elongation of the volcano (Stearns and Macdonald, 1942). Other dike orientations and vent concentrations have led to proposals for additional minor rift zones oriented southwest and northeast, but those trends lack gravity or topographic expressions (Diller, 1981; Macdonald and others, 1983). Judging from the published record, West Maui has the greatest number of mappable stocks, plugs, and sills in its shield-stage unit (Stearns and Macdonald, 1942); on the other islands, most intrusions are found as dikes.

The Honolua Volcanics overlie the Wailuku Basalt, forming a thin cap of benmoreite and trachyte lava flows and domes (fig. 23). The Honolua Volcanics are found chiefly on the volcano's northern and southern flanks, but a few domes form prominent hills on the west flank. Honolua rocks tend to weather light to very light gray. Seen from Kahului, the light-colored cliffs along the northeast shore of West Maui are built of Honolua Volcanics trachyte.

Radiometric ages from the Wailuku Basalt range from about 2 to 1.3 Ma, and those from the Honolua Volcanics range from 1.3 to 1.1 Ma (fig. 24) (McDougall, 1964; Naughton and others, 1980; Sherrod and others, 2007). The overlap of ages at about 1.3 Ma suggests that very little time elapsed between the switchover from latest shield-stage eruptions to those of the postshield stage. No field-based evidence of interfingering is known, so the shield stage might be thought of as ending abruptly, geologically speaking, before the onset of postshield-stage volcanism.

Four cinder and spatter cones, two of which issued lava flows, represent rejuvenated-stage volcanism on West Maui. These deposits are named the Lahaina Volcanics for the town where the most extensive of the lava flows is exposed. All are broadly basanitic. Two eruptions occurred about 0.6 Ma and two others about 0.3 Ma (Tagami and others, 2003). Chemical analyses indicate some compositional diversity within each of the two Lahaina eruptive episodes.

West Maui is flanked on its southwest and east sides by alluvial fans substantially older than those now being deposited by modern streams (fig. 22). West Maui has the third-greatest expanse of older alluvium of the Hawaiian volcanoes, 57 km^2, and more extensive deposits are found only on Waiʻanae and Koʻolau volcanoes, Island of Oʻahu (153 and 102 km^2, respectively). One of West Maui's older fans underlies the Olowalu lava flow of the Lahaina Volcanics, emplaced about 0.61 Ma (Tagami and others, 2003), the only place on West Maui where a limiting minimum age has been ascertained for at least part of the older alluvium.

Haleakalā volcano

East Maui volcano, better known today as Haleakalā, is one of the largest volcanoes in the island chain

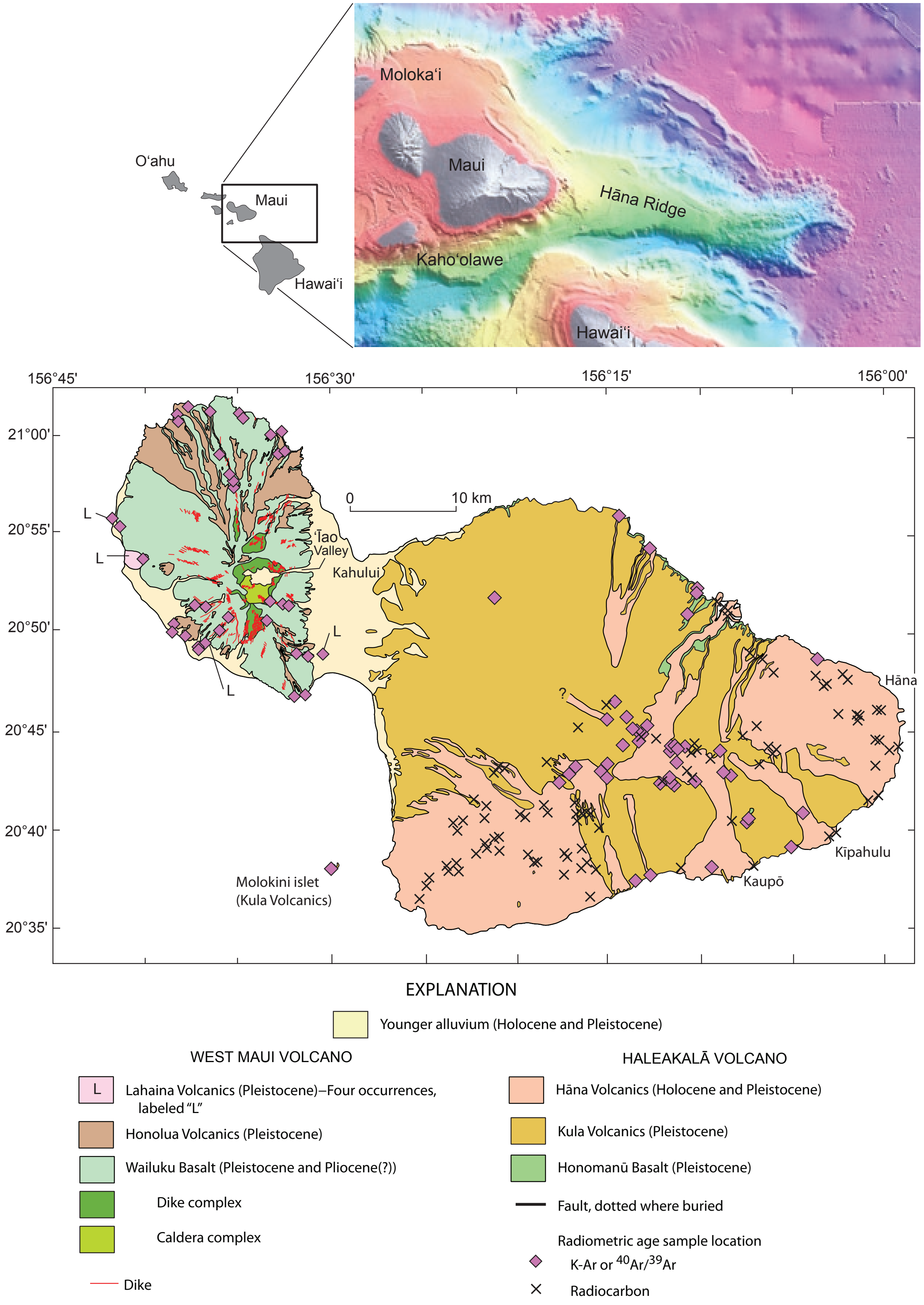
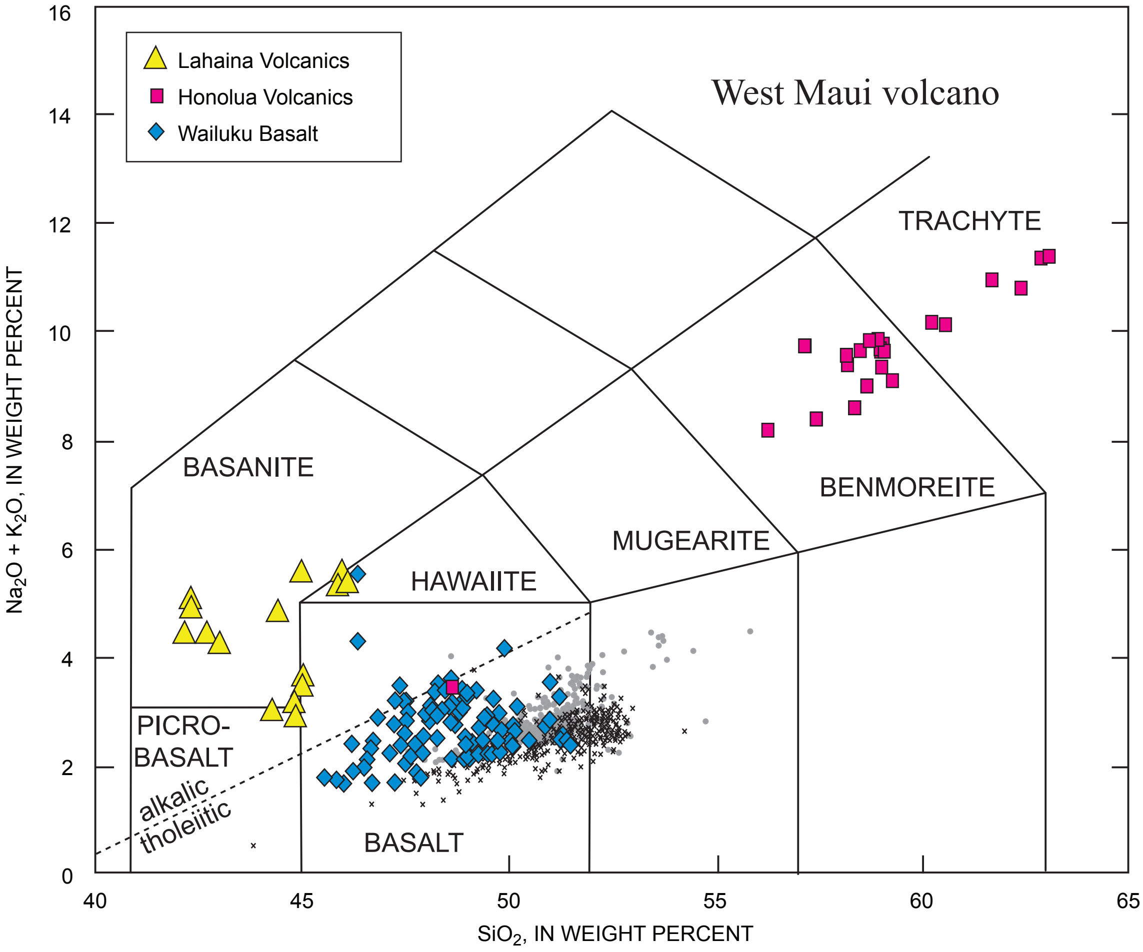


Figure 22. Geologic map of Maui, generalized from this publication’s digital map database. Geology from Stearns and Macdonald (1942) and D.R. Sherrod (this map). Inset bathymetric map from Eakins and others (2003).



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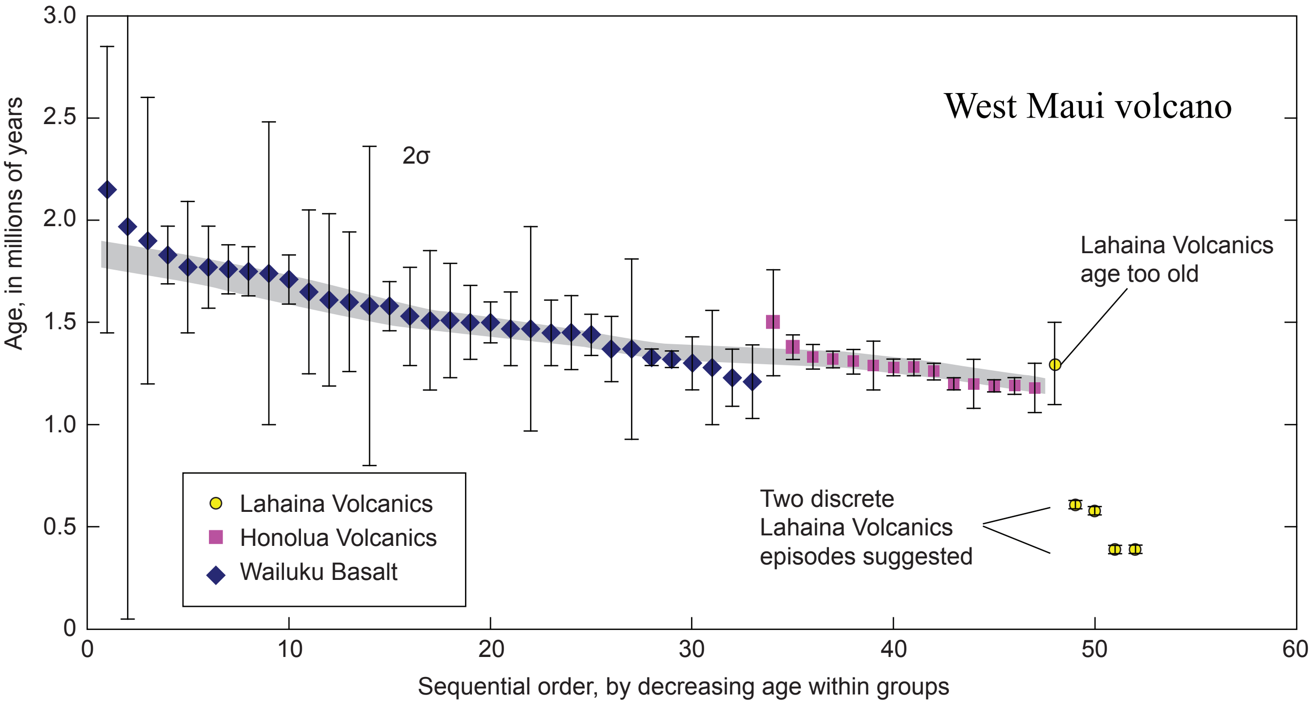

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Figure 23. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from West Maui. Grid fields labeled for those commonly used in Hawaiian islands; grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. West Maui chemical data from Sherrod and others (2007, 31 analyses), Diller (1982, 30 analyses), Gaffney and others (2004, 29 analyses), Macdonald and Katsura (1964, 18 analyses), Tagami and others (2003, 10 analyses), Macdonald (1968, 7 analyses), Sinton and others (1987, 4 analyses), and Sinton and Rowland (1997, 2 analyses).

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Figure 24. Radiometric ages from West Maui volcano. Gray band shows likely range of ages across the suite. One Lahaina age is considered much too old, compared to four other more precisely dated lava flows. Data from McDougall (1964), Naughton and others (1980), Tagami and others (2003), and Sherrod and others (2007).

(Robinson and Eakins, 2006). It also is the only volcano beyond the Island of Hawai‘i that is considered potentially active, having erupted frequently during Holocene time and as recently as about A.D. 1600 (Sherrod and others, 2006).

The oldest exposed lava flows on Haleakalā are tholeiitic and alkalic basalt of the Honomanū Basalt (fig. 25). The Honomanū was considered part of the shield-building stage by Stearns and Macdonald (1942), and chemical analyses show that its lava flows are typical of those occurring in the late shield or transitional stages of several Hawaiian volcanoes, where lava compositions become increasingly alkalic. Ages from the Honomanū Basalt range from about 1.1 to 0.97 Ma (fig. 26) (Chen and others, 1991).

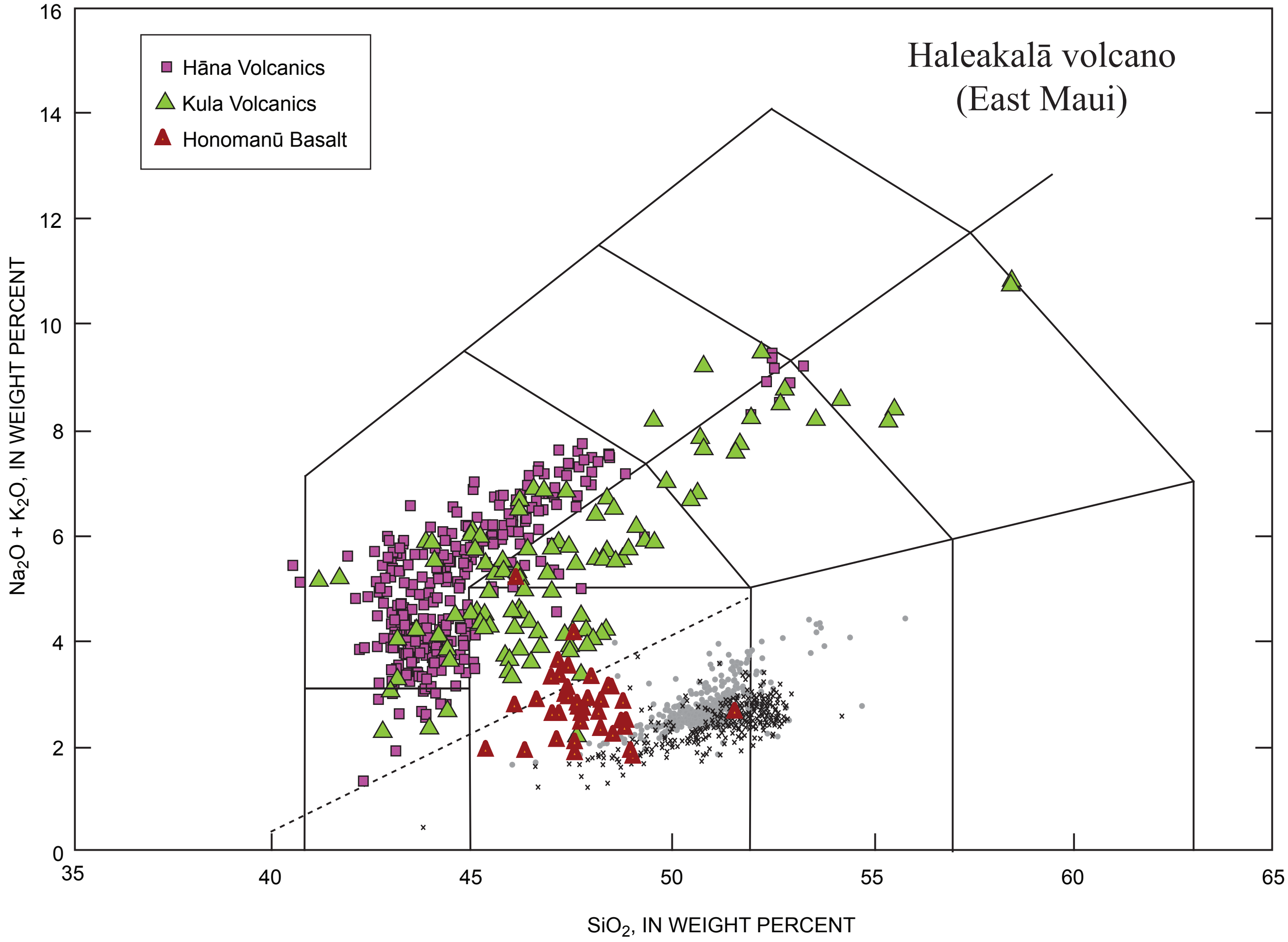
A substantial episode of postshield volcanism is represented by the Kula and the Hāna Volcanics (Stearns and Macdonald, 1942). The Kula thickly mantles most of Haleakalā. It is more than 1 km thick at the summit of the volcano, where it forms the walls of Haleakalā Crater. Kula volcanism must have begun almost immediately at the close of Honomanū time, because the oldest dated Kula lava flow has an age of 0.93±0.33 Ma (Chen and others, 1991), and several other ages are only slightly younger (fig. 26). Rocks of the Kula Volcanics around the rim of Haleakalā Crater have produced ages as young as about 0.15 Ma (Sherrod and others, 2003).

The Kula Volcanics are chiefly ‘a‘ā lava flows, in contrast to the predominantly pāhoehoe lava in the Honomanū Basalt. Near the volcano’s summit, pāhohoe is exposed low in the walls of Haleakalā Crater, at a stratigraphic position near the base of the Kula Volcanics. Its stratigraphic setting and lithologic character led Stearns and Macdonald (1942) to assign the pāhoehoe lava flows to the Honomanū Basalt. Subsequent geochemical analyses lent doubt to this correlation, owing to their higher total alkali content, and for a short time the pāhoehoe was assigned to a newly named Kumu‘iliahi Formation (Macdonald, 1978). Since the 1980s, these same strata have been considered part of the Kula Volcanics because of their alkalic character (Macdonald and others, 1983; Langenheim and Clague, 1987), a convention followed as part of our mapping.

A thick sequence of debris-flow deposits is exposed on the volcano’s south flank. Its stratigraphic name, the Kaupō Mud Flow, is anachronistic, given the advances in understanding how such poorly sorted deposits come to be emplaced; but we avoid changing the name in this publication, a task better left for a more detailed investigation of East Maui geology. The Kaupō is older than 0.12 Ma on the basis of a K–Ar age from a lava in the overlying Hāna Volcanics, described next (Sherrod and others, 2003).

Young lava flows on Haleakalā, assigned to the Hāna Volcanics, issued from the same rift zones that produced the Kula Volcanics. Recent mapping and new radiocarbon and K–Ar ages have allowed a fairly detailed depiction, by age grouping, of lava-flow units within the Hāna Volcanics (fig. 27). The groupings are incorporated into the digital database for this geologic map, as are many informal flow-unit names, some of which are shown on figure 27. We abandon the term Kīpahulu Member, which designated a part of the Hāna Volcanics on the southeast side of East Maui (Stearns and Macdonald, 1942; Langenheim and Clague, 1987). Our mapping and dating find that these lava flows range widely in age and lithology, including ankaramitic lava flows erupted from a cinder cone at the mouth of Kīpahulu Valley about 25,000 yr ago (Sherrod and others, 2006) and aphyric bench-capping lava flows that filled an ancestral Kīpahulu Valley as early as 0.12 Ma (Sherrod and others, 2003). These latter units are depicted as informally named sequences within the Hāna Volcanics on our map.

The lava flows of the Hāna were thought to have been emplaced following a lengthy period of erosion, which led to their interpretation previously as rejuvenated-stage deposits. Radiometric dating, however, shows that the



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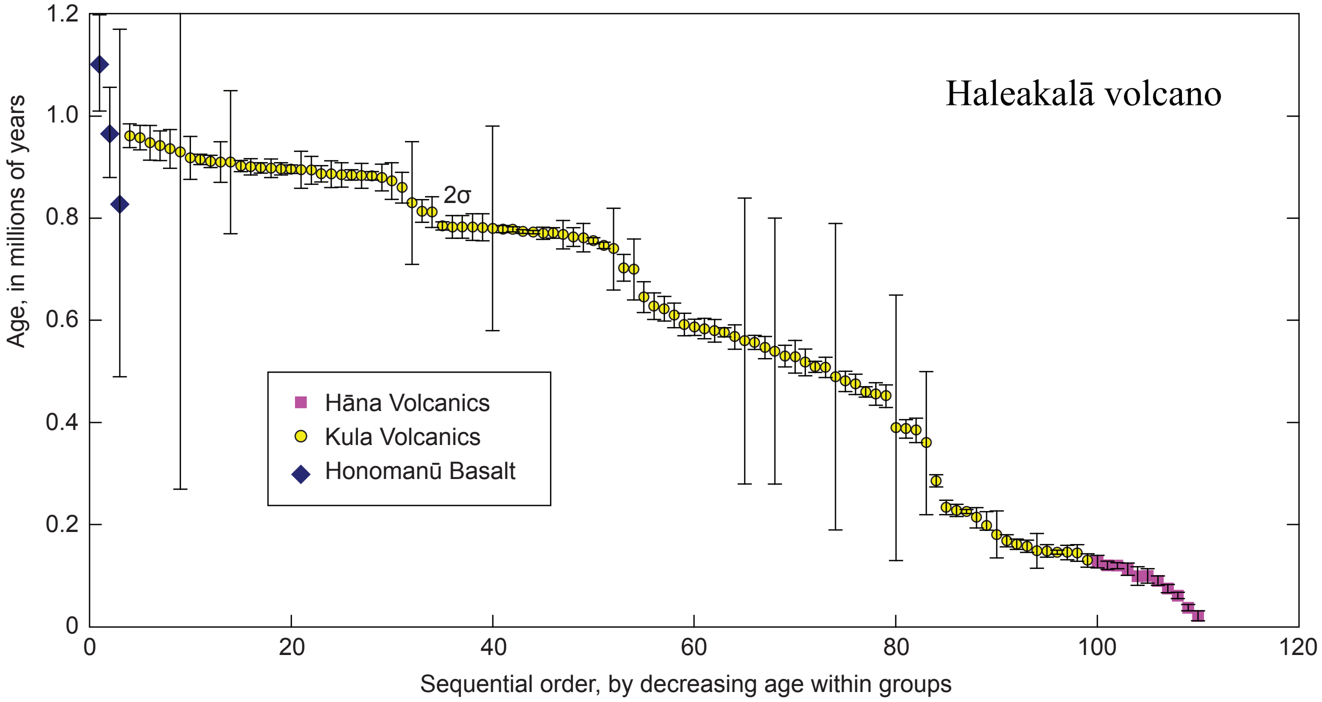

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Figure 25. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Haleakalā volcano, East Maui. Grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Haleakalā chemical data from D.R. Sherrod (unpub. data, 184 analyses), Bergmanis (1998, with many appearing in Bergmanis and others, 2000, 99 analyses), Sherrod and others (2003, 52 analyses), West and Leeman (1994, 43 analyses), West (1988, 31 analyses), Chen and Frey (1985) and Chen and others (1990) (together, 29 analyses), Chen and others (1991, 23 analyses), Macdonald (1968, 16 analyses), Macdonald and Powers (1968, 15 analyses), Macdonald and Katsura (1964, 8 analyses), Brill (1975, 8 analyses), Macdonald and Powers (1946, 6 analyses), Horton (1977, 6 analyses).

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Figure 26. Radiometric ages from Haleakalā. Data from McDougall (1964), Naughton and others (1980), Chen and others (1991), Baksi and others (1992), Singer and Pringle (1996), Singer and others (1999), Sherrod and others (2003), Coe and others (2004), and Kirch and others (2004).

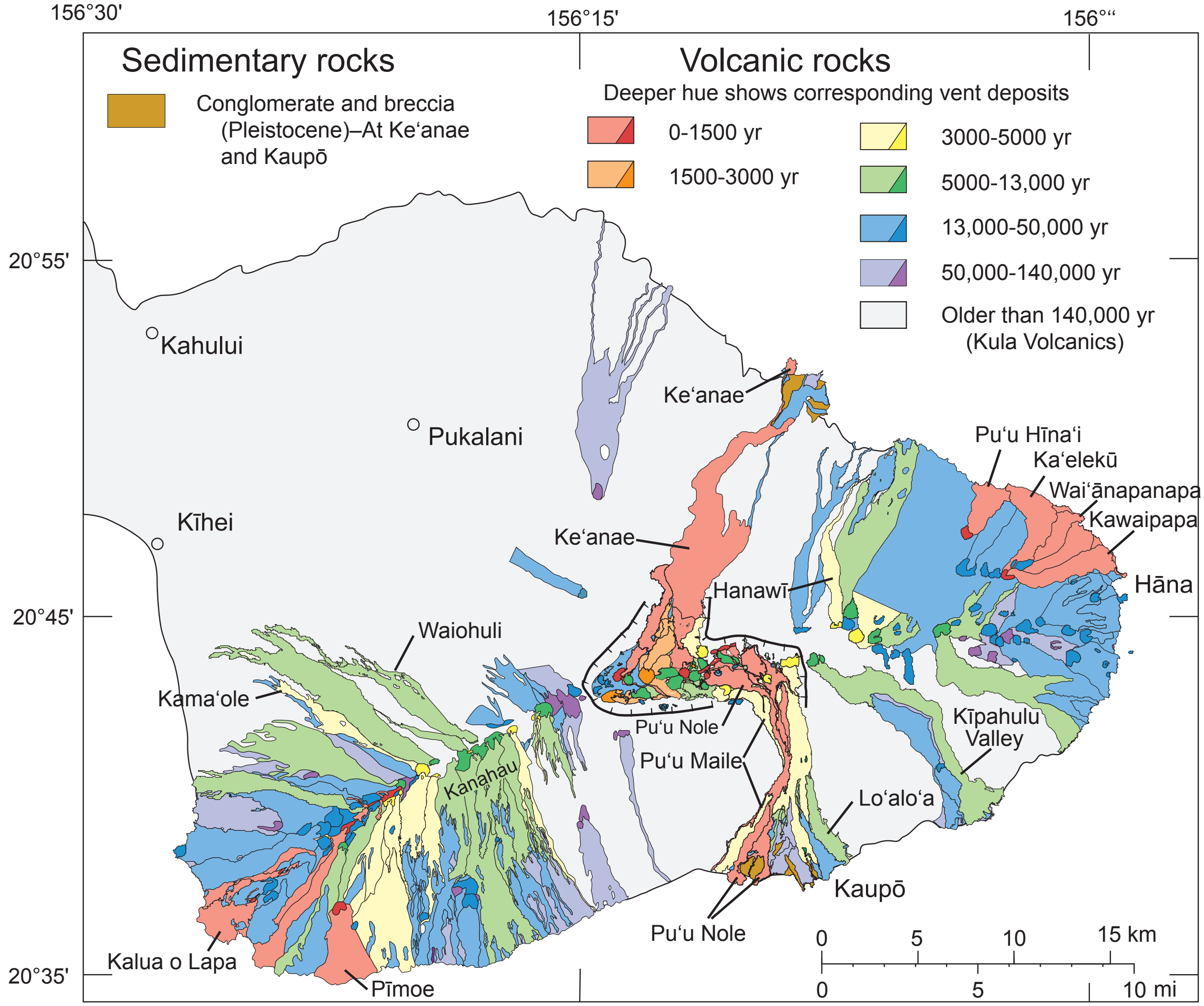


Figure 27. Map showing strata of the Hāna Volcanics, by age (from Sherrod and others, 2006). Labeled are some informally named units.

gap in ages between Kula and Hāna lava flows is small, only about 0.03 myr. This brevity, and the geochemical similarity between Hāna and underlying Kula lava, indicates that the Hāna Volcanics unit marks the waning of postshield-stage volcanism, not a separate rejuvenated stage (Sherrod and others, 2003). Thus, the postshield volcanic strata of Haleakalā include both the Kula and Hāna Volcanics, whose combined ages span more than 900,000 years. This postshield longevity, more than three times that of any other Hawaiian volcano, is the most lengthy in the island chain. The reason for prolonged postshield activity at Haleakalā is speculative, with one idea relating it to the volume of lava produced during the shield stage, which may be a crude proxy for the amount of heat emplaced into the base of the lithosphere during a particular volcano's shield stage (Sherrod and others, 2003).

Though its volcanic vigor has lessened, Haleakalā has continued to erupt every 200 to 500 years (Bergmanis and others, 2000; Sherrod and others, 2006). It is the only volcano in the Hawaiian group besides those on the Island of Hawaiʻi to show any recent activity. Its youngest lava, once thought as young as A.D. 1750–1790 (Stearns and Macdonald, 1942; Oostdam, 1965), is now thought to have formed between A.D. 1449 and 1633, on the basis of calibrated radiocarbon ages from two sites (Sherrod and others, 2006).

Hawaiʻi

Youngest of the islands in the Hawaiian archipelago, the Island of Hawaiʻi encompasses five major shield volcanoes. A sixth volcano, Māhukona, lies flooded offshore north of Kailua–Kona (fig. 28). A seventh

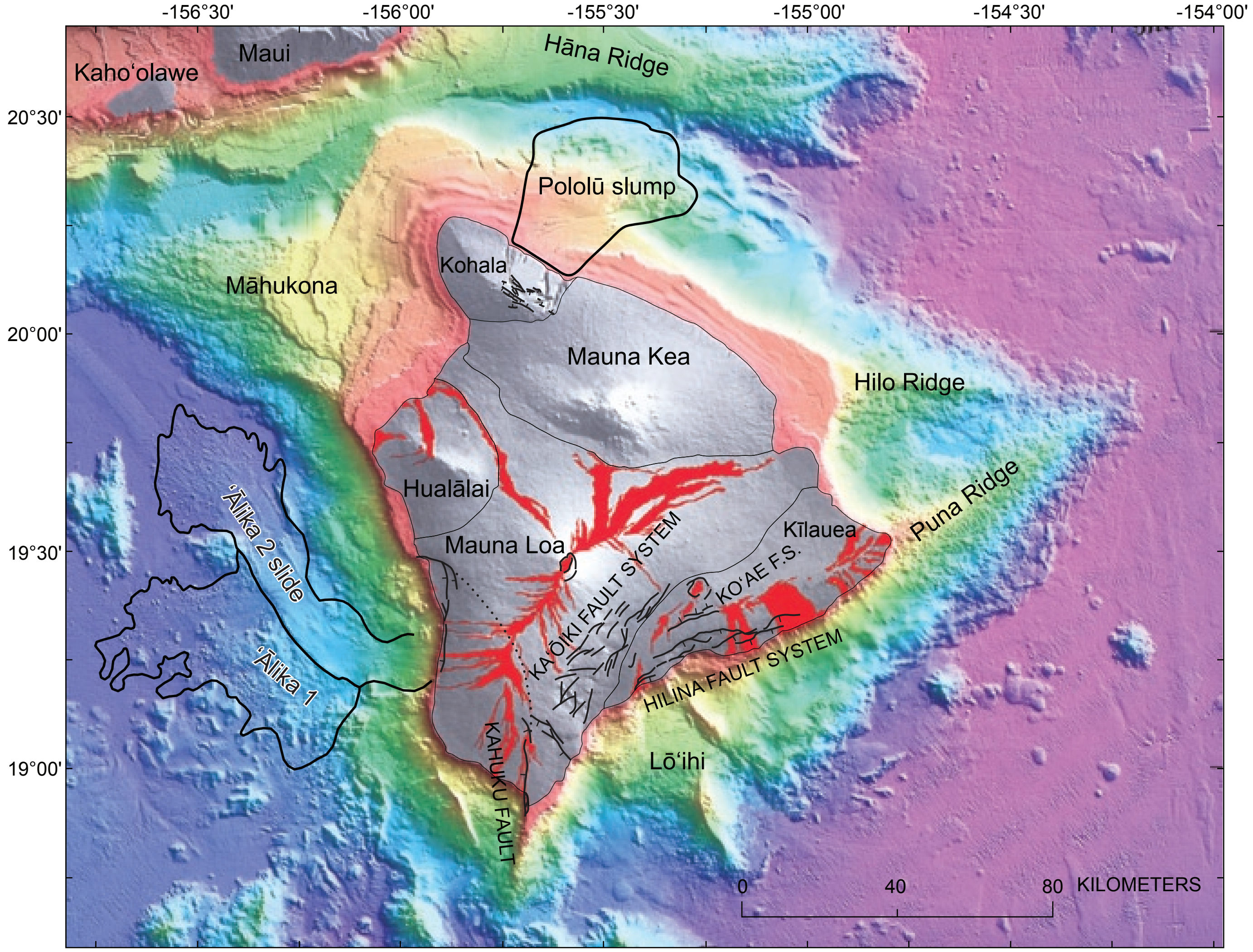


Figure 28. Bathymetric map for Island of Hawaiʻi, from Eakins and others (2003). Faults from Wolfe and Morris (1996a). Proposed buried trace of Kahuku fault shown dotted (from Lipman and others, 1990). Pololu slump from Smith and others (2002). ʻĀlika 2 Slide from Lipman and others (1988).

volcano, Lōʻihi, is the newest in the chain, albeit still lying 980 m beneath the sea. For an excellent synopsis of volcano growth and evolution, both conceptually for the island chain and specifically for the Island of Hawaiʻi, the reader is referred to Moore and Clague (1992).

Kohala

Kohala is the oldest of the volcanoes on the Island of Hawaiʻi. Its exposed lava flows are all younger than 0.78 Ma. Given growth rates of shield-stage volcanoes and rate for lithospheric plate transport above the Hawaiian hot spot, it is likely that the oldest parts of Kohala, now buried and below sea level, range back in age to as old as about 1 Ma, an estimate substantiated by newly obtained ages from offshore, discussed next.

Kohala has an axial rift zone that was active in both shield and postshield time. The trace of the southeast rift zone passes beneath Mauna Kea. By modern interpretations, it reappears farther southeast as the submarine Hilo Ridge, on the basis of correlation of submarine terraces between the ridge and Kohala's slopes and isotopic similarity of ridge samples and Kohala lava (for example, Holcomb and others, 2000). Also, the gravity expression of the Hilo Ridge aligns more directly with the trend of the gravity field coincident with Kohala (Kauahikaua and others, 2000) than with that of neighboring Mauna Kea, of which Hilo Ridge was once thought a part (Fiske and Jackson, 1972; Macdonald and others, 1983; Moore and Clague, 1992). The Hilo Ridge has bulk magnetic character that indicates it is built chiefly by reversed-polarity volcanic rocks, evidence that much of the ridge is older than 0.78 Ma (Naka and others, 2002). Recently obtained ^{40}Ar/^{39}Ar ages from pillow basalt clasts collected from the distal toe of the Hilo Ridge are about 1.1-1.2 Ma (Andrew Calvert, written commun., 2007).

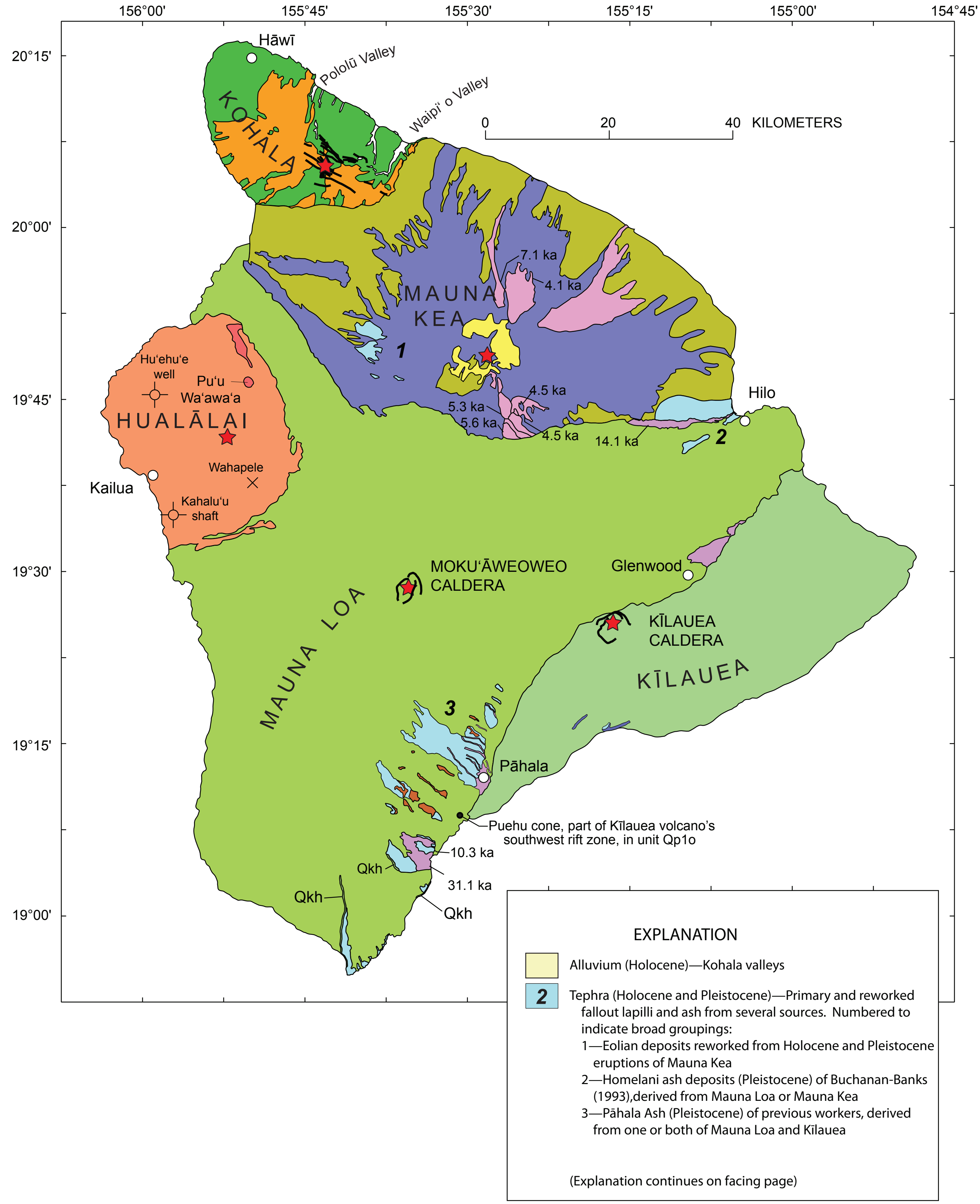
Kohala shield-stage strata are assigned to the Pololū Volcanics (fig. 29). Fifty flow units from the lowest 140 m of exposed strata possess normal-polarity magnetization, which led to the interpretation that the entire sequence is younger than 0.78 Ma (Doell and Cox, 1965). Radiometric ages are mostly in the range 0.45 to 0.32 Ma (fig. 30) (McDougall, 1964; Lanphere and Frey, 1987). Three ages in the range 0.27–0.25 Ma were portrayed by Spengler and Garcia (1988, their fig. 2) and ascribed to G.B. Dalrymple (unpub. data); 2σ error is about ±0.012 Ma as estimated by scaling from the published figure. These ages are not included in our database owing to their ambiguous details.

Overlying the Pololū Volcanics is the postshield-stage Hāwī Volcanics, which ranges compositionally from hawaiite to trachyte (fig. 31). Most Hāwī ages range from 0.26 to 0.14 Ma (fig. 30). The oldest of these ages may instead belong to a Pololū volcanic layer, on the basis of its low phosphorus content and stratigraphic position beneath a porphyritic Pololū lava flow (Spengler and Garcia, 1988). Regardless, the time interval that separates Pololū and Hāwī volcanic episodes is exceedingly brief, as first noted by Spengler and Garcia (1988).

Not tabulated in our database are five or six ages from Hāwī lava flows that are difficult to assess because they have never been published except by way of the small figure showing the distribution of Hāwī ages (Spengler and Garcia, 1988, their fig. 2). Two of these correspond to ages of 0.116 and 0.137 Ma, as determined by scaling from the graphical presentation of Spengler and Garcia (1988). Presumably the younger of these was the basis for assigning an age of 0.120 Ma as the young limiting age of the Hāwī Volcanics (Wolfe and Morris, 1996a). The 2σ error, also determined by scaling, corresponds to ±0.011 myr.

The Hāwī Volcanics may contain strata younger than 0.12 Ma. For example, replicate ages of about 0.06 Ma were obtained from two samples of the same lava flow on the volcano's east flank, collected about 170 m apart near the east rim of Waipiʻo Valley (McDougall and Swanson, 1972). In a separate study, replicate ages of about 0.08 Ma were obtained from two sites on a west-flank lava flow (Malinowski, 1977). These four youngest Hāwī ages, which lie apart from other Hāwī ages on figure 30, might be viewed skeptically, and two of them have been challenged directly. The young east-flank ages (0.064±0.004 and 0.061±0.002 Ma; McDougall and Swanson, 1972), which are disputed by Wolfe and Morris (1996a), were obtained from a lava flow that reportedly lies beneath a Mauna Kea flow with an age of 0.187±0.080 Ma (Wolfe and others, 1997). The young west-side ages have not been tested by subsequent experiments. In summary, the Hāwī Volcanics is probably at least as young as about 0.12 Ma, conceivably younger. We accept the 0.12-Ma age limit as a conservative estimate for the end of Hāwī volcanism but find the question of youngest age yet to be rigorously answered.

Kohala is notable for several geomorphic features, all of which may be related to a large landslide or slump from its northeast side late in Pololū time (Moore and others, 1989). In plan view, the northeast coast has a prominent indentation extending along 20 km of shoreline from Waipiʻo to Pololū Valleys (fig. 28). Large stream valleys have cut deeply into the volcano, perhaps a consequence of stream gradients thrown out of equilibrium when the landslide severed their paths.



EXPLANATION

🟨 Alluvium (Holocene)—Kohala valleys

2 Tephra (Holocene and Pleistocene)—Primary and reworked fallout lapilli and ash from several sources. Numbered to indicate broad groupings:
1—Eolian deposits reworked from Holocene and Pleistocene eruptions of Mauna Kea
2—Homelani ash deposits (Pleistocene) of Buchanan-Banks (1993),derived from Mauna Loa or Mauna Kea
3—Pāhala Ash (Pleistocene) of previous workers, derived from one or both of Mauna Loa and Kīlauea

(Explanation continues on facing page)

Figure 29. Map showing stratigraphic formations for volcanoes on Island of Hawai'i. See facing page for map-unit explanation.

Figuare 29. Continued.

Kīlauea volcano

🟩 Puna Basalt (Holocene and Pleistocene)

🟦 Hilina Basalt (Pleistocene)

Hualālai volcano

🟧 Hualālai Volcanics (Holocene and Pleistocene)

🟥 Wa‘awa‘a Trachyte Member (Pleistocene)

Kohala volcano

🟧 Hāwī Volcanics (Pleistocene)

🟩 Pololū Volcanics (Pleistocene)

— Fault

★ Volcano summit

Mauna Loa volcano

🟩 Ka‘ū Basalt (units Qk1-5) (Holocene and Pleistocene)

🟪 Oldest part (unit Qk) (Pleistocene)

Qkh Kahuku Basalt (unit Qkh) (Pleistocene)

🟫 Nīnole Basalt (Pleistocene)

Mauna Kea volcano

Laupāhoehoe Volcanics (Holocene and Pleistocene)

🟪 Younger volcanic rocks member (Holocene and Pleistocene(?))

🟦 Older volcanic rocks member (Holocene and Pleistocene)

🟨 Mākanaka Glacial Member (Pleistocene)

🟩 Hāmākua Volcanics (Pleistocene)

🟨 Waihu Glacial Member (Pleistocene)

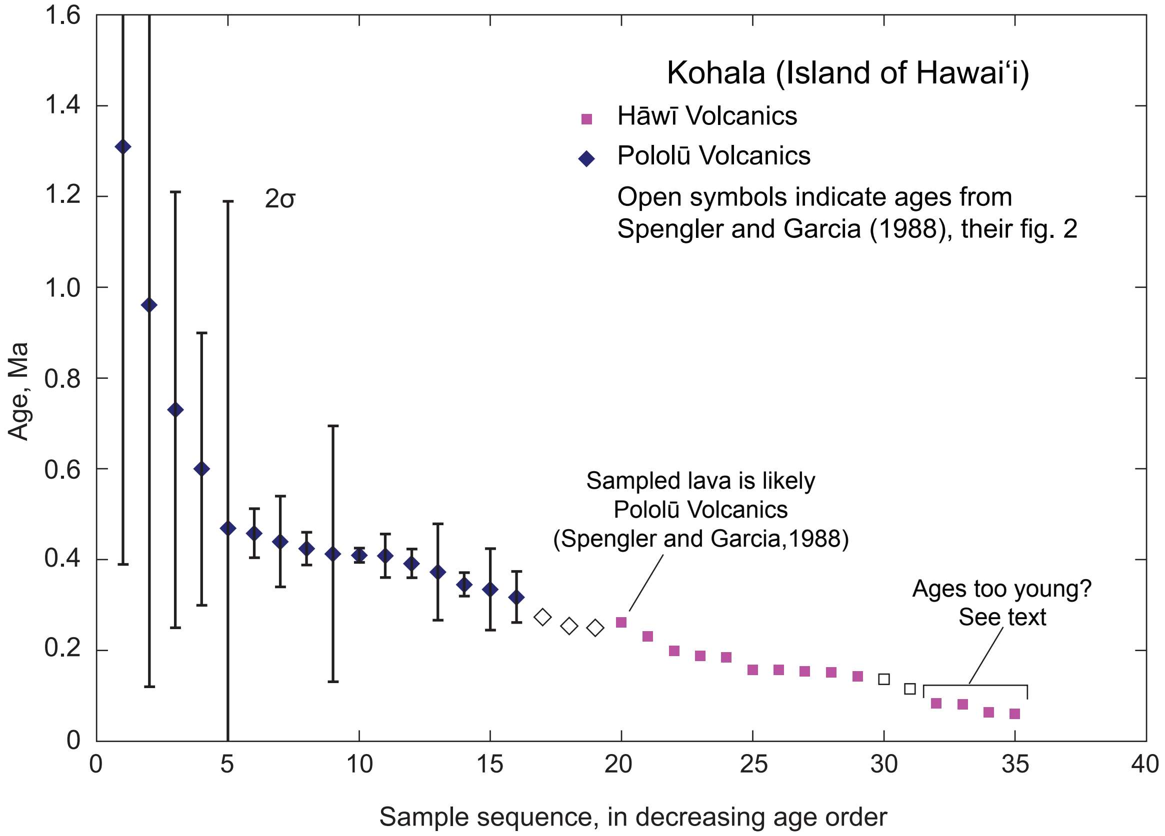


Figure 30. Radiometric ages from Kohala. Evernden and others (1964), McDougall (1969), Dalrymple (1971), McDougall and Swanson (1972), Malinowski (1977), Lanphere and Frey (1987), G.B. Dalrymple, in Spengler and Garcia (1988).

The summit of the volcano has faults that parallel the indented northeast coastline. “The resulting structural depression is regarded as a pull-apart graben developed at the head of the landslide” (Moore and others, 1989, p. 17,477). No faults are mapped connecting this summit graben with the coastal reach, however, so we prefer an interpretation in which the landslide headscarp is at the coast and the graben formed as a far-field response to changes in stress precipitated by the landslide. Regardless, volcanism continued after the landslide and after much of the large valleys had been carved, inasmuch as Hāwī lava flows draped the valley walls and flowed down into Pololū Valley (as first mapped by Stearns and Macdonald, 1946). Recent seafloor mapping has further elucidated details of the Pololū Slump (Smith and others, 2002).

Mauna Kea

On an island rich in superlatives, Mauna Kea brings it own title as highest summit in the State of Hawai‘i and the state’s only volcano known to have been glaciated. It is more symmetrical than other volcanoes on the island, lacking well-defined rift zones.

The oldest exposed volcanic strata of Mauna Kea are assigned to the Hāmākua Volcanics. The Hāmākua is found on all flanks, although the south-flank outcroppings are limited. It was divided into lower and upper members by Stearns and Macdonald (1946), of which the lower was later assigned to shield-stage volcanism and the upper to the postshield stage (Macdonald and others, 1983; Langenheim and Clague, 1987). The contact separating lower and upper members was described as gradational and, in many places, indefinite; consequently it was mapped only on the

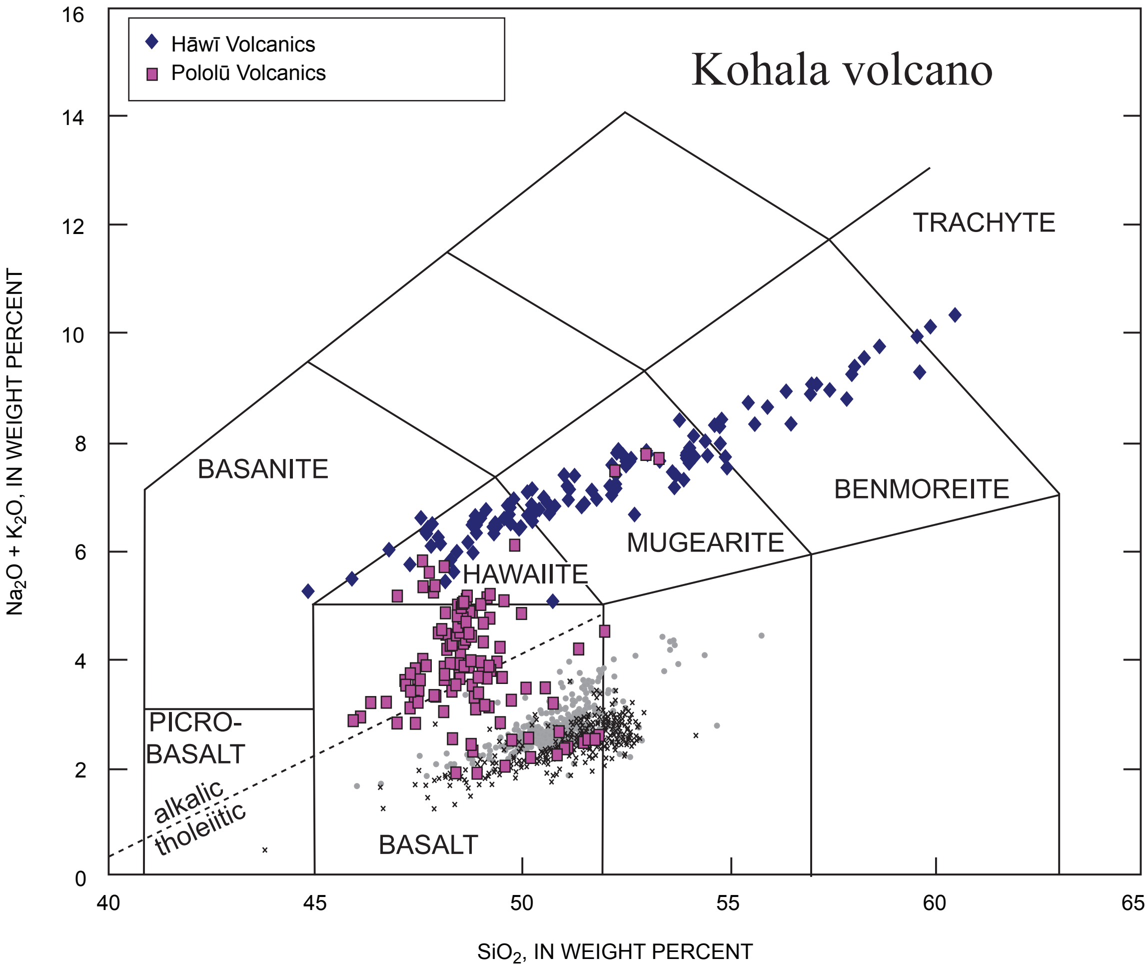


Figure 31. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Kohala. Grid fields labeled for those commonly used in Hawaiian islands; grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Data from Wolfe and Morris (1996b, 235 analyses).

east flank and depicted by way of a small-scale figure (Stearns and Macdonald, 1946, their fig. 31). In contrast, Wolfe and others (1997) interpreted the Hāmākua's origin entirely as postshield volcanism and stated that no shield-stage strata are exposed, an interpretation based on the geochemical characteristics of lava in the Hāmākua Volcanics. They noted, however, that lava flows exposed near sea level in Laupāhoehoe Gulch may represent the uppermost part of a transition zone between the tholeiitic shield and overlying alkaline (postshield) strata (Wolfe and others, 1997, p. 122).

Some more recent insight into this stratigraphic dilemma is found in the geochemical analyses from deeper Mauna Kea strata that were penetrated by the

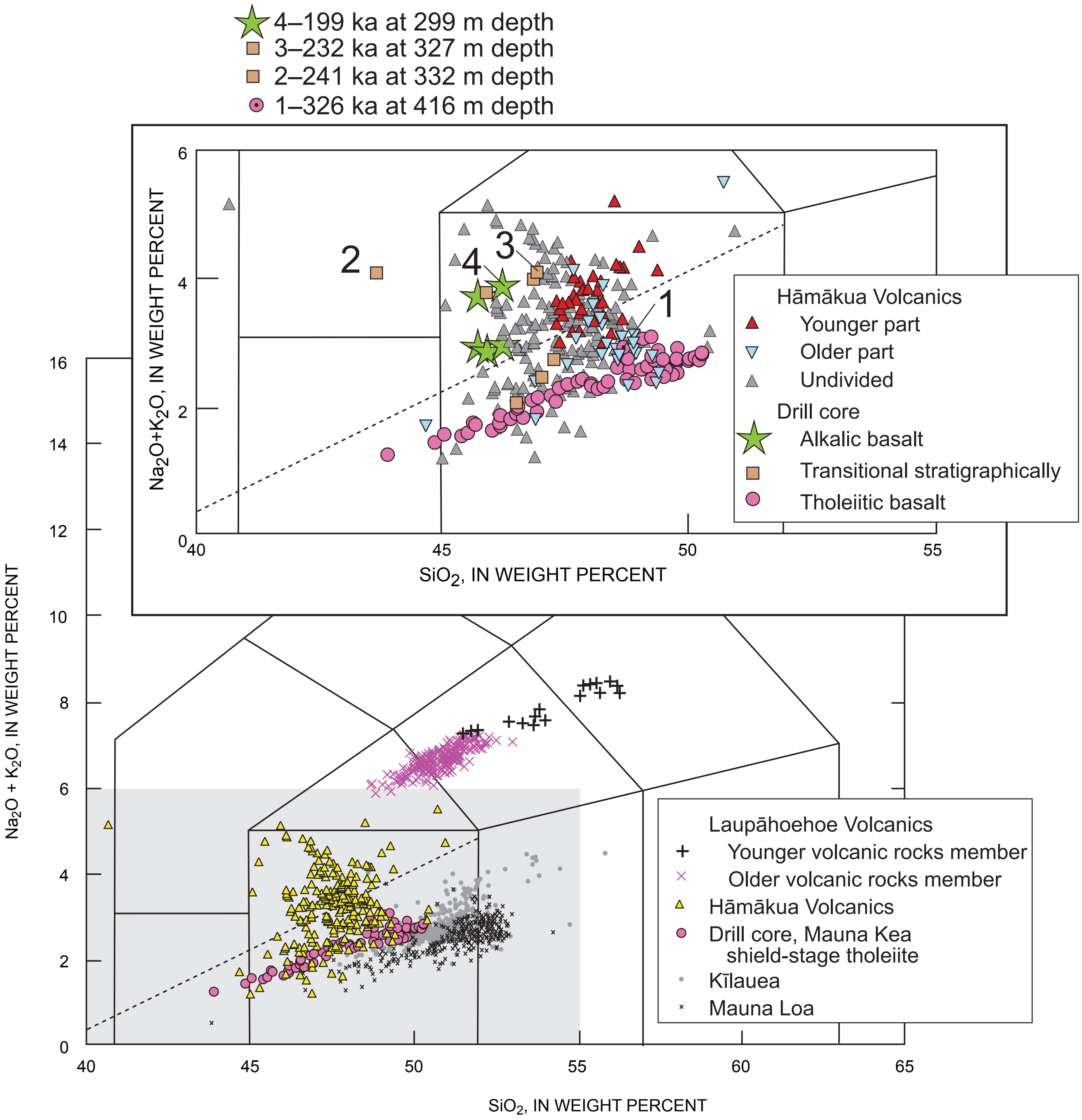


Figure 32. Alkali-silica (Na$_2$O+K$_2$O versus SiO$_2$) diagram for rocks from Mauna Kea, as sampled at surface (Wolfe and Morris, 1996b) and in Hilo drill hole (Rhodes, 1996). Grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Shaded box in lower main graph is enlarged in the overlapping inset. Ages from drill-core samples from Sharp and others (1996). Division of Hāmākua Volcanics into older and younger parts corresponds to Hopukani Springs and Liloe Spring Volcanic Members, respectively, as annotated in table 1 of Wolfe and others (1997).

Hawai‘i Scientific Drilling Program’s phase-1 drill hole near Hilo (fig. 32). Tholeiitic basalt lava flows below 340 m depth form a linear array similar to that of shield volcanoes like Kīlauea and Mauna Loa. Mauna Kea strata above have chemical compositions that spread broadly from tholeiitic to alkalic basalt, largely coincident with the field defined by samples from the Hāmākua Volcanics sampled at the surface (Rhodes, 1996). The distinction, as seen in figure 32, supports the view that no typical shield-stage strata are exposed today at Mauna Kea and that the Hāmākua Volcanics is therefore entirely postshield in origin (Wolfe and others, 1997). A corollary is that neither Haleakalā nor East Moloka‘i volcanoes have their shield-stage strata exposed today, if the total alkalies–silica diagrams are definitive (figs. 15, 25).

The age of the Hāmākua Volcanics is known from K–Ar dating. The radiometric ages range widely, in part because some samples have large analytical error. The span of likely age for the exposed Hāmākua sequence is as old as 300 ka and as young as 74–64 ka, at the 95-percent confidence level (fig. 33). A similar interpretation, albeit slightly narrower—about 265 to 65 ka—was offered previously by Wolfe and others (1997).

On the upper flanks of Mauna Kea, two glacial sequences, including till and outwash, are interbedded with the upper part of the Hāmākua Volcanics. The older of these is the Pōhakuloa Glacial Member; the younger is the Waihū Glacial Member. The Pōhakuloa Glacial Member is small in outcrop area and for that reason was not shown on the published compilation of Hawai‘i island geology (Wolfe and Morris, 1996a). We have added it to our map by digitizing it from the larger-scale map of Mauna Kea (Wolfe and others, 1997), in order to depict all the glacial units.

The latest episodes of Mauna Kea volcanism are assigned to the Laupāhoehoe Volcanics, which consists chiefly of hawaiite, mugearite, and benmoreite lava flows. The Laupāhoehoe has been subdivided into various members by Wolfe and others (1997), all of

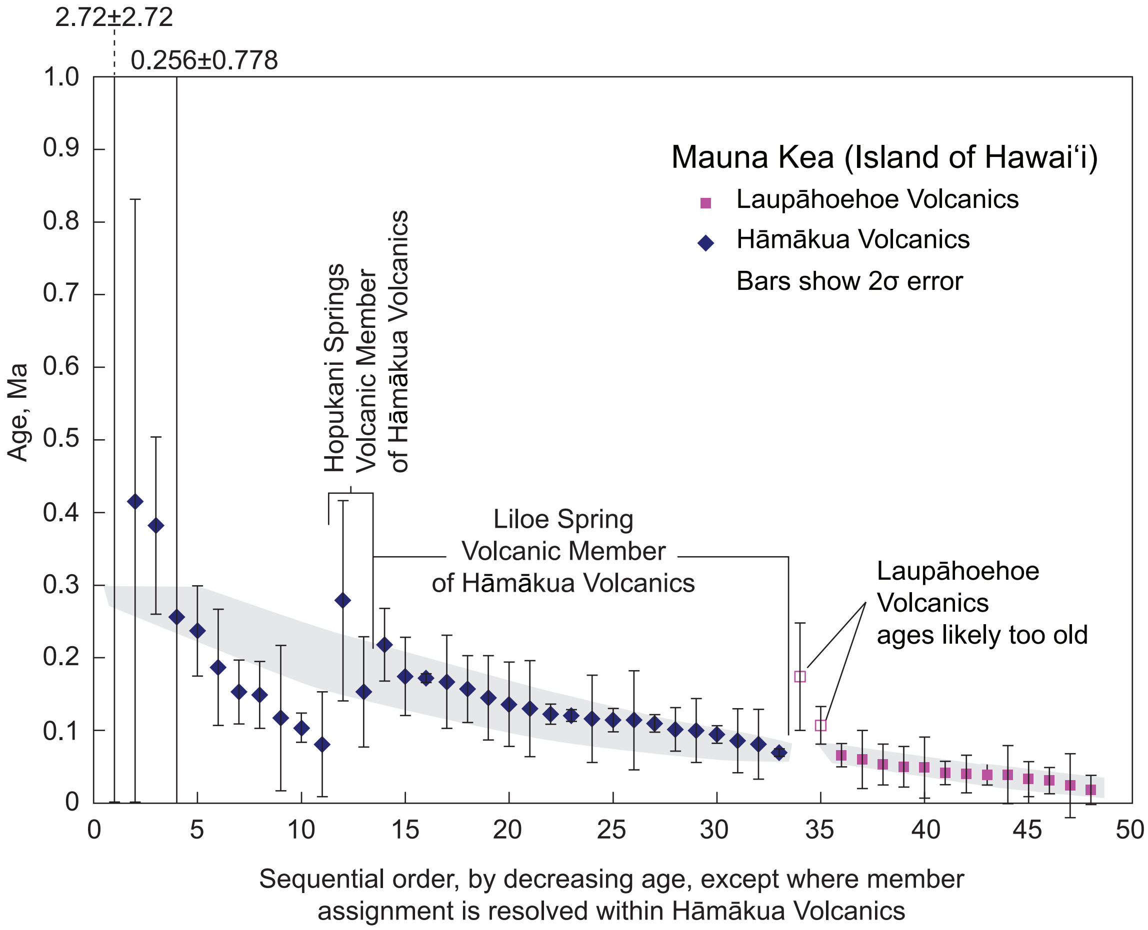


Figure 33. Potassium-argon ages from Mauna Kea’s surface volcanic rocks. Data from Porter (1979) and Wolfe and others (1997). Samples 1 through 11, from the Hāmākua Volcanics, undivided, were collected from exposures on the lower flanks of Mauna Kea. Open symbols, Laupāhoehoe Volcanics ages likely too old.

which are shown on this map.

Mauna Kea's youngest lava flows, in the upper part of the Laupāhoehoe Volcanics, are dated by way of nine charcoal ages from beneath the lava flows of six stratigraphic units. These ages range from 7,100 to 4,400 radiocarbon years (Porter, 1979; Wolfe and others, 1997). Calibrated ages correspond to the time between about 8,200 and 4,580 yr ago (fig. 34).

Some reports have cited a carbon-14 age of 3,600 yr B.P. as the most recent volcanic event (for example, Porter, 1979). This age was derived by interpolating depth–age relations for tephra layers in sediment of Lake Waiau, at Mauna Kea's summit (Woodcock and others, 1966). In that experiment, two radiocarbon ages from organic matter (algae planktonic spicules and frustules) in the sediment were obtained from depths of about 1 and 2 m; the ages are 2,270±500 and 7,160±500 ^{14}C yr B.P., respectively (Woodcock and others, 1966; Ives and others, 1967). Calibrated ages correspond to the intervals 9,190–6,958 yr B.P. at 2-m depth and 3,477–1,182 yr B.P. at 1-m depth (inset, fig. 34). Porter (1973) mentioned a tephra layer at 1.3-m depth and reported an approximate age of 3,600±300 ^{14}C yr for it as the evidence of youngest volcanism. This age has also been reported as "3,300 years" (Porter and others, 1987; Moore and Clague, 1992). A Mauna Kea eruption is the most likely source for the drill-hole tephra, but no compositional data unequivocally relate the ash to Mauna Kea.

A graphical estimate for the calibrated age of the 1.3-m-deep tephra is in the range 3,130–5,380 years B.P., which overlaps substantially with ages of eruptions known from dated lava flows (fig. 34). Indeed, correlation with known events seems the simplest explanation for the origin of the tephra in the Lake Waiau drill core, in the absence of chemical or mineralogic evidence to negate the correlation. Of course, deriving the age of youngest volcanism by this analysis is hampered by the large analytical errors on the ages from bounding sedimentary strata and the assumption of unvarying sediment accumulation during the interim period. We take a conservative approach, citing "about 4.6 ka" as the age of most recent volcanism, concurring with a similar finding by Wolfe and Morris (1996a) but reported here in calibrated, not radiocarbon, years.

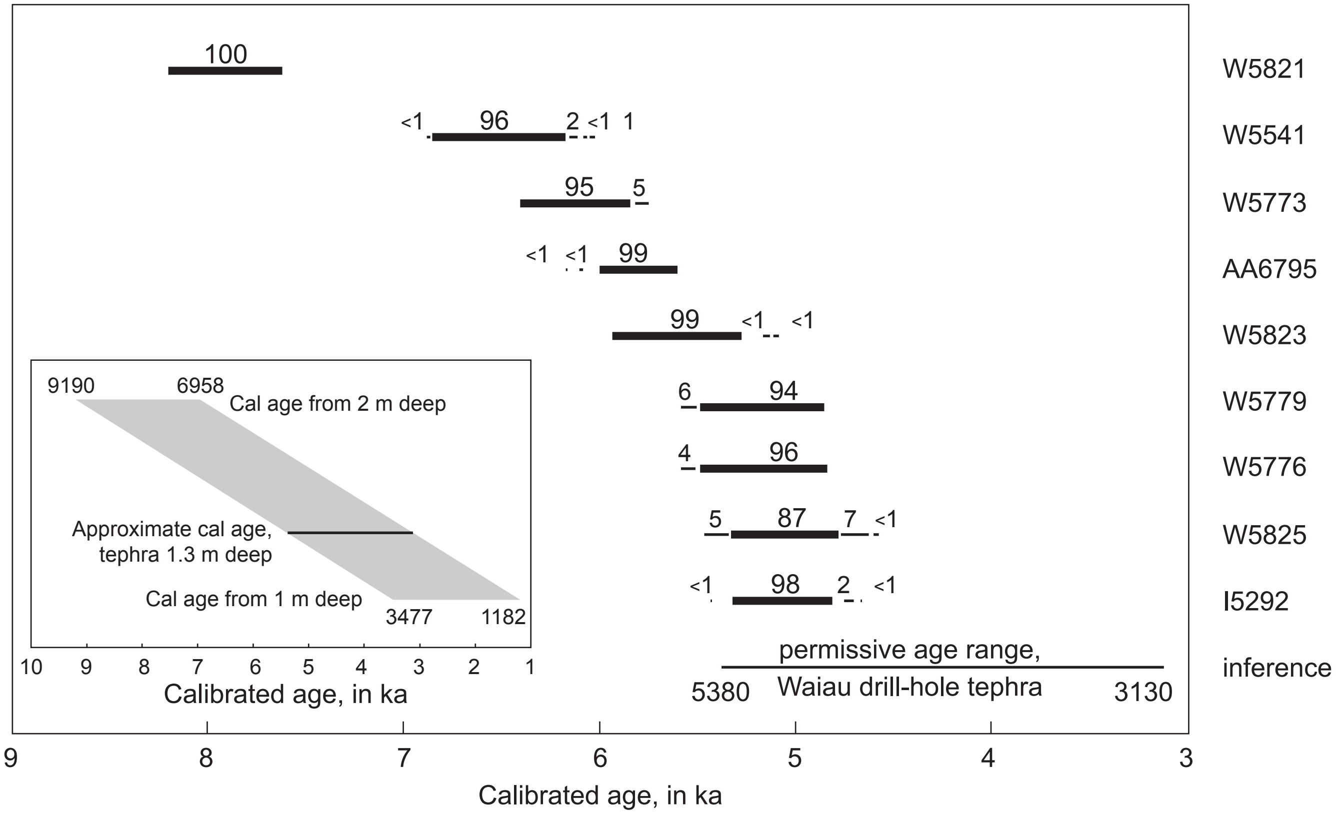


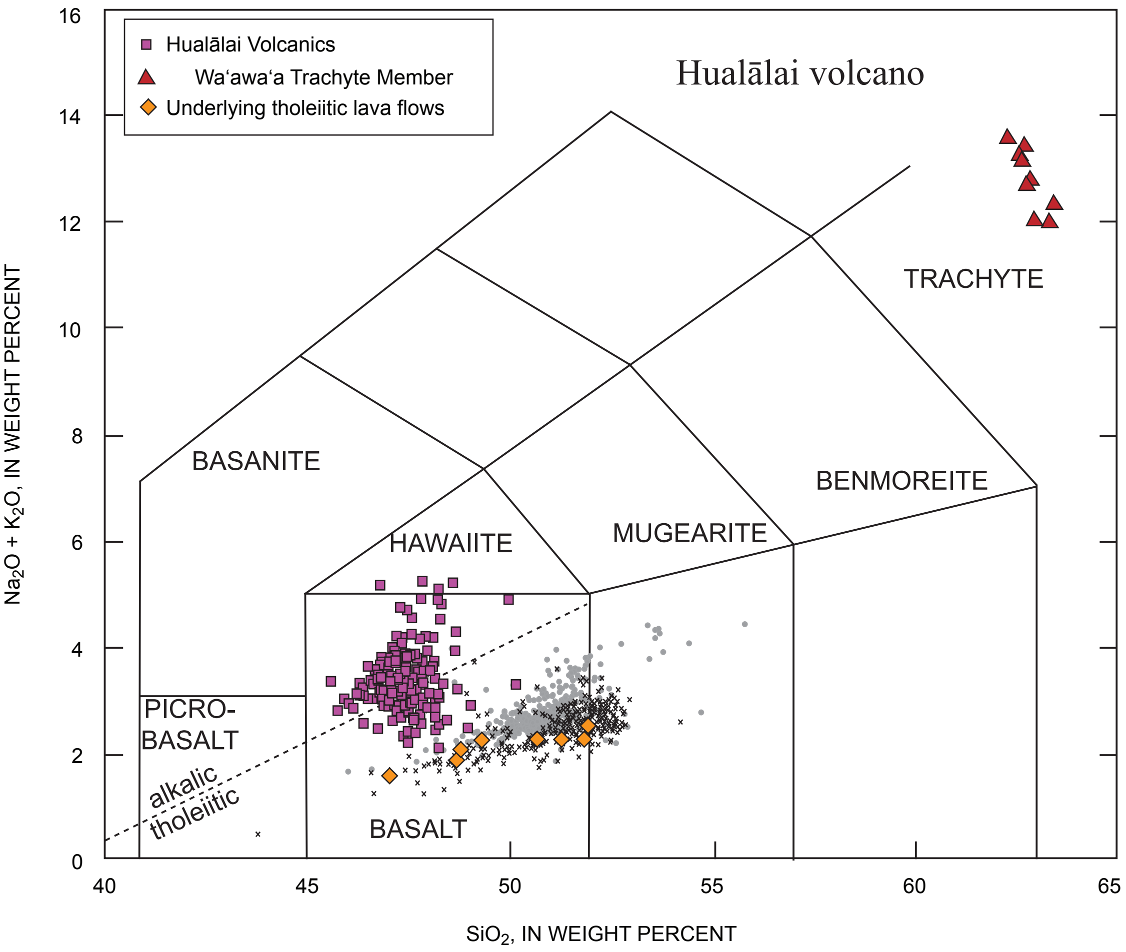
Figure 34. Calibrated ages from charcoal beneath Holocene volcanic rocks, Mauna Kea. Sample numbers along right axis. Bold bars indicate age range with greater than 85 percent probability for each calibrated age. Number above bar shows probablility (percent) that sample's age corresponds to that interval. Inset shows graphical solution for simply estimated age range of tephra in a shallow drill hole at summit; that age range labeled "inference" on main graph.

Mauna Kea's three glaciations have scoured lava flows at higher altitudes, leaving striated surfaces that lead down to the moraines and outwash left by the glaciers. Some lava flows in the summit area have ice-contact features such as steep margins, pillows, glassy surfaces, spiracles, and palagonitized zones (Porter, 1987). The evidence for ice-contact features is found in deposits originating beneath the Mākanaka and Waihū ice caps. Likely the Pōhakuloa glaciation produced similar effects, but none has been found among its sparse outcrops (Porter, 1987).

The estimated age and duration of the three glaciations have varied as the number of bracketing, dated lava flows increases; thus we report the interpretations offered by Wolfe and others (1997). Even so, the large analytical error for the ages precludes more than a general estimation for each. Knowledge from worldwide correlations, such as the cooling of ocean water as correlated with changes in oxygen isotope data, is critical to the final analysis. The oldest event, the Pōhakuloa, corresponds to marine oxygen isotope stage 6, so it is thought to have occurred sometime between about 180 and 130 ka. The Waihū Glacial Member is thought to have been deposited during oxygen isotope stage 4, or roughly 80–60 ka. The youngest, the Mākanaka, was underway by about 40 ka. It had ended by about 13 ka, the time when Lake Waiau became an ice-free depression capable of accumulating sediment (Peng and King, 1992). A small discontinuous body of permafrost, less than 25 m breadth, was present in the late twentieth century near the summit of Mauna Kea (Woodcock, 1974) and perhaps persists today.

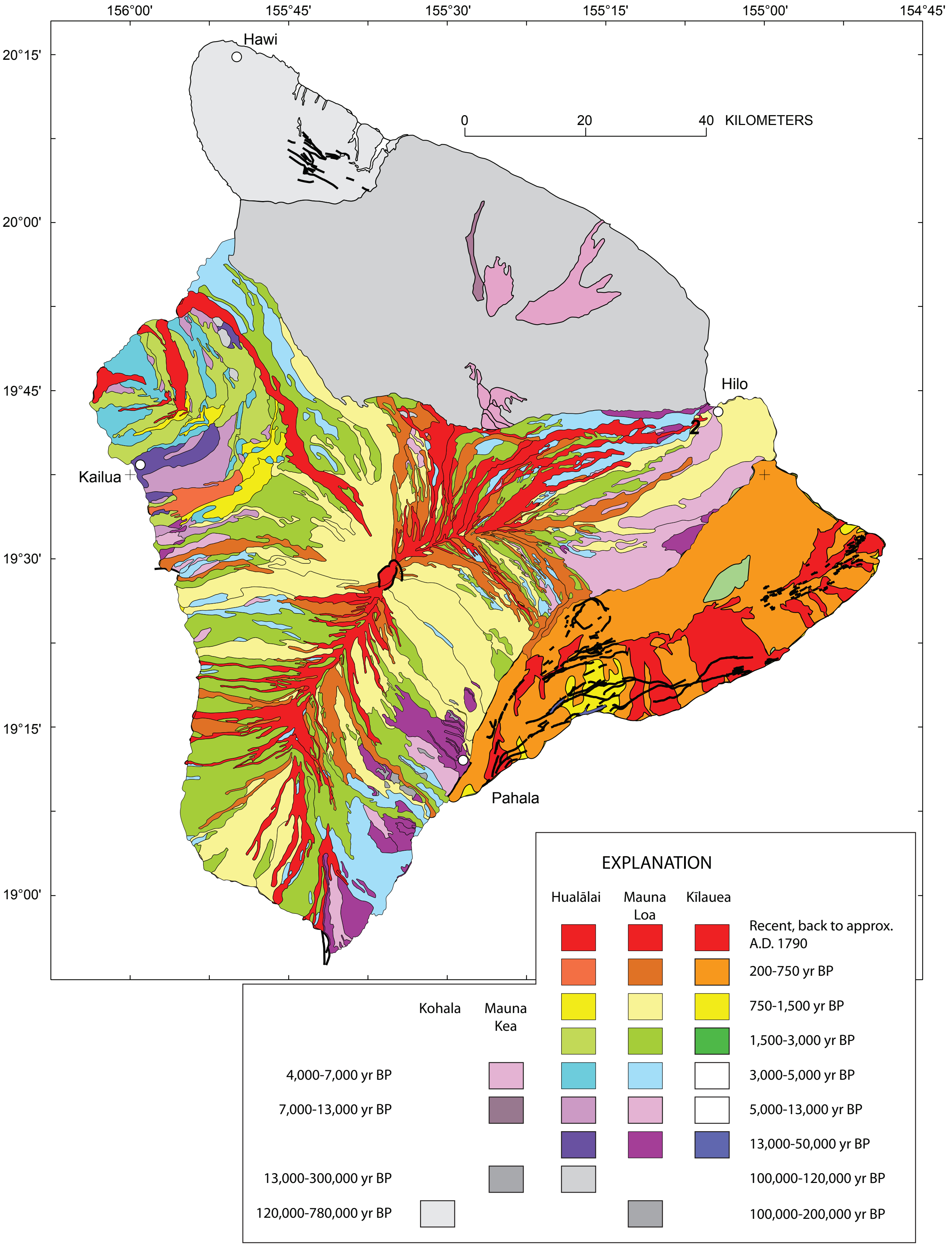
Hualālai

Travelers arriving at, or departing from, Kailua–Kona's Keāhole International Airport taxi across alkali basalt lava flows emplaced in A.D. 1801–02 (fig. 35),



igure 36. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Hualālai. Grid fields labeled for those commonly used in Hawaiian islands; grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Hualālai chemical data from Wolfe and Morris (1996b, 106 analyses), Clague (1987b, 2 analyses), R.B. Moore and others (1987, 4 analyses), J.G. Moore and Clague, 1987 (2 analyses), and Cousens and others (2003, 7 analysis).

Figure 35. Distribution of volcanic rocks by age for Hualālai, Mauna Loa, and Kīlauea. Generalized from this publication’s digital map database. Geology from Wolfe and Morris (1996a).



Hualālai's youngest volcanic products (Kauahikaua and others, 2002). Hualālai volcano's subaerial edifice is completely coated with these and other postshield-stage alkali basalt, hawaiite, and trachyte, all assigned to the Hualālai Volcanics (fig. 36). Vents for the Hualālai Volcanics define rift zones trending northwest and southeast from the volcano's summit. These zones are displaced by 4 km from the volcano's dense substructure, which presumably marks the pathways for eruptions of the shield-building stage (Kauahikaua and others, 2000).

Shield-stage lava flows are found offshore along the volcano's northwest rift zone (Clague, 1982; Clague, 1987b; Hammer and others, 2006). Tholeiitic lava flows were also intercepted in the Kahaluʻu water well (R.B. Moore and others, 1987), an inclined shaft that penetrates about 230 m of stratigraphic section from a surface altitude of 175 m (R.T. Holcomb, unpub. USGS report for Hawaiian Volcano Observatory, 1975). The depth for the Kahaluʻu samples has not been reported, but tholeiite apparently occurs as shallow as 75 m below surface (Clague, 1987b, his fig. 1 caption). Tholeiitic lava flows were also collected from below 440 m depth in the Huʻehuʻe water well, north of Kailua-Kona (Clague, 1987b), corresponding to altitudes lower than 14 m (sea-level datum). Tholeiitic flows dredged from the volcano's west flank about 8 km south of Kailua-Kona are likely from Hualālai, but they lie within 2 km of Mauna Loa offshore lava of similar composition, so they were assigned cautiously (Moore and Clague, 1987). Hualālai's tholeiitic eruptions persisted until sometime after 130 ka (Moore and Clague, 1992)

A widespread sequence of trachyte, the Waʻawaʻa Trachyte Member, presumably marks the base of the Hualālai Volcanics. Erupted in part from Puʻu Waʻawaʻa (fig. 29), a pumice cone on the north flank of Hualālai (R.B. Moore and Clague, 1991), the trachyte is penetrated by several water-well holes. Trachytic fragments were disgorged as xenoliths from vents southeast of the volcano's summit (Clague and Bohrson, 1991), so doubtless other vents are buried along the northwest rift zone or thereabouts. Numerous radiometric ages indicate that the trachyte was erupted sporadically for about 20,000 yr, from 114 to 92 ka (Clague, 1987b; Cousens and others, 2003).

Hualālai is one of several Hawaiian volcanoes known to have had phreatic explosions at high altitude along its rift zone. The vent, Wahapele, at about 1600 m altitude, disgorged blocks of country rock and shed a layer of light gray to white ash as thick as 3 m during activity that culminated by about 700–800 yr B.P. (Moore and Clague, 1991).

Mauna Loa

The world's largest volcano, Mauna Loa, has come to epitomize shield-stage volcanism. Its volume is in the range 65,000–80,000 km^3 of lava flows, vent deposits, and intrusions, an estimate that includes the edifice above the ocean floor but also that created by the 8–9 km of load-induced subsidence of the Pacific plate beneath Mauna Loa's summit (Lipman, 1995; Robinson and Eakins, 2006). The volcano's growth has been accompanied by several large landslides. Deposits of these slides retain their geomorphic form on the ocean floor west of Mauna Loa (for example, Lipman, 1980; Lipman and others, 1988; Moore and others, 1989). The headwalls for these slides coalesce to encompass a large sector of Mauna Loa's west flank. Exposed today at the northern and southern onshore limit are two normal faults, the Kahuku and Kealakekua faults, on Mauna Loa's west flank. The headwall's trace between these faults has been masked by subsequent lava flows (fault shown dotted on figure 28), but it likely had subaerial exposure in excess of 1500–2000 m, exceeding the modern topographic expression of the Hilina fault, a similar fault on Kīlauea.

Oldest of Mauna Loa's exposed subaerial rocks are lava flows of the Nīnole Basalt, which forms the Nīnole Hills (fig. 29). The Nīnole Basalt is thought to be 0.1–0.2 Ma in age (Lipman and others, 1990) on the basis of several K–Ar ages (fig. 37), but the samples have low potassium content, low radiogenic argon yield, and fairly large analytical error—a problem that haunts the dating of young tholeiitic lava flows along the Hawaiian island chain. The Nīnole Hills form an erosionally dissected terrane against which younger Mauna Loa lava flows have banked. Their depth of incision and minor topographic isolation from the slope of Mauna Loa's south flank are thought to result from rapid erosion following an abrupt change in stream-base equilibrium after an ancestral slump truncated the island shoreline seaward of the hills (Lipman and others, 1990).

Mauna Loa strata similar in age to the Nīnole Basalt were dated from two drill holes on the lower east flank (fig. 37). A ^{40}Ar/^{39}Ar plateau age of 132±64 ka (2σ) from 268 m depth was viewed cautiously (Sharp et al., 1996) owing to a discordant spectrum. It is within the range of a similar ^{40}Ar/^{39}Ar isochron age, 122±86 ka, from 245 m depth (Sharp and Renne, 2005).

Younger lava flows from Mauna Loa are divided into two formations on the basis of an intervening thick ash deposit found on the lower southwestern flank of the volcano. The older of the two is the Kahuku Basalt, which is sparsely exposed in two escarpments on the lower southwest rift zone. The younger, and far more widespread, is the Ka‘ū Basalt (fig. 29).

The intervening ash deposits are probably best known from the area near Pāhala, from which comes the name most commonly assigned to them, Pāhala Ash. The unit consists of numerous primary and reworked beds that accumulated over a substantial period of time. Most of the glass is devitrified and altered, which has hindered efforts to subdivide the unit in a way that leads to new stratigraphic or structural insight. It had been suggested that the main body of the ash near Pāhala town is at least 30 ka in age (Lipman and Swenson, 1984) on the basis of a radiocarbon age of 31,100±900 ^{14}C yr B.P. from a lava flow in the overlying Ka‘ū Basalt (sample W3935; Rubin and others, 1987). But subsequent dating and mapping indicates that younger ash deposits predominate, mainly with ages from about 30 to 13 ka (F.A. Trusdell, oral commun., 2006). These ages are from charcoal beneath Mauna Loa lava flows interbedded with the ash along the southwest rift zone, mapped as the oldest part of the Ka‘ū Basalt. This latter age range—30 to 13 ka—also characterizes a similar thick sequence where dated on nearby Kīlauea Volcano, discussed later.

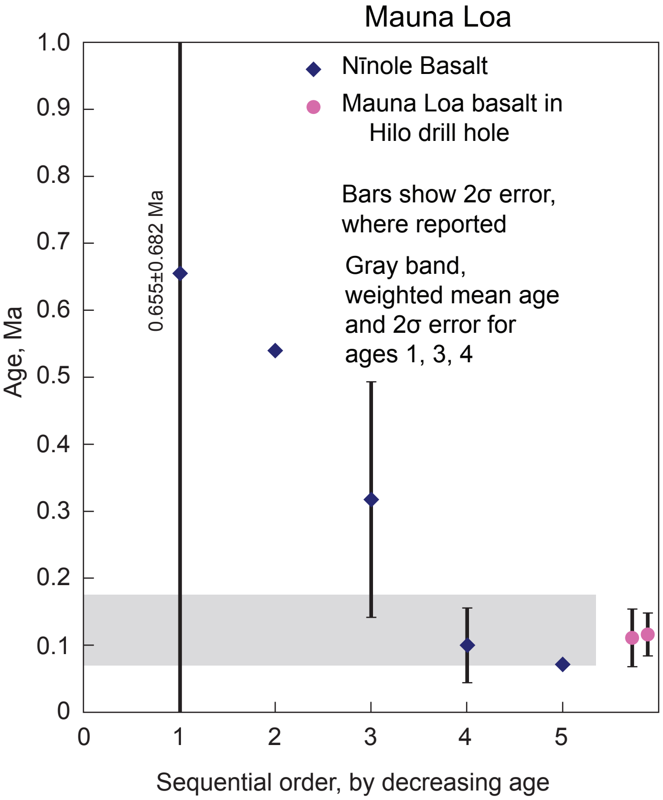


Figure 37. Radiometric ages from lava flows in the Nīnole Basalt (sampled in Nīnole Hills and from Mauna Loa lava flows of similar age from the Hilo HSDP drill hole. Shown without analytical error are two Nīnole Basalt ages from Evernden and others (1964), whereas the three others (from Lipman and others, 1990) were used to calculate weighted mean age and 2σ error limit shown by gray band. Not shown are two ages from dikes that yielded impossibly old ages of 1.28 and 7.18 Ma (Lipman and others, 1990). HSDP drill hole ages from Sharp and others (1996) and Sharp and Renne (2005).

Was Mauna Loa glaciated? The volcano had sufficient area above the ice equilibrium line altitude to maintain an ice cap in the time of the last glaciation 25–15 ka. This estimate is drawn after correcting Mauna Loa’s current altitude downward by 150–300 m to compensate for lava accumulation at rates that characterize shield growth (for example, Sharp and others, 1996; Sharp and Renne, 2005). Till and outwash deposits that may have resulted from glaciation would be buried now throughout the summit region. Suitably old strata lie below 2000 m altitude, too low to carry the evidence of glaciation if the example from Mauna Kea is a useful guide. Today, sporadic ice persists each summer in caves above 3700 m, serving as an emergency source of water in the otherwise arid summit region. But unlike Mauna Kea, no permafrost zone has been mapped at Mauna Loa. The aforementioned revision in age for much of the Pāhala Ash raises the tantalizing possibility that phreatomagmatic explosive eruptions related to glaciation at Mauna Loa may have been a contributing factor for the ash genesis (D.A. Swanson, oral commun., 2005).

Substantially younger, thin deposits of explosion debris mantle the northwest and southeast rims of Moku‘āweoweo caldera, at the summit of Mauna Loa. These deposits, which include blocks as large as 1 m across, originated from the caldera and were interpreted as phreatic in origin with no juvenile magmatic material (Macdonald, 1971). Those at the summit are probably only slightly younger than 1,000 yr, on the basis of recently obtained exposure ages of the deposits and ages ranging from 1,000 to 1,250 years from underlying lava flows (Trusdell and Swannell, 2003), but other deposits 3 km to the southeast are overlain by lava flows from the summit and likely are older, indicating at least two episodes of phreatic explosions. These explosions may have been driven by magma as it intercepted ground water perched in the dike swarms of the upper rift zones. Perhaps more likely, trapped CO_2 may have been the expulsive agent (D.A. Swanson, written commun., 2006).

Kīlauea

Kīlauea, youngest of the emergent volcanoes in Hawai‘i, is also perhaps the most active volcano in the world. The distinction certainly applies from the point of view of historical lava-flow production. (Some have argued that Stromboli volcano, Italy, has a longer record of perennial activity, disgorging tephra frequently during the past 2000 years.) An essentially continuous eruption ongoing since 1983 (for example, bibliography in Heliker and Mattox, 2003) has furthered the shield-building process at Kīlauea.

Kīlauea's oldest strata include preshield-stage alkalic basalt as old as about 275 ka, the only Hawaiian volcano besides submarine Lōʻihi and possibly Hualālai where these early-erupted rocks haven't been buried by shield lava (Lipman and others, 2002; Sisson and others, 2002; Hammer and others, 2006). The preshield alkalic samples were collected from the southern submarine slope by remotely operated submersibles. Ages are chiefly in the range 275–225 ka (fig. 38) (M.A. Lanphere, *in* Lipman and others, 2002) and presumably represent submarine lava flows.

Drill holes on Kīlauea's east rift zone have penetrated

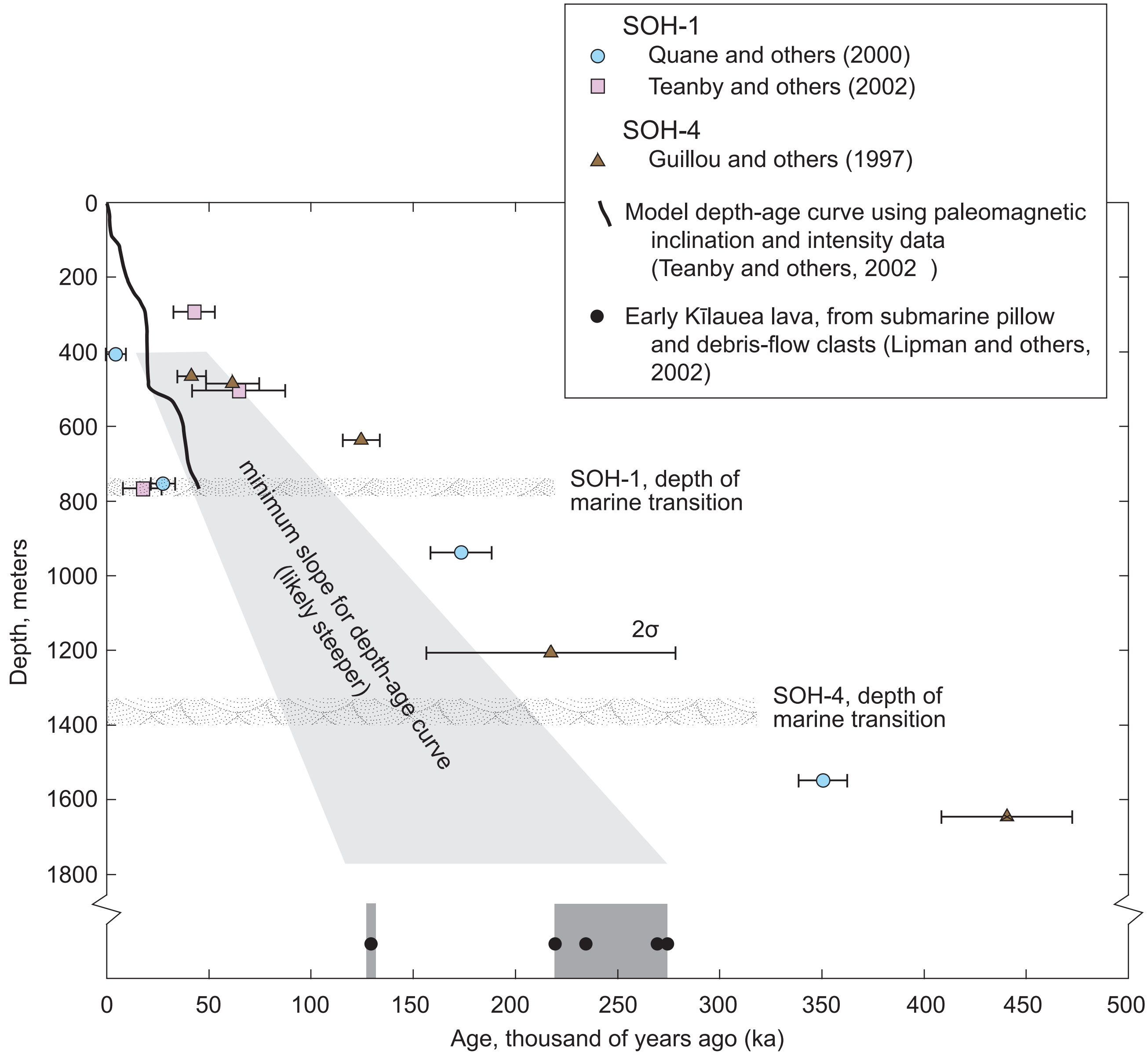


Figure 38. Radiometric ages from early alkalic volcanic rocks on Kīlauea's submarine flank (Lipman and others, 2002) and from tholeiitic lava in SOH–1 and SOH–4 drill holes (Guillou and others, 1997; Quane and others, 2000; Teanby and others, 2002). Early Kīlauea submarine ages were reported without analytical error and are shown here as dots; other ages shown with 2σ analytical error. Depth-age curve based on inclination reversals seen in drill core samples and correlation with worldwide geomagnetic data (from Teanby and others, 2002). Shaded area showing minimum slope for depth-age curve is fixed by shallowest possible depth for the early Kīlauea ages, which are at least as deep as, and more likely deeper than, base of holes. Depth of marine transition in SOH–1 and SOH–4 from Trusdell and others (1999 and 1992, respectively).

below the subaerial–submarine boundary—at about 738–787 m depth for hole SOH–1, corresponding to 551 m below sea level (Trusdell and others, 1999). The drilled sequence is entirely in tholeiitic lava flows and dikes (fig. 39). Ages from the different core holes are as old as about 450 ka (Guillou and others, 1997; Quane and others, 2000), and the older ages seemingly form a rudely linear age-depth curve (fig. 38). (In our graphical analysis we ignore an unreasonably old age of about 1.2 Ma from 1808 m depth in SOH–1 described by Guillou and others, 1997). Paleomagnetic inclination and intensity data from the SOH–1 samples suggest the strata in the hole are younger than several of the ages might suggest, on the basis of correlation with short-lived magnetic reversals known from elsewhere in the world. That, and the constraining ages already mentioned for early Kīlauea alkaline fragments (fig. 38), indicates that the entire tholeiitic shield stage is younger than about 225 ka.

From surface mapping, Kīlauea's subaerial stratigraphic sequence is divided into three major units: from oldest to youngest they are (1) the Hilina Basalt, (2) an overlying thick accumulation of basaltic ash (Pāhala Ash of many workers), and (3) the capping Puna Basalt (fig. 29). The Hilina Basalt is composed of tholeiitic lava flows thicker than 300 m in aggregate where exposed in fault escarpments along Kīlauea's south flank. Tephra-fall deposits are scattered within the sequence of Hilina lava flows, and a few have been assigned member status (for example, Easton, 1987). None of these individual ash beds is sufficiently thick to show on our map, however. Consequently, none is depicted in our GIS map database.

The base of the exposed lava-flow sequence was estimated to be about 100 ka in age by Easton (1987), who calculated a stratigraphic accumulation rate of about 2.3 m per 1,000 yr for a 17-m-thick section of the overlying Puna Basalt at Nanahu arroyo, a site where several radiocarbon ages were obtained (fig. 40). A slightly lower rate, about 1.93±0.08 m per 1,000 yr, is

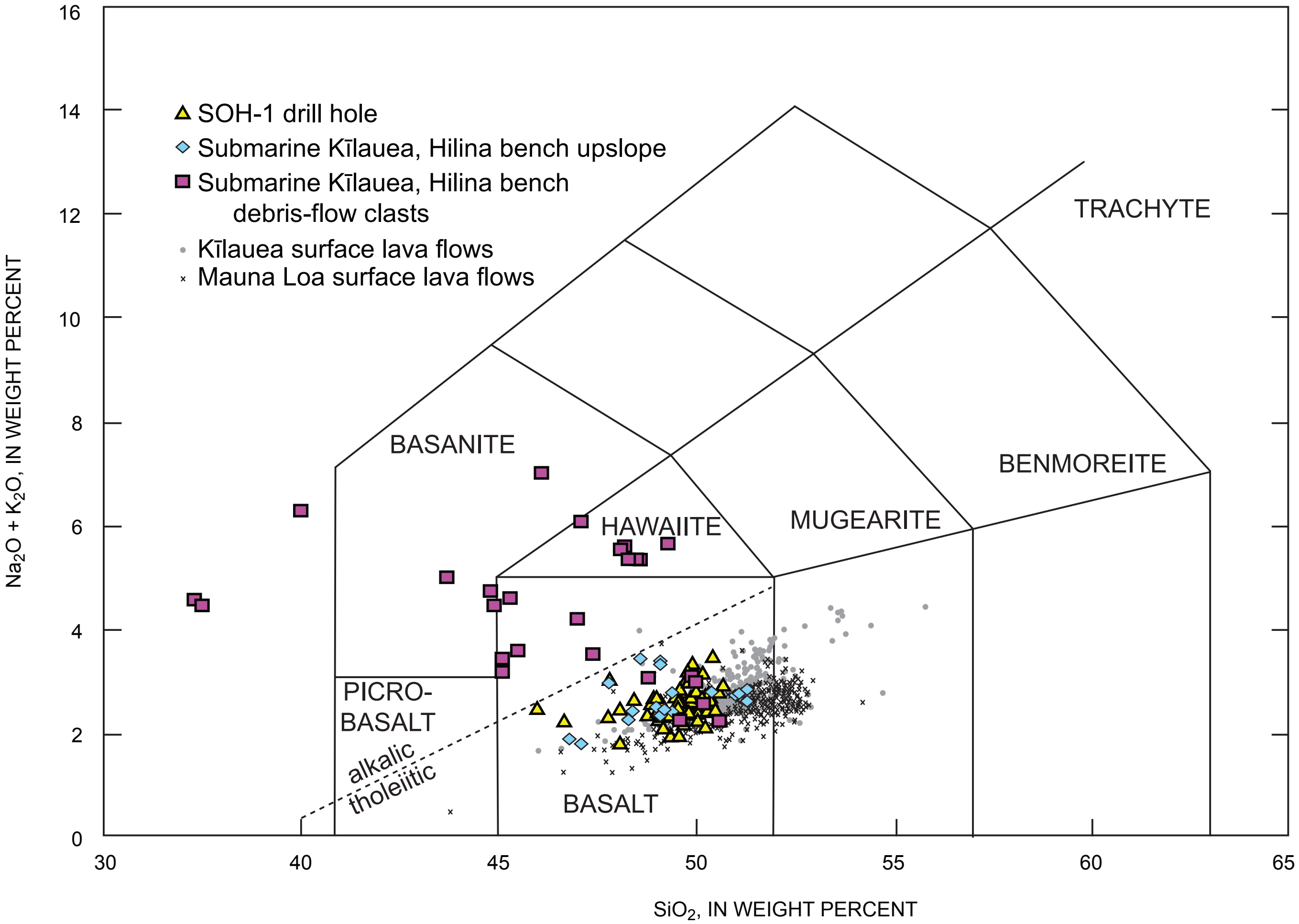


Figure 39. Alkali-silica (Na_2O+K_2O versus SiO_2) diagram for analyzed rocks from Kīlauea sampled in SOH–1 drill hole and offshore submarine setting (Sisson and others, 2002). Grid fields labeled for those commonly used in Hawaiian islands; grid boundaries and Mauna Loa-Kīlauea data (small black symbols) referenced in figure 2 caption. Data for Kīlauea's and Mauna Loa's subaerially exposed lava from Wolfe and Morris (1996b).

obtained if the radiocarbon ages are first calibrated to sidereal years (table 2). But the Nanahu exposure lies within an area periodically sheltered from summit-derived lava flows by uplift along the Koaʻe fault system, so its accumulation rate during Puna time (past 16,000 yr) is likely nonrepresentative. Radiocarbon ages of 28.3 and 43 ka from charcoal beneath lava flows within the Hilina Basalt (D.A. Clague, data reported by Riley and others, 1999) and the likely occurrence of the Mono Lake (35 ka) and Laschamp (40 ka) geomagnetic excursions in the Hilina section (data of Riley and others, 1999, interpreted by Teanby and others, 2002) indicate accumulation of the Hilina Basalt at a rate about 6 m per 1,000 yr. This latter rate is in the range of the rate 7.8–8.6 (±3.1) m per 1,000 yr that was calculated for Mauna Kea's shield-stage growth on the basis of radiometric ages from the Hilo deep drill hole (Sharp and others, 1996; Sharp and Renne, 2005). Thus we estimate that exposed Hilina lava flows are no older than about 50,000–70,000 years (at rate 6 m per 1,000 yr).

The capping Puna Basalt dominates the surface of Kīlauea. The Puna includes latest Pleistocene strata, judging from ages at its base that range from about 16,290±400 cal B.P. (13,675±50 ^{14}C yr B.P.) to 12,240±480 cal B.P. (10,290±35 ^{14}C yr B.P.) (table 2). But the older part of the sequence is difficult to show at the scale of this map. Indeed, the oldest Puna Basalt is grouped with unit Qp2, owing to its exposure only in cliffy sections along Hilina Pali (fig. 41). A single cinder cone, Puehu, is the only feature mapped as the lowest unit in the Puna Basalt, Qp1o; it lies isolated among younger Mauna Loa lava flows near Punaluʻu. Similarly restricted in areal extent is unit Qp1y, which encompasses a fissure vent and lava flows near Pāhala.

Lava flows younger than 1,500 years coat 90 percent of the volcano (fig. 35). The relative ease of distinguishing and mapping these flows has yielded a geologic map more detailed than elsewhere along the island chain (fig. 35). Also, many of Kīlauea's flows tend to be less extensive than those erupted at nearby Mauna Loa, where high lava production rates create areally extensive sheets of pāhoehoe and ʻaʻā. Somewhat anomalous for Kīlauea's lava distribution pattern is the north flank of its east rift zone, which appears devoid of the detail found elsewhere on the volcano (fig. 35). This result is not a consequence of mapping hampered by the windward slope's high rainfall and dense vegetation but results instead from the emplacement of a single sequence of lava flows, the ʻAilāʻau flows of the Puna Basalt (unit Qp4). These tube-fed flows spread from a small shield just east of the volcano's summit during a 50-yr period, mainly in the first half of the 15th century (A.D. 1410–1460), just prior to the development of Kīlauea caldera (Clague and others, 1999).

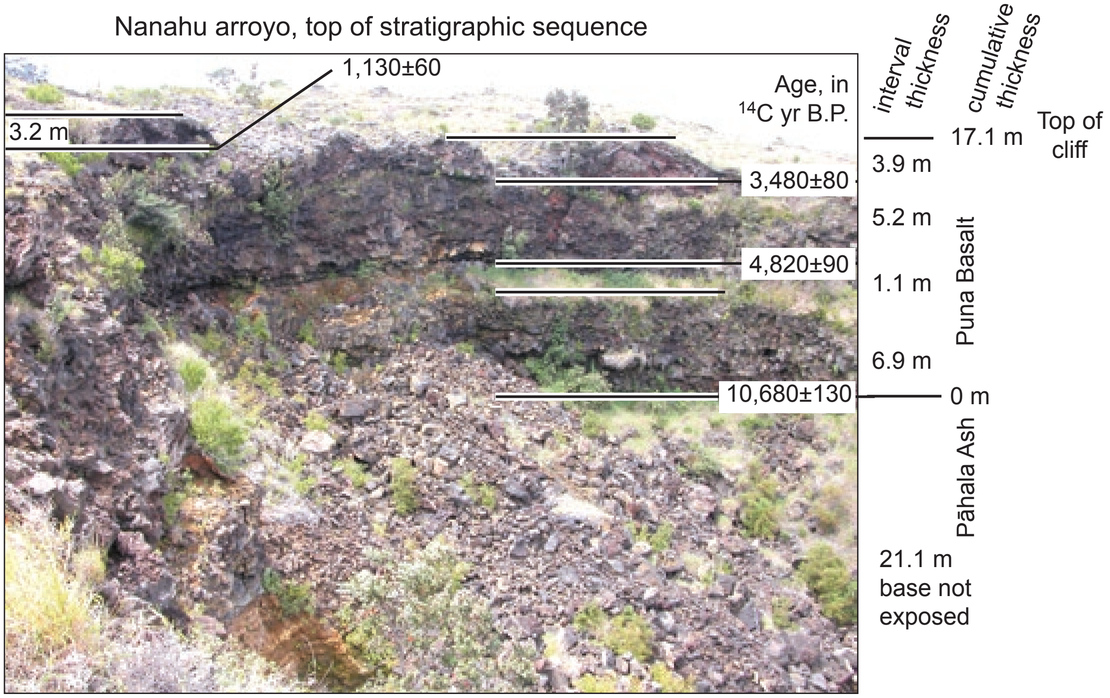


Figure 40. Exposure of well-dated Puna Basalt sequence and underlying thick tephra deposits (Pāhala Ash), Nanahu arroyo. Thickness measured by total-station tacheometer in 2004. See table 2 for calibrated ages, geographic coordinates, and sources of data.

Table 2. Radiocarbon ages to determine rate of stratigraphic accumulation and age at base of Puna Basalt in Hilina Pali, Kīlauea Volcano, Hawai‘i.

[New ages, referable to this map, by John P. McGeehin, U.S. Geological Survey. Ages calibrated to sidereal years at 2σ confidence using 2005-vintage CALIB radiocarbon calibration program, version 5.0.1 (Stuiver and Reimer, 1993), in conjunction with IntCal04 calibration dataset (Reimer and others, 2004). Oldest age, which dates lava flow near base of thick tephra deposits (Pāhala Ash) that underlie Puna Basalt, is beyond calibration range (older than about 21,000 ^{14}C yr B.P.) and was not used for accumulation rate calculations. Two named arroyos are informal geographic features (from Easton, 1987). Geographic coordinates in WGS84.]

Age, ^{14}C yr B.P.	Calibrated B.P.	Probability	Sample No.	Lab No.	Reference
Nanahu arroyo 155º18.1788' 19º17.8980' Ka‘ū Desert quadrangle					
1,130±60	930–1,178 1,215–1,221	0.995 0.005			D.A. Swanson, unpub. data
3,480±80	3,561–3,973	1.000		W3831	Rubin and others, 1987
4,820±90	5,321–5,421 5,437–5,732	0.166 0.834		W3798	Rubin and others, 1987
10,680±130 Base of Puna Basalt	12,237–12,320 12,344–12,902	0.028 0.972		W3809	Rubin and others, 1987
Unnamed crease 155º18.9326' 19º17.3475' Ka‘ū Desert quadrangle					
10,290±35 Base of Puna Basalt	11,760–11,820 11,859–12,379 12,508–12,556 12,627–12,686 12,709–12,719	0.072 0.902 0.011 0.012 0.002	S03-KSW251	WW4439	This map
Pōhāka‘a arroyo 155º19.8282' 19º16.5487' Ka‘ū Desert quadrangle					
13,675±50 Base of Puna Basalt	15,939–16,691	1.000	S01-KSW8	WW4118	This map
30,990±250 near base Pāhala Ash	--		S01-KSW7	WW4113	This map

Though better known for its effusive eruptions, Kīlauea also ranks as an explosive volcano (Mastin and others, 1999). Tephra deposits in the stratigraphic record indicate a frequency of large explosive events that rivals that of Mount St. Helens, State of Washington (Swanson and others, 2002). The summit of the volcano is mantled with thick tephra known as the Keanakāko‘i Ash Member (a tephra sequence in the Puna Basalt, unit Qpa4y; for example, McPhie and others, 1990), which accumulated during a series of explosive eruptions spanning the time from about A.D. 1500 to 1790 (Swanson and others, 2004). These deposits had been thought to be emplaced about A.D. 1790 and were thus shown slightly younger on previous renditions of Hawaii island geologic maps (Wolfe and Morris, 1996; Trusdell and others, 2006). Another extensive deposit, the Uwēkahuna Ash Member and its upper part, the Kulanaokuaiki tephra (Fiske and others, 1999), is in the range 1,000–2,500 yr old (D.A. Swanson, written commun., 2006). Older, late Pleistocene tephra on Kīlauea is exposed chiefly near and at the top of the Hilina Basalt but is included within a regionally distributed tephra unit (Qt) owing to the uncertainty in assigning the tephra to specific volcanic sources.

Kīlauea’s Hilina fault system, a prominent south-flank structure, has the greatest offset of any subaerially exposed faults within the island chain. The faults are highly active, with long-term vertical offset ranging from 2 to 20 mm per year along the system (Cannon and Bürgman, 2001). Physiographic relief is about 500 m, and cross sections suggest separation as great as 670 m near Keanabihopa (Walker, 1969). These faults may penetrate to a detachment fault at or below the ocean floor–volcano boundary (for example, Lipman and others, 1985); or they may be shallow-rooted listric faults that flatten at depth within the volcanic pile (Swanson and others, 1976; Riley and others, 1999; Cannon and Bürgman, 2001). The back-rotation of strata as might occur along listric faults was depicted on Walker’s (1969) map. It has been corroborated independently by using paleomagnetic directions of strata in tilted and nontilted sequences (Riley and others,

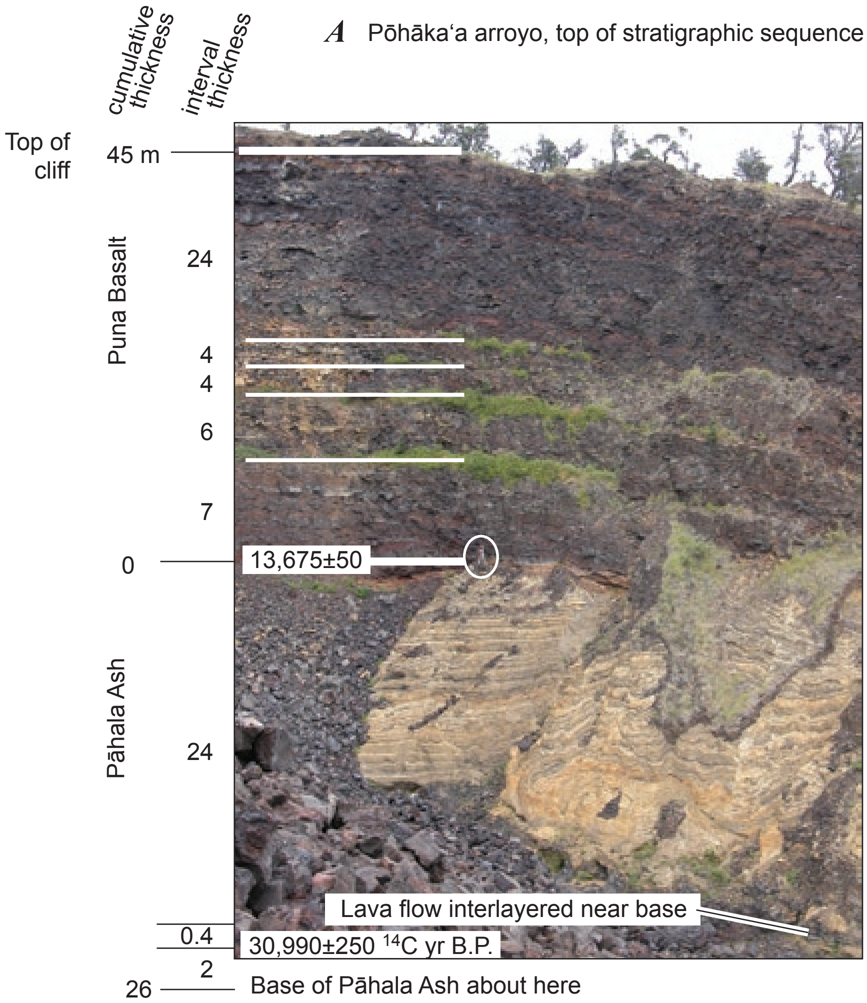
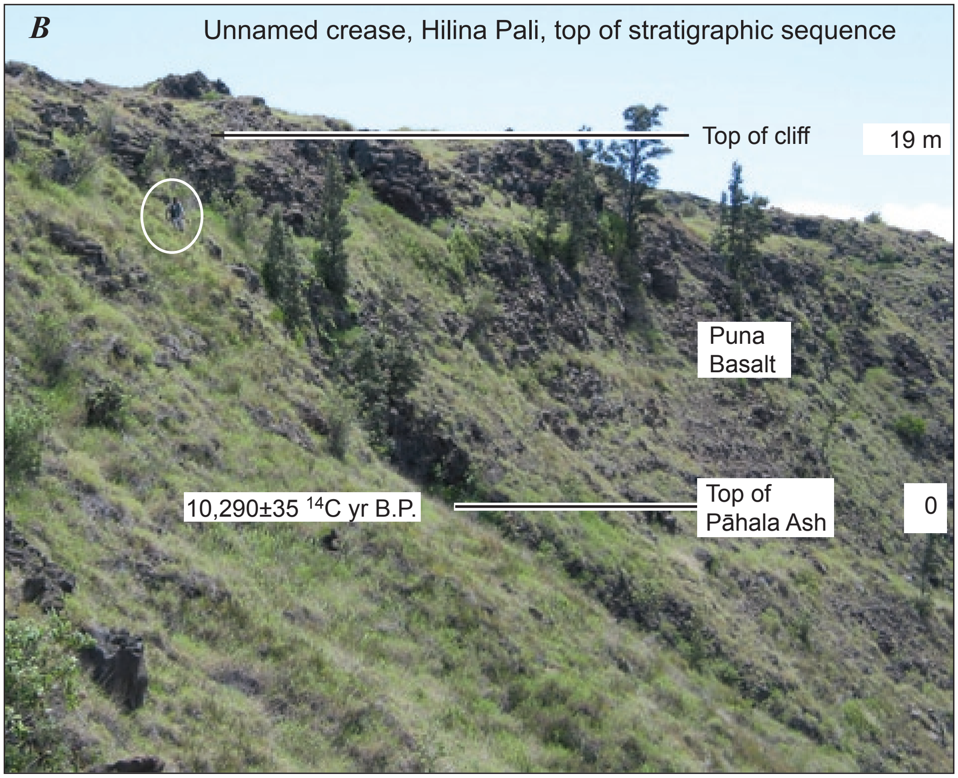


Figure 41. Exposures in Hilina Pali where erosion has exposed base of Puna Basalt. Thickness, measured by total-station tacheometer in 2004, rounded to nearest meter owing to variations along depositional surfaces that render more precise reporting meaningless. See table 2 for calibrated ages, geographic coordinates, and sources of data.

A, Pōhāka‘a arroyo; T.R. Orr, surveyor; rodwoman for scale (circled).

B, Unnamed crease; J.P. Kauahikaua, surveyor; rodman for scale (circled).



1999). The rapidity of strain accumulation along the Hilina fault system led Swanson and others (1976) to anticipate the likelihood of a major earthquake—a forecast fulfilled when a magnitude 7.2 earthquake struck the volcano's south flank in November 1975, 15 months after Swanson and his colleagues had submitted their paper for publication.

Our map depicts the Hilina and other fault systems of Kīlauea as shown by Wolfe and Morris (1996a). We make a few small changes, however, positioning the fault within the escarpment near Keanabihopa instead of at the escarpment's foot (fig. 42). The escarpment is gullied deeply enough that the seaward limit of the upthrown block is exposed. The geomorphic escarpment has advanced seaward beyond that limit because young lava flows mantle the slope faster than the faults can extend upward. Placing the fault as the foot of the slope, as has been done in the past, indicates escarpment retreat. Exposures in the gullies near Keanabihopa show that escarpment advance is operative. The distinction centers neither on fault occurrence nor magnitude of offset (incontestable) but instead on positional accuracy, which is improved by 100–200 m if our interpretation is correct.

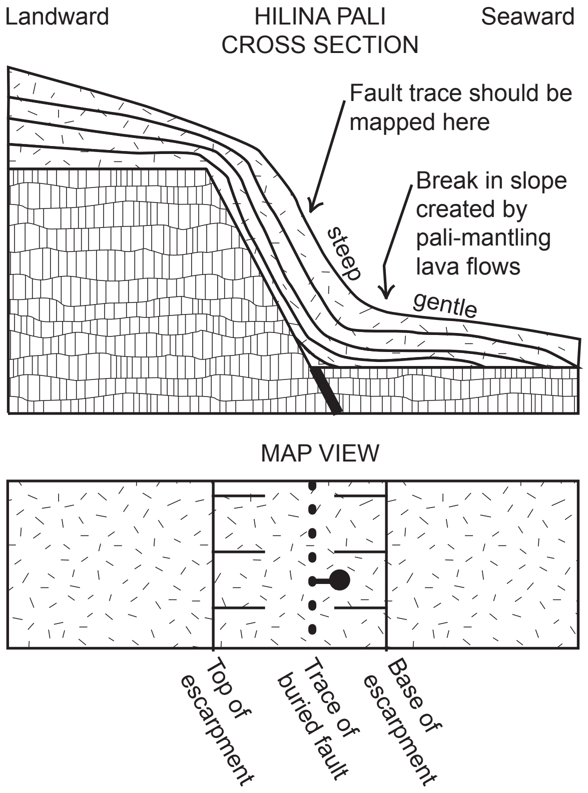


Figure 42. Escarpment-mantling lava flows and positioning of faults. Existing geologic mapping places buried trace of fault at foot of slope, whereas fault-block exposure indicates location within the escarpment. Positional difference is 100–200 m in plan view for Hilina fault system near Keanabihopa, south flank of Kīlauea.

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DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Qf	**Fill (Holocene)**—Manmade fill forming piers and harbor breakwaters along coastline
Qa	**Alluvium (Holocene and Pleistocene)**—Unconsolidated deposits of silt, sand, and gravel along streams and in valley bottoms. In some areas, grades upslope to talus and colluvium (unit Qtc). Where information is lacking, may include deposits more appropriately assigned to older alluvium (QTao) by virtue of greater consolidation or topographic settings not at grade with modern drainages
Qbd	**Beach deposits (Holocene)**—Sand and gravel worked by surf into unconsolidated strand-line deposits along coastline. Chiefly cream-colored and calcareous in composition, derived from comminuted coral, shells, and foraminifera. Locally includes substantial stream-derived volcanic detritus (“black sand”), notably on East Moloka‘i, East Maui, and Hawai‘i. Also contains minor sandstone, known in Hawai‘i as beach rock. Typically forms deposits parallel to coast, in contrast to alluvium, which extends up drainages perpendicular to coast. This criterion was used to demarcate beach deposits on those islands like Kaho‘olawe where source maps showed all deposits as alluvium (unit Qa)
Qdy	**Younger dune deposits (Holocene)**—Unconsolidated, mostly coralline sand forming eolian sheets and dunes. Found chiefly adjacent to beach deposits, but some reach inland as far as 2 km on Ni‘ihau and Kaua‘i and 7 km on western Moloka‘i. As thick as 15 m. On Kīlauea volcano, comprises black glassy and lithic sand reworked downwind onto the volcano’s southwest rift zone from 200–500-yr-old tephra deposits in the summit area
Qld	**Lake deposits (Holocene)**—On Ni‘ihau. Exceedingly fine-grained calcareous sand blown into intermittent Halāli‘i Lake and washed into beach ridges by the lake. Natural lakes are rare in Hawai‘i and exposures of lake deposits even rarer
Qlg	**Lagoon deposits (Holocene)**—Unconsolidated or poorly consolidated mud, silt, and sand. Found chiefly as mudflats in back-beach setting and some estuaries, where sediment from beach deposits and younger dune deposits (units Qbd and Qdy) is washed by water of brackish lagoons. May include marine marl or limey beds. On south-central Moloka‘i, includes reddish-brown mud “carried into the sea as a result of overgrazing in the past 150 [now 200] years” (Stearns and Macdonald, 1947). As a consequence, the Moloka‘i shoreline west of Kaunakakai has prograded substantially since the mapping by Stearns and Macdonald (1947), so that several nearshore areas shown on their topographic base map as ocean or mangrove swamp have now become fully emergent
Qls	**Landslide deposits (Holocene)**—Blocks of lava flows and admixed soil that have slid from steep valley walls and sea cliffs. Some deposits incorporated preexisting volcanic ash deposits, which locally contributes high proportion of matrix, as in the Wood Valley area on south flank of Mauna Loa (Stearns and Macdonald, 1946; Wolfe and Morris, 1996a)
Qtc	**Talus and colluvium (Holocene)**—Unconsolidated or poorly consolidated, poorly sorted silt, sand, and blocks that mantle slopes. Typically forms sheet or wedge-shaped deposits downslope from cliffy bedrock outcrops
Qt	**Tephra (Pleistocene)**—Ash deposits, commonly well sorted and well bedded. Includes primary and reworked tephra. Windblown glassy tephra on Ni‘ihau was derived from Lehua cone (in unit QTekt) and forms both primary and reworked deposits (Stearns, 1947). This ash, which weathers into tan powdery soil, is younger than about 0.4 Ma on basis of its position above lava flows of Kiekie Basalt with ages 0.40±0.14 and 0.47±0.06 Ma (table 1). On Lāna‘i, includes four small accumulations described as tuffaceous sandstone (Stearns, 1940c). These deposits, on southeast side of island, may have originated by downwind drift of ash from Haleakalā. Low on west flank of Mauna Kea (Island of Hawai‘i), comprises unconsolidated, crossbedded, very fine grained to fine grained dune sand and loess blankets interpreted as deposits of wind-reworked ash derived from eruptions at vents of the Laupāhoehoe Volcanics (units Qlcy, Qlc, Qlbc) (Wolfe and Morris, 1996a; Porter, 1997). Deeply weathered elsewhere on Island of Hawai‘i where encompassing the “Pāhala Ash,” a stratigraphic name applied to both primary and reworked tephra-fall deposits that originated from Kīlauea, Mauna Loa, Mauna Kea, and perhaps Kohala volcanoes (Wolfe

and Morris, 1996a). Younger tephra of Kīlauea has been mapped as units within encompassing volcanic formations; for example, Keanakākoʻi Ash Member is labeled as ash beds of age 200 to 500 yr within the Puna Basalt (unit Qpa4). So too for deposits on other islands; for example, widespread ash of the Hāna Volcanics that mantles the summit crater and southwest rift zone of Haleakalā Crater is contained within that formation (unit Qhnt)

QTao **Older alluvium (Pleistocene and Pliocene)**—Consolidated sand and gravel, some of it sufficiently lithified to warrant the designation "conglomerate." Chiefly well rounded and moderately sorted, but includes minor, poorly sorted colluvial deposits. Forms terrace deposits and thick valley fills now being incised by modern drainages. Less commonly found mantling ridges, as on western Molokaʻi. Similar sedimentary strata on Kauaʻi and Oʻahu, not widespread, are found interbedded with Pliocene volcanic rocks and customarily mapped as sedimentary members within associated volcanic formations there

Qdo **Older dune deposits (Holocene and Pleistocene)**—Lithified calcareous sand or eolianite. Forms dune fields inland of modern coastline. Ranges in lithification downsection, corresponding to deposits of increasingly older age. Youngest are typically weakly cemented cream-colored sand without capping caliche or red paleosol (Hearty and others, 2000), whereas older part includes eolian limestone in which pore space is completely replaced by calcite cement and individual sand grains have lost much original texture (Blay and Longman, 2001). On Oʻahu these deposits, encompassing 700 ha, have been assigned to the Bellows Field Formation of Lum and Stearns (1970) and Stearns (1970). On Kauaʻi, deposits exceed 28 m thickness and are mapped as the Māhāʻulepū Formation of Blay and Longman (2001). Most extensive is the 2,000-ha dune field that mantles the isthmus between West and East Maui, where dune-sand thickness is as great as 10–12 m. Holocene age assignment for youngest part stems from shells and bird bones that yielded radiocarbon ages roughly from 4,700 to 6,750 ^{14}C yr BP (for example, Hearty and others, 2000). A minimum age for the oldest part on Kauaʻi was obtained by dating an interbedded lava flow of the Kōloa Volcanics, which yielded a ^{40}Ar/^{39}Ar age of 375±4 ka (Hearty and others, 2005)

Qcrs **Calcareous reef rock and marine sediment (Pleistocene)**—Chiefly emerged coral reefs, but includes finely laminated lagoonal limestone. Reefs consist of coral heads and coralline algae cemented by a lime matrix (Stearns and Vaksvik, 1935, p. 169). Exposed subaerially on Oʻahu only, although similar deposits are found as active and extinct submarine reefs that ring all the islands

Qcbc **Calcareous breccia and conglomerate (Pleistocene)**—Poorly to moderately sorted sedimentary deposits of marine provenance, as inferred from the presence of coralline detritus. Deposits on Lānaʻi, which were subsequently assigned to the Hulopoʻe Gravel (Moore and Moore, 1984) were described thusly: calcareous conglomerate consisting of subangular and angular lava rock, pebbles, and cobbles in a matrix of coral, coralline algae, and shells, or their weathered products (Stearns, 1940b, p. 52). Found on the south and southwest sides of the island at altitudes mostly below 170 m (550 ft) (Stearns, 1940b), these deposits emplaced during one or several events between about 105 and 137 ka, on basis of ages from coral fragments in deposits and estimated age of the ʻĀlika 2 Slide (Moore and Moore, 1988; Rubin and others, 2000; McMurtry and others, 1999). Two sites at higher altitude were described, including crevice-filling fossiliferous marine limestone at 326 m (1069 ft) (Stearns, 1938). Molokaʻi deposits, which extend 2 km inland and to altitudes as high as 72 m, have a matrix of sandy lime mud cemented with calcite (Moore and others, 1994). Their carbonate clast component is mostly branching coral and coralline algae, with lesser gastropod shells, echinoid spines, and carbonate mud rip-up clasts, whereas the basaltic rock clasts range from angular to subrounded (A.L. Moore, 2000). On Niʻihau, two occurrences of fossiliferous limestone are shown by an an ×, mimicking the style on the source map (Stearns, 1947)

[In the following descriptions, many geologic notes for island stratigraphic features are drawn directly from bulletins of the Hawaiʻi hydrography publication series, and separate headnotes for each island's formations indicate the specific reference]

VOLCANIC AND INTRUSIVE ROCKS ON THE ISLAND OF NIʻIHAU

[Bracketed page numbers refer to Stearns (1947) and Macdonald (1947), which are the chief source for description of Niʻihau geologic map units]

Kiʻekiʻe Basalt (Pleistocene and Pliocene)—Moderately porphyritic and lesser nonporphyritic alkalic basalt

(Langenheim and Clague, 1987). Olivine, less than 1.5 mm across, is generally the only phenocryst [p. 46]. Some samples have sufficient olivine phenocrysts to be described as transitional to picrite [p. 49]. Commonly overlain by as much as 1 m of red lateritic soil [p. 22]. Thickness above sea level ranges from 6 to 90 m, but base of thicker sections not exposed because unit buries submarine bench 100 m deep [p. 19]. Fourteen radiometric ages range from about 2.28 to 0.35 Ma. Divided into:

QTekl	**Lava flows**—Pāhoehoe, commonly massive and nearly horizontal, in contrast to the thin-bedded flows in the Pānīʻau Volcanics [p. 14]. One ʻaʻā flow was erupted from the Puʻulehua cone, 1.3 km S86E of Nonopapa
QTekv	**Vent deposits**—Thin-bedded, highly vesicular scoria, commonly with spatter at the summit
QTekt	**Tuff**—Well-bedded vitric-lithic tuff, now mostly palagonitic, and tuffaceous breccia containing blocks of older tuff, lava, and reef limestone. Forms cones of Kawaihoa vent at southern tip of Niʻihau and on Lehua island, 1 km north of Niʻihau. Upper parts of cones contain subaerially deposited consolidated ash. Thinner deposits elsewhere on northern Niʻihau, the larger two at mouth of Keanauhi Valley and north edge of island. Geographic relation of these thinner deposits to vent location unknown
	Pānīʻau Basalt (Pliocene and Miocene)—Chiefly tholeiitic basalt. Aphyric to moderately porphyritic, with olivine phenocrysts 1–5 mm and sporadic augite to 4 mm [p. 42]. Total exposed thickness 390 m. Radiometric ages range from about 4.68 to 6.30 Ma (table 1). The large analytical error associated with the oldest age and the lack of other ages older than about 5.54 Ma suggests that the exposed sequence is entirely younger than 6 Ma. Vent marked by plug at Kaʻeo hill was retained in the Pānīʻau Basalt by Langenheim and Clague (1987) but described by them as belonging to postshield-stage volcanism, on the basis of unpublished chemical analyses. Two samples from that plug yielded ages of 4.67±0.08 and 5.15±0.11 Ma (table 1), indistinguishable from ages obtained elsewhere in the Pānīʻau. No lava flows of postshield origin have been mapped separately. Divided into:
Tpl	**Lava flows**—Thin-bedded, vesicular ʻaʻā and pāhoehoe [p. 18], tholeiitic in composition. Includes a few beds of altered vitric basaltic tuff, the thickest of which is 1.5 m and traceable for 3 km [p. 18]
Tpi	**Intrusive rocks**—Dikes 0.2–5 m wide. Some are vesicular, but most are dense and cross jointed [p. 18]. Two small plugs mapped near east tip of island and another at Kaʻeo hill. Kaʻeo plug has alkalic basalt composition

VOLCANIC AND INTRUSIVE ROCKS ON THE ISLAND OF KAUAʻI

[Bracketed page numbers refer to Macdonald and others (1960), which is the chief source for description of Kauaʻi geologic map units]

	Kōloa Volcanics (Pleistocene and Pliocene)—Slightly porphyritic and aphyric basanite. Olivine typically is only phenocryst and is smaller than 2 mm across, but clinopyroxene is reported from some localities (Reiners and others, 1999). Unit found chiefly in unconformable contact with underlying volcanic units. Thickness in most exposures rarely exceeds 240 m. A reported "exposed thickness" of 640 m (2100 ft) in east wall of Hanalei River valley [p. 53] must be in error, since topographic relief there is no greater than 280 m (920 ft). Thickness in Līhuʻe basin is at least 270 m in Northeast Kilohana monitoring well (fig. 8, well NEK) and may exceed 300 m in Hanamāʻulu monitoring well (fig. 8, well H) if the lower 36 m of alkali basalt there is part of the unit. Includes sparse dikes and plugs. Sedimentary interbeds mapped separately in the Palikea Breccia Member of the unit. Divided into:
QTkol	**Lava flows**—ʻAʻā and lesser pāhoehoe [p. 60]
QTkov	**Vent deposits**—Cinder and spatter that form cones. Some rest on small lava shields [p. 68–70]
QTkot	**Palagonitic tuff**—Gray to brown palagonitized vitric ash with lesser bombs and bomb fragments of basanitic lava. Contains blocks as large as 0.5 m of lava and reef limestone fragments. Forms large near-shore vent of Kīlauea Point, characteristic of eruptions that encountered near-surface water [p. 70–71]
QTkoa	**Ash**—Ash and cinder beds. Mapped separately only for three small exposures on northeastern part of island
QTkoi	**Intrusive rocks**—Oligoclase gabbro plug upslope of Kalāheo and dike near the Manuhonohono vent west of Kōloa town. Other dikes too small to map were described [p. 74], as were the possible occurrence of two

	additional plugs on the basis of float found in streams
QTkop	**Palikea Breccia Member**—Sedimentary breccia and conglomerate, derived chiefly from erosion of the Waimea Canyon Basalt but also of Kōloa Volcanics locally. Thickness 210 m at type section in Palikea Ridge [p. 75]. Underlies and interbedded with lower part of the Kōloa Volcanics mainly along the east face of the Waiʻaleʻale Range and in the larger valleys stemming from it. Age probably Pliocene and Pleistocene, but age span unknown. A Koloa Volcanics lava flow with age of 2.59±0.06 Ma (Clague and Dalrymple, 1988) in Wainiha River valley may overlie some part of the Palikea Breccia. Shown queried for four exposures of well-cemented conglomerate of uncertain age in Honopū and Nuʻalolo Valleys along the Nāpali coast
	Waimea Canyon Basalt (Pliocene and Miocene(?))—Comprises all rocks of Kauaʻi's major shield volcano, including thin-bedded flank lava flows, caldera-filling lava flows, lava that fills a graben possibly related to caldera growth, sedimentary interbeds, and dikes and sparse sills. Composition chiefly tholeiitic basalt, but upper parts of caldera- and graben-filling sequence include minor hawaiite and mugearite. Age of Nāpali Member is late Miocene(?) and Pliocene, on basis of radiometric ages ranging from 5.1 to 4 Ma. (Range of analytical error allows that some lava flows could be older than the 5.3-Ma Miocene-Pliocene age boundary.) Other members are Pliocene in age. Divided into:
	Makaweli Member (Pliocene)—Tholeiitic and lesser alkalic basalt or hawaiite that fills graben adjacent to Olokele caldera. Divided into:
Twml	**Lava flows**—ʻAʻā greatly predominates over pāhoehoe [p. 46]. Slightly porphyritic, with olivine phenocrysts less than 3 mm across. Minor picrite and aphanitic basalt.
Twmv	**Vent deposits**—Cinders and scoria that form cone in Nāwaimaka Stream gorge. Another mapped occurrence of cinders was thought to have been washed or blown into position from Olokele caldera source [p. 46]
Twma	**Ash**—Forms beds as thick as 1 m interbedded among lava flows. Several are described by Macdonald and others (1960), but only one found on their map and depicted on our rendition—a bed in the east wall of Waimea Canyon
Twmm	**Mokuone Breccia Beds**—Comprises talus and conglomerate. Conglomerate is interbedded with lava flows of the unit. Poorly sorted talus breccia found at contact of unit with older members of the Waimea Canyon Basalt
	Hāʻupu Member (Pliocene)—Nearly flat-lying thick lava flows and underlying breccia. Found only in area of Hāʻupu peak, southwest of Līhuʻe [p. 40–41]. Divided into:
Twhl	**Lava flows**—Thick vesicular olivine basalt and picrite closely resembling lava flows in the Olokele Member. No published chemical analyses. Undated but younger than underlying Nāpali Member, which in this area is probably earliest Pliocene in age
Twhb	**Breccia**—Poorly sorted, indurated breccia. Interpreted by Macdonald and others (1960) as talus that mantles wall of a presumed Hāʻupu caldera [p. 40], but may be landslide deposit related to origin of the Līhuʻe basin structural trough
	Olokele Member (Pliocene)—Chiefly tholeiitic basalt lava flows except in upper part, where more alkalic flows, including sparse hawaiite and mugearite, occur. Thickness in excess of 800 m; base nowhere exposed [p. 32]. Contact with adjacent Nāpali Member, where exposed, is along steep faults, some of which were mantled by ancient talus breccia prior to emplacement of buttressing lava flows. Divided into:
Twol	**Lava flows**—Pāhoehoe and ʻaʻā. Tend to be thicker—about 15 m—than lava flows in adjacent Nāpali Member, and this distinction is a criterion for defining the caldera-filling nature of the unit
Twov	**Vent deposits**—Cinder cones (two mapped) and, at Koali hill, a small lava shield [p. 39]. Most eruptions from fissure vents that built no substantial edifices [p. 39]
Twob	**Breccia**—Angular to subangular indurated breccia forming moderately to steeply dipping depositional wedges less than 15 m in thickness [p. 34–37]. Originated as caldera wall-mantling deposits; exposed today along fault that bounds the Olokele caldera
	Nāpali Member (Pliocene and Miocene(?))—Chiefly lava flows. Pyroclastic rocks form less than 1 percent

	of unit [p. 26]. Almost entirely tholeiitic basalt in composition. Divided into:
Twnl	**Lava flows**—Pāhoehoe and ‘a‘ā approximately equal in abundance [p. 26]. Thin beds of ash and reddish ashy soil found between flows in many places, but beds more than a few millimeters thick are rare [p. 29]
Twnv	**Vent deposits**—Cinder and scoria found in segments of cinder cones exposed by erosion. Includes some breccia deposits that may be pit-crater fillings [p.30]. Some vents mapped on basis of thick dense lava thought to be crater fill; that at Pu‘u Ka Pele, on west rim of Waimea Canyon, is well crystallized, notably coarse-grained olivine basalt [p. 31]
Twi	**Intrusive rocks**—Basaltic dikes and a few sills. No intrusive bodies larger than dikes have been found [p. 49]. Numerous dikes and the few sills are mapped in the Nāpali Member, but only 29 dikes were mapped in the Olokele and five in the Makaweli. Most of those in the Nāpali Member, mapped in Waimea Canyon and along Nāpali coast, trend chiefly south-southwest [p. 50], the basis for a postulated south-southwest rift zone [p. 49]. One sill at least 17 m thick is known from Koai‘e canyon, about 0.5 km above confluence with Kawaiiki stream

VOLCANIC AND INTRUSIVE ROCKS ON THE ISLAND OF O‘AHU

[Bracketed page numbers refer to Stearns and Vaksvik (1935), which is the chief source for description of O‘ahu geologic map units. Mapping in Wai‘anae Range is newly presented here (J.M. Sinton)]

	Honolulu Volcanics (Pleistocene)—Lava flows, vent deposits, and some wind-drifted tephra-fall deposits. Comprises a sequence of isolated, informally named lava-flow units (and their vents) or, where no lava issued, only a named vent (Stearns and Vaksvik, 1935; Winchell, 1947; Clague and Frey, 1982). Vent deposits form cones ranging from 10 to 150 m high. Informal names are coded in the GIS database for this map but, with two exceptions, are not described separately. Age is Pleistocene, and prior Holocene estimations are discounted, on basis of radiometric ages discussed in explanatory pamphlet to this map. Geomorphologic evidence is consistent with assessment of an entirely Pleistocene age. Divided into:
	Deposits from Koko fissure system—Consists of:
Qokl	**Lava flows**—Includes informally named Kalama and Kaupō flows of Stearns and Vaksvik (1935) or Winchell (1947). Some units contain lherzolite xenoliths
Qokt	**Tuff**—Gray to brown bedded crystal-lithic-vitric tuff and lapilli tuff. Includes Koko Crater, Koko Head, and Mānana Island. The alignment—from Koko Head to Manana Island—of tuff and spatter deposits implies cogenetic eruptions along a northeast-trending fissure referred to as the Koko fissure system
Qoks	**Spatter**—Red to brown coarse cinder and spatter
	Deposits from Tantalus Peak and Sugar Loaf vents—Consists of:
Qotl	**Lava Flows**
Qott	**Tuff**—Bedded black cindery ash and lapilli. Ejected during strombolian eruptions. Blankets large area southwest of vents, likely owing to position of vents on high ridge and subsequent deflection of eruptive plume by trade winds
Qol	**Lava flows**—Columnar jointed massive lava and flows typically described as ‘a‘ā. Thickness generally 15–30 m where well exposed. Some flows (for example, Kalihi and Pali) contain lherzolite xenoliths
Qov	**Cinder vent deposits**—Cinder, spatter, and ash that form cones
Qobr	**Breccia**—Blocks of extrusive and intrusive basalt in fine-grained matrix. Typically structureless. Thought to fill throats of explosive vents (Stearns, 1939)
Qot	**Tuff cone deposits**—Gray to brown bedded tuff, lapilli tuff, and tuff breccia. Includes prominent vents such as Diamond Head, Punchbowl, and Salt Lake crater. Accidental lithic clasts include blocks of Ko‘olau Basalt, limestone ripped from reef deposits, and, locally, xenoliths of pyroxenite, garnet pyroxenite and lherzolite. Interpreted as hydromagmatic in origin, in contrast to cinder-vent deposits, which likely involved little entrainment of ground or marine water during their eruptions

Koʻolau Basalt (Pleistocene(?) and Pliocene)—Aphyric to porphyritic basalt, entirely tholeiitic in composition. Phenocrysts are olivine and plagioclase, rarely with clinopyroxene [p. 93] and orthopyroxene. Age certainly Pliocene and possibly Pleistocene owing to analytical error associated with youngest radiometric ages and their placement close to the 1.81-Ma Pliocene-Pleistocene boundary. Divided into:

QTkl **Lava flows**—ʻAʻā and lesser pāhoehoe; proportions estimated to be 60 percent ʻaʻā, with pāhoehoe thought to be more abundant near the crest of the Koʻolau Range [p. 93]

QTkt **Vitric and lithic tuff**—Vitric tuff is primary magmatic material, now fully devitrified, that originated as medial or distal fallout from small vents. Lithic tuff includes many angular rock fragments and is thought to have formed by phreatomagmatic eruptions [p. 94]. Thickness among the tuff beds commonly varies greatly over short distances and ranges from a few centimeters to 3 m. Two occurrences of vitric tuff were recognized as erosional relicts of cinder cones underlain and overlain by lava flows within the Koʻolau Basalt. One of these, in the Nuʻuanu Pali 2 km south of Waimānalo (northeast slope of Puʻu o Kona), lies at about 460 m altitude and is riddled with dikes; the other, near Kaimukī, was described only in text [p. 94]

QTkdc **Dike complex**—Zone of abundant diking, corresponding to the denuded main rift zone of the Koʻolau volcano [p. 95]. Dikes constitute more than 40 percent of exposed rock over much of area, at expense of lava flows (unit QTkl) (Walker, 1987). Locally forms a sheeted complex where dikes have split existing dikes or intruded along their margins to create essentially 100 percent of exposed rock

QTki **Intrusive rocks**—Dikes similar in composition to lava flows (unit QTkl). Width ranges from a few centimeters to 3.6 m but averages 0.6–1.5 m. Mapped chiefly to indicate strays that lie outside dike complex [p. 97]; some shown in the dike complex give sense of average trend, as depicted on source map of Stearns (1939). Across the Koʻolau Range, northwest-striking dikes predominate, defining the structural grain of the volcano's principal rift zone. A secondary minor trend S30W may be inferred from dikes in the head of Pālolo Valley and may indicate a secondary rift zone of that orientation [p. 97]

Kailua Member—Amygdaloidal basaltic lava flows and feeder dikes. Was once thought part of separate volcano that predated the Koʻolau, but later recognized as highly altered rocks of a caldera complex in the core of the Koʻolau volcano (Stearns, 1940a, p. 49). Divided into:

QTkkl **Lava flows**—ʻAʻā and pāhoehoe. Joints and vesicles filled with quartz, zeolite, and other secondary minerals. Clinker in ʻaʻā lava has been cemented into hard breccia [p. 88]. Age is Pliocene, given the depth of erosion needed to expose the sequence and the Pliocene age for all but youngest part of Koolau Volcanics

QTkkdc **Dike complex within Kailua Member**—Similar to dikes of the Koʻolau dike complex (unit QTkdc), from which they differ not so much in age as in extent of hydrothermal alteration (Stearns, 1940a, p. 49). Retained on this geologic map because the extent of the Kailua caldera is commonly drawn on the basis of the extent of the mapped dike complex and also because the alteration has greatly reduced the unit's permeability, which likely has important ground-water implications. May include Pleistocene rocks owing to intrusive nature for much of sequence

QTkkbr **Breccia deposits**—Angular to subangular basalt clasts in a fragmental matrix. Cemented and highly zeolitized; found in the eroded core of the Koʻolau volcano. Interpreted as deposits that fill pit craters associated with an ancient caldera [p. 97]

Waiʻanae Volcanics (Pliocene)—Comprises all volcanic rocks of the Waiʻanae Range. Stratigraphic members assigned on basis of mapping and nomenclature of Sinton (1987), Presley and others (1997), and this map. Divided into:

Kolekole Member—Alkali basalt lava flows and cinder deposits. Phenocrysts mainly olivine 1–3 mm across (Presley and others, 1997). Commonly found are gabbro, pyroxenite, and dunite xenoliths as large as 10 cm across. Pyroxene and plagioclase xenocrysts are locally abundant, especially at Puʻuokapolei. Possesses normal-polarity magnetization throughout and is younger than about 3 Ma (Presley and others, 1997). Divided into:

Talel **Lava flows**—ʻAʻā

Talev **Vent deposits**—Cinder and spatter that form cones. Some deposits, like those at Kolekole Pass, are deeply weathered, structureless, and of uncertain relation to specific vent locations

Talec	**Debris flows**—Poorly sorted, moderately indurated sedimentary deposits. Includes Kolekole Conglomerate of Stearns (1946), which is overlain by lava flows of Kolekole Member. Other occurences are conglomerate cut by dikes at end of ridge south of Schofield valley and debris-flow deposits along the crest of the northern Waianae Range, all of which are likely to have formed before cessation of volcanic activity
	Pālehua Member—Aphyric hawaiite with lesser porphyritic basalt, alkali basalt, and mugearite. Maximum thickness 250 m, near Palikea in southern part of range. Divided into:
Tapl	**Lava flows**—Characterized by ʻaʻā 2–30 m thick with massive centers and thin rubbly tops and bases [p. 75]. Tends to form high cliffs of conspicuously light color in exposures near the top of the western slope of the Waiʻanae Range (Macdonald, 1940a, p. 78)
Tapv	**Vent deposits**—Cinder and spatter that form cones
	Kamaileʻunu Member—Tholeiitic and alkalic basalt and hawaiite that form a caldera-filling sequence and adjacent flanking strata. Generally possesses lower dips than underlying Lualualei Member in the central part of the range. Includes lava flows with normal- and reversed-polarity magnetization. Equivalent to middle member of Waiʻanae volcanic series of Stearns and Vaksvik (1935). Age ranges from 3.5 to 3.1 Ma (McDougall, 1964; McDougall and Aziz-ur-Rahman, 1972; Doell and Dalrymple, 1973; Laj and others, 1999; and Guillou and others, 2000). Divided into:
Takl	**Lava flows**—Pāhoehoe and lesser ʻaʻā, similar to Lualualei Member (unit Tall) but with more ʻaʻā than the Lualualei. Almost always contains plagioclase phenocrysts, which are mostly lacking in the Lualualei Member
Takv	**Vent deposits**—Chiefly cinder
Takbr	**Breccia**—Angular to subangular fragments of basaltic lava flows in a sedimentary sandy matrix. Generally well indurated. Interpreted as talus that accumulated against cliffs of caldera wall (Macdonald and others, 1983, p. 427)
Takmk	**Mauna Kūwale Rhyodacite Flow**—Hornblende-biotite rhyodacite lava flow. Phenocrysts as large as 1 mm of plagioclase (20 percent), hornblende (12 percent), biotite (8 percent), and hypersthene (1 percent) (Macdonald, 1940a, p. 82). Weathers to conspicuous white outcrops. Ranges in thickness from 40 to 110 m
Takil	**Icelandite lava flows**—ʻAʻā and blocky flows 5–15 m thick of icelandite (Al-poor, Fe-rich andesite) composition
Takiv	**Icelandite vent deposits**—Coarse- to medium-grained scoria
	Lualualei Member—Aphyric and porphyritic olivine basalt. Includes rare tuff beds distributed sporadically. All parts possess reversed-polarity magnetization and are older than 3.5 Ma (Guillou and others, 2000). Divided into:
Tall	**Lava flows**—Predominantly pāhoehoe, with minor ʻaʻā [p. 68]. Individual flows range in thickness from 1.5 to 22 m. Lava flows with about 50 percent olivine phenocrysts are present in Puʻu o Hulu Ridge and a few other places [p. 68]
Talv	**Vent deposits**—Cinder cone exposed in south side of Puʻu Heleakalā
Tai	**Intrusive rocks**—Olivine basalt dikes a few centimeters to 5 m thick; most are fine grained and resemble lava flows in hand sample. Microgabbroic texture characterizes a few dikes large enough to have cooled slowly (Macdonald, 1940a, p. 73). Also includes medium- to coarse-grained intrusion of plagioclase-rich diorite in Kauaʻōpuʻu Ridge. Comprises feeders for lava flows and vents of all four members of the Waiʻanae Volcanics. Dikes in the northern part of the range oriented mainly 305° and define a well-developed northwest rift zone; whereas elsewhere dike trends are more typically radial (Zbinden and Sinton, 1988)

VOLCANIC AND INTRUSIVE ROCKS ON THE ISLAND OF MOLOKAʻI

[Bracketed page numbers refer to Stearns and Macdonald (1947), which is the chief source for description of Molokaʻi geologic map units]

Qppl	**Kalaupapa Volcanics (Pleistocene)**—Porphyritic pāhoehoe lava flows that built the broad Kalaupapa

Peninsula at base of the great windward cliff of East Moloka‘i. Ranges in composition from tholeiitic to alkalic basalt (four analyses) and basanite (two analyses). Age is middle or late Pleistocene on basis of three K–Ar ages ranging from about 0.57 to 0.34 Ma (Clague and others, 1982). Shown separately is:

Qppv **Vent deposits**—Low lava cone and its surmounting Kauhakō Crater and a cinder cone plastered on base of main Moloka‘i escarpment

Qmv **Tuff of Mokuho‘oniki cone (Pleistocene)**—Palagonitic basaltic ash, spatter, sparse lava flows, and a few dikes that built Mokuho‘oniki and Kanahā, two small islands 1.6 km off the eastern end of Moloka‘i. The only petrographic description available, perhaps representative of the deposits as a whole, is for a picritic dike that contains about 30 percent olivine phenocrysts as large as 1 mm [p. 109]. Lithic fragments and coralliferous limestone commonly found as blocks in the bedded ash. Deposited chiefly by hydromagmatic eruptions, indicating substantial entrainment of water—probably sea water—into the shallow eruptive column. Commonly assigned an age similar to that of the Kalaupapa Volcanics [p. 109], although the unit is undated and known only to be younger than upper member of the East Moloka‘i Volcanics; that is, younger than about 1.3 Ma

East Moloka‘i Volcanics (Pleistocene and Pliocene)—All volcanic rocks of the East Moloka‘i topographic edifice, exclusive of Kalaupapa Peninsula. Divided into:

Upper member (Pleistocene)—Composition ranges from basanite to benmoreite, with a single trachyte dike. Nonporphyritic and porphyritic lava occur about equally [p. 100]. Phenocrysts chiefly feldspar, 1–2 mm and as much as 10 percent in abundance. Olivine much less common but where present is less than 2 mm across and less than 5 percent. Upper member lacks mapped intrusive rocks. Age ranges from about 1.45 to 1.31 Ma, on basis of three K–Ar ages (McDougall, 1964). Consists of:

Qemul **Lava flows**—‘A‘ā ranging from 6 to 30 m thick. Pāhoehoe is rare [p. 100]. Flows commonly separated by ashy soil beds. Lava flows weather medium to light gray, producing a distinct light-on-dark color contrast where contact is exposed with underlying darker-gray lava flows of the lower member of the East Moloka‘i Volcanics

Qemuv **Vent deposits**—Cinder and spatter that forms bulky cones, the eruptive sites for the lava flows of the upper member. Shown queried are deposits east of Wailau, where two hills have geomorphic form of cinder cones but no exposures were found despite searching by Stearns and Macdonald (1947)

Qemud **Domes**—Extrusions of lava that likely piled up over vent sites. Some are found within the craters of vent deposits

Lower member (Pleistocene and Pliocene)—Tholeiitic and alkalic basalt. Age near top is as young as 1.52 Ma (McDougall, 1964; recalculated using modern decay constants) for a sample from the type locality along the trail to Kalaupapa Peninsula. At the east end of the island, a sample collected about 300 m beneath the top of the unit yielded an age of 1.75 Ma (Naughton and others, 1980). Consists of:

QTemll **Lava flows**—Pāhoehoe and ‘a‘ā of aphyric to porphyritic olivine basalt. Youngest flows include lava rich in olivine and augite phenocrysts

QTemlv **Vent deposits**—Cinder and spatter cones

QTemlcc **Caldera complex**—Thick lava flows, numerous intrusive plugs, and talus and fault breccias cut by dike swarms. Greater thickness of individual flows due to ponding, in contrast to thinner flows elsewhere in the East Moloka‘i sequence. Rocks of caldera complex characterized by substantial secondary mineralization, occurring as vesicle linings and amygdules of calcite, quartz, and chalcedony, and irregular nodules of quartz and chalcedony. Many lava flows partly altered to smectite-group clay minerals

QTemli **Intrusive rocks**—Dikes, steep to vertical in inclination. Not mapped separately are stocks and plugs within the caldera complex (unit QTemlcc)

West Moloka‘i Volcanics (Pleistocene and Pliocene)—Tholeiitic basalt and sparse hawaiite and mugearite, the latter two compositional types thought limited to lava flows emplaced high in the volcanic sequence. Unusual is the abundance of nonporphyritic lava flows when compared to shield-building flows from other Hawaiian volcanoes [p. 105]. Porphyritic lava contains plagioclase mostly less than 2 mm and less abundant olivine phenocrysts. Augite phenocrysts are present in a few rocks. Hypersthene is rarely a phenocryst, found in only three samples [p. 108]. Divided into:

QTwmw **Wai‘eli and other late lava flows of West Moloka‘i**—Informally named unit whose extent was shown only on page-size figure [p. 106]. Locally underlain by red ashy soil 0.2–1.2 m thick, whereas flows of the main sequence (unit QTwml) lack intervening soil horizons. Includes hawaiitic lava from Wai‘eli vent (Potter, 1976) and Ka‘a (Sinton and Sinoto, 1997). Other analyzed samples range in composition from alkalic basalt to hawaiite (Clague, 1987a; J.M. Sinton, unpub. data). Massive lava at Ka‘eo, which is included in the late lava sequence, is a tholeiitic basalt (Sinton and Sinoto, 1997). Three samples studied by Clague (1987a) range in age from 1.80 to 1.73 Ma. Likely much or all of the Wai‘eli and other late lava flows are products of postshield-stage volcanism, but our understanding remains fragmentary about the areal, temporal, and compositional range of these products and their relation to postshield activity. Several late lava flows were quarried by early Hawaiians, giving rise to the local name Kalua ko‘i—the adze pit—for the west end of West Moloka‘i. Shown separately are:

QTwmwv **Vent deposits**—Cinder and spatter cones

QTwml **Lava flows**—Pāhoehoe and ‘a‘ā that form the main volcanic sequence on West Moloka‘i, notably thin bedded (less than 0.6 m) at many localities

QTwmv Vent deposits—Cinder and spatter cones

QTwmi Intrusive rocks—Dikes

VOLCANIC AND INTRUSIVE ROCKS ON THE ISLAND OF LĀNA‘I

[Bracketed page numbers refer to Stearns (1940b), which is the chief source for description of Lāna‘i geologic map units]

Lāna‘i Basalt (Pleistocene)—Tholeiitic basalt. Olivine phenocrysts, 1–3 mm in diameter, are found in about 40 percent of flow sequences; plagioclase is a less common phenocryst, and pyroxene phenocrysts are seen only rarely. Divided into:

Qll **Lava flows**—Pāhoehoe and ‘a‘ā, the former more abundant in the summit areas, the latter along the periphery of the island. Individual flows range in thickness from 0.3 to 30 m, average about 6 m. Massive lens-shaped columnar-jointed flows seen in Kaholo cliff and cliff east of Mānele are crater-filling lava accumulations, not sills [p. 27]

Qlv **Vent deposits**—Lava cones with subordinate amounts of spatter and cinder [p. 29]; no cones existing exclusively of cinders were found

Qlcr **Filled craters**—Pit craters originating by collapse and infilled by later lava flows. They may be marked by ponded flows, or steep, nonconformable contacts may be exposed, some with talus breccia onlapped by the infilling lava flows [p. 30–31]

Qlbr **Breccia in craters**—Small patches of breccia filling eroded pit craters. Possibly related to northwest rift zone, as the unit forms a northwest-trending alignment defined by nine separate exposures along Wai‘alalā Gulch, just east of the central part of the island

Qli **Intrusive rocks**—Dikes, steep to vertical in orientation and ranging from 0.15–1.5 m in width. As on the source map, those dikes exposed only in sea cliffs have been extended inland to give them sufficient length to show on the map

VOLCANIC AND INTRUSIVE ROCKS ON THE ISLAND OF KAHO‘OLAWE

[Bracketed page numbers refer to Stearns (1940c) and Macdonald (1940b), which are the chief sources for description of Kaho‘olawe geologic map units]

Qyvk **Young volcanic rocks of Kaho‘olawe (Pleistocene)**—Dikes and isolated patches of cinder exposed in the wall of Kanapou Bay. Tholeiitic basalt. Some dikes cut older alluvium. One view of relative age was implied in a description of some cinder deposits, “the cinders are easily eroded and lie on such a steep cliff that they obviously could not persist long.” [p. 143]. Recent dating and sparse magnetic sampling suggests an age about 0.9–1.0 Ma (Sano and others, 2006). Considered products of rejuvenated-stage volcanism by Langenheim and Clague (1987) and Fodor and others (1992), but we find them the last gasp of late shield-postshield volcanism (Sano and others, 2006)

Kanapou Volcanics (Pleistocene)—All volcanic rocks of Kahoʻolawe exclusive of the four small occurrences assigned to young volcanic rocks of Kahoʻolawe (unit Qyvk). Comprises lava flows and vent deposits ranging in composition from tholeiitic basalt to hawaiite, including those that belong to the conceptual “shield” and “postshield” stages of Hawaiian volcanism. In original mapping (Stearns, 1940c), lava flow units were divided on basis of age relative to formation and filling of a caldera exposed at Kanapou Bay. Divided into:

Qnppl **Postcaldera lava flows**—Lava flows typically less vesicular than precaldera flows and thicker, even where not ponded. Unit is thickest where it fully filled the caldera; forms a thin cap over most of the rest of the island. Many flows are moderately porphyritic, with olivine, augite, and plagioclase, and “they form so much of the surface that one gains the impression at first that all the rocks of Kahoʻolawe are augite, olivine, feldspar ʻaʻā porphyries.” [p. 140]. Hypersthene was reported in four of seven postcaldera samples analyzed by Macdonald [p. 156]. Considered products of postshield-stage volcanism by Langenheim and Clague (1987) and postshield- or late-shield-stage volcanism by Fodor and others (1992)

Qnppv **Postcaldera vent deposits**—Chiefly cinder cones, but includes lava domes or small shields of Makika and Keālialalo. The cones locally contain thin interbedded lava flows

Qnpcl **Caldera-filling lava flows**—Thickness of individual flows ranges from 3 to 60 m. Many flows exhibit columnar jointing. Resemble precaldera lava flows petrographically but tend to be slightly coarser grained owing to greater flow thickness. Shown as fault bounded, in keeping with source maps (for example, Stearns, 1940c, his fig. 25) but may lie partly or entirely in buttress unconformity with precaldera lava flows (unit Qnpl)

Qnpct **Tuff bed in caldera fill**—Vitric tuff 10–15 m thick. Becomes finer in texture north and south of its midpoint. Other tuff beds in caldera fill are too thin and discontinuous to be depicted on source map (scale 1:62,500)

Qnpl **Precaldera lava flows**—Thin-bedded, slightly porphyritic and nonporphyritic ʻaʻā and lesser pāhoehoe [p. 160]. Olivine and plagioclase phenocrysts are widespread but not abundant; clinopyroxene phenocrysts are rare. Individual flows range in thickness from 2 to 30 m and average about 8 m. Includes sparse beds of vitric tuff less than 0.3 m in thickness

Qnpv **Precaldera vent deposits**—Small lava mounds, tens of meters across, surmounted by cinder and spatter [p. 169]

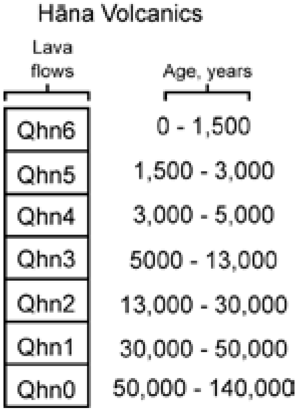
Qnpi **Intrusive rocks**—Dikes, steep to vertical in orientation and chiefly less than 0.5 m wide

VOLCANIC AND INTRUSIVE ROCKS ON THE ISLAND OF MAUI
HALEAKALĀ VOLCANO

[Bracketed page numbers refer to Stearns and Macdonald (1942). Mapping includes substantial new work presented here (D.R. Sherrod)]

Hāna Volcanics (Holocene and Pleistocene)—Lava flows, vent deposits, and sparse debris-flow deposits. Aphyric lava flows predominate, but slightly to highly porphyritic rocks are common. Olivine, 1–3 mm in diameter, is most common phenocryst. Clinopyroxene increases in proportion in more porphyritic rocks. Scant plagioclase phenocrysts (xenocrysts?), typically as large as 1 cm. Includes debris-flow deposits on Kaupō fan that originated by slope collapse early in Hāna time. Holocene and Pleistocene age is formally adopted herein, owing to numerous radiometric ages, the oldest of which indicate emplacement as early as 0.12 Ma (Sherrod and others, 2003). Divided into:

Lava flows (Holocene and Pleistocene)—Predominantly ʻaʻā lava flows, with minor pāhoehoe. Shown queried where abruptly terminated for three lava-flow sequences whose downslope extent is poorly known (one each in units Qhn0 and Qhn1 on upper west flank and another in unit Qhn4 on upper northeast flank). Divided on the basis of age according to the following matrix:



Hāna Volcanics

Lava flows	Age, years
Qhn6	0 - 1,500
Qhn5	1,500 - 3,000
Qhn4	3,000 - 5,000
Qhn3	5000 - 13,000
Qhn2	13,000 - 30,000
Qhn1	30,000 - 50,000
Qhn0	50,000 - 140,000

Qhnv	**Vent deposits (Holocene and Pleistocene)**—Scoria and spatter that form vent deposits, mainly cinder cones. Not divided by age
Qhnt	**Tephra deposits (Holocene and Pleistocene)**—Fallout tephra ranging from coarse to fine grained lapilli, ash, and crystals, deposited chiefly during downwind distribution from vent-building eruptions. Includes intervening thin beds reworked by slope wash. Individual beds generally less than 5 cm thick, but aggregate deposits are locally thicker than 10 m. Mapped where sufficiently extensive to blanket large areas completely; otherwise not shown separately
Qhni	**Intrusive rocks (Holocene and Pleistocene)**—Dikes. Sparsely exposed, owing to lack of erosion into Hāna Volcanics. Exposure in Haleakalā Crater results from small fault north of Halāli‘i that uncovered the dike and striated its east-facing surface
Qhne	**Explosion crater deposits (Pleistocene)**—Sandy blanket of gray lithic lapilli and coarse ash. Surrounds two craters at 2740 m (9000 ft) altitude along southwest rift zone. No known relation to volcanic vent, but may have formed by heating of perched water as magma rose to feed vents farther east or west. State of preservation suggests late Pleistocene age
Qkamd	**Kaupō Mud Flow (Pleistocene)**—Debris-flow deposits of breccia with clasts locally greater than 3 m across in a poorly sorted lithic-sand matrix. Older than 120 ka, the age of an overlying lava flow (in unit Qhn0). Mapped separately is:
Qkamc	**Conglomerate**—Sparse roundstone conglomeratic strata interbedded with debris-flow deposits
	Kula Volcanics (Pleistocene)—Aphyric to porphyritic lava flows, vent deposits, and intrusive rocks. Lower part ranges from hawaiite to mugearite with rare trachyte; upper part is more alkalic and includes basanite. Divided into:
Qkul	**Lava flows**—Chiefly ‘a‘ā; pāhoehoe is minor. Mapped separately is:
Qkuls	**Summit ankaramite**—Highly porphyritic ‘a‘ā lava flows. Informally named for exposures at and downslope from Summit Visitor Center in Haleakalā National Park. Erupted from a vent now eroded but near there, judging from abundance of dikes and sills in east slope of Pāka‘ao‘ao. Likely youngest Kula stratum on west flank. Age 0.214±0.020 Ma (2σ analytical error; Sherrod and others, 2003)
Qkuv	**Vent deposits**—Scoria and spatter that form cinder cones and sparse spatter ramparts
Qkui	**Intrusive rocks**—Mainly dikes similar in composition and mineralogy to lava flows in Kula Volcanics. A few stocks are exposed in western summit area of volcano
Qmnl	**Honomanū Basalt (Pleistocene)**—Pāhoehoe and ‘a‘ā lava flows. Surface exposures found along north and northeastern coast of East Maui and, near Ke‘anae, upslope along canyon walls to as high as 900-m altitude. Most of exposed sequence possesses reversed-polarity magnetization. Exposures in Haleakalā Crater, mapped as Honomanū Basalt by Stearns and Macdonald (1942), are now considered part of Kula Volcanics on basis of whole-rock chemical and isotopic analyses (Macdonald and others, 1983; West and Leeman, 1987). We made similar finding for those in walls of Kīpahulu Valley, which have normal-polarity magnetization and basanitic composition

WEST MAUI VOLCANO

[Bracketed page numbers refer to Stearns and Macdonald (1942), which is the chief source for description of West Maui geologic map units]

Lahaina Volcanics (Pleistocene)—Lava flows and vent deposits of basanitic composition. Aphyric. Erupted from four discrete vents, two active about 0.6 Ma and another two about 0.4 Ma (Tagami and others, 2003). Divided into:

Qlhl **Lava flows**—Thick ‘a‘ā flows

Qlhv **Vent deposits**—Cinders, spatter, and bombs

Honolua Volcanics (Pleistocene)—Lava flows, lava domes, vent deposits, and intrusive rocks. Unit is as thick as 230 m but averages 20 m. Mainly benmoreite with lesser trachyte. Divided into:

Qul **Lava flows**—‘A‘ā. Massive central parts are columnar jointed. Thickness generally ranges from 7 to 90 m but approaches 150 m thick near vents.

Qud **Domes**—Bulbous masses of lava, mostly extrusive but including some shallow intrusive necks. (An excellent example of a bulbous dome grading down to a dike only 8 m wide is found about 3.6 km east of Olowalu [p. 179]). Concentric jointing prominent on some domes

Quv **Vent deposits**—Bedded cinders similar in composition to lava flows. Some cinders surround and underlie lava domes, whereas those northwest of Olowalu have built a cone that lacks associated lava dome

Qui **Intrusive rocks**—Dikes ranging in width from 2.5 to 8 m

Wailuku Basalt (Pleistocene and Pliocene?)—Comprises the main mass of West Maui’s shield volcano, including thin-bedded flank lava flows, caldera-filling lava flows, and dikes and sparse sills. Composition chiefly tholeiitic basalt, but upper part contains some alkalic basalt and minor hawaiite. Age is formally revised herein, Pliocene (?) and early Pleistocene, to include the probable Pliocene strata, on basis of radiometric ages ranging from about 2 to 1.3 Ma (Sherrod and others, 2007). Divided into:

QTwl **Lava flows**—Thin pāhoehoe and ‘a‘ā

QTwv **Vent deposits**—Scoria and spatter of cinder cones.

QTwt **Tuff**—Thin beds interspersed among lava flows, forming less than 1 percent of Wailuku Basalt [p. 163]. More numerous in upper part of lava-flow unit (QTwl) and closer to rift zones. Generally mappable only on arid southwest side of volcano.

QTwpc **Pit crater deposits**—Lava flows, breccia, talus, and slope wash that define the extent of collapse craters that formed along rift zones during Wailuku time. Lava flows are compositionally similar to those elsewhere in Wailuku Basalt but are found in buttress unconformity with adjacent deposits. Sedimentary units, also in unconformable contact, are well indurated and composed of Wailuku Basalt fragments

QTwlc **Lava cone**—Numerous, very thinly bedded lava flows thought to define near-vent accumulation. Mapped only along south coast

QTwp **Phreatic explosion debris**—Thin beds of lithic breccia containing blocks of Wailuku Basalt lava in a gray comminuted matrix [p. 172]. Deposits thin rapidly seaward, indicating explosions from vents in or near south end of summit caldera [p. 172]

QTwdc **Dike complex**—Closely spaced dikes. Individual dikes mostly less than 1 m wide, but abundance sufficiently great to exceed the area exposed by intervening wall rock

QTwcc **Caldera complex**—Firmly cemented vent breccia, lava flows, indurated talus, and pyroclastic deposits—an amalgam described as “the whole gamut of rocks” by Stearns and Macdonald (1942, their map-plate description). Characterizes a sequence of lithologically diverse volcanic products that individually are too restricted in their extent to be mapped separately [p. 166]. Interpreted as the accumulation of material in main summit caldera of West Maui volcano

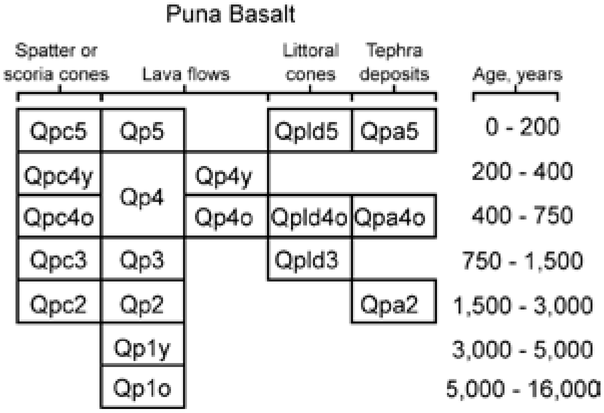
QTwi **Intrusive rocks**—Basaltic dikes and sparse plugs

VOLCANIC AND INTRUSIVE ROCKS ON THE ISLAND OF HAWAIʻI

KĪLAUEA VOLCANO

[Bracketed page numbers refer to Geologic Map of Island of Hawaiʻi (Wolfe and Morris, 1996a), which is the chief source for description of Hawaiʻi Island geologic map units]

Puna Basalt (Holocene and Pleistocene)—Lava flows (unit Qp), vent deposits (unit Qpc), littoral deposits (unit Qpld), and tephra deposits (unit Qpa) of tholeiitic basalt and rare transitional and alkalic basalt [p. 10]. Among lava flows, pāhoehoe slightly more abundant than ʻaʻā. Variably porphyritic, with phenocrysts of olivine, plagioclase, and rarely, pyroxene. Divided on the basis of lithology and age according to the following matrix (y, younger; o, older). West of Glenwood (fig. 29), a vast area blanketed by tephra of the Puna Basalt (unit Qpa2; Wolfe and Morris, 1996a) is mapped to show the extents of partially buried lava flows from Kīlauea and Mauna Loa, following the presentation of Trusdell and others (2006). Similarly, unit Qpa4y, which corresponds to the Keanakākoʻi Ash Member of the Puna Basalt, is shown more restrictively across its extent in the summit area of Kīlauea volcano. Age formally redefined here as Holocene and Pleistocene, in order to include lava flows of late Pleistocene age exposed at base sequence in upper slope of Hilina Pali (table 2).



Puna Basalt

Spatter or scoria cones	Lava flows		Littoral cones	Tephra deposits	Age, years
Qpc5	Qp5		Qpld5	Qpa5	0 - 200
Qpc4y	Qp4	Qp4y			200 - 400
Qpc4o		Qp4o	Qpld4o	Qpa4o	400 - 750
Qpc3	Qp3		Qpld3		750 - 1,500
Qpc2	Qp2			Qpa2	1,500 - 3,000
	Qp1y				3,000 - 5,000
	Qp1o				5,000 - 16,000

Qhi **Hilina Basalt (Pleistocene)**—Lava flows and minor interbedded tephra deposits of tholeiitic basalt [p. 11]. Lithologically similar to overlying Puna Basalt, but the two units are separated by a widespread sequence of fallout tephra (unit Qt), the Pāhala Ash of previous workers

MAUNA LOA VOLCANO

Kaʻū Basalt (Holocene and Pleistocene)—Lava flows (unit Qk), vent deposits (unit Qkc), littoral deposits (unit Qkld), and tephra deposits (unit Qka) of tholeiitic basalt and rare transitional and alkalic basalt [p. 10]. Among lava flows, pāhoehoe slightly more abundant than ʻaʻā. Variably porphyritic, with phenocrysts of olivine, plagioclase, and rarely, pyroxene. Divided on the basis of lithology and age according to the following matrix (y, younger; o, older).

Ka‘ū Basalt

Spatter or scoria cones		Lava flows		Littoral cones	Tephra deposits	Age
Qkc5		Qk5		Qkld5		0 - 200
Qkc4		Qk4		Qkld4		200 - 750
Qkc3		Qk3		Qkld3	Qka3	750 - 1,500
Qkc2		Qk2		Qkld2		1,500 - 3,000
Qkc1	Qkc1y	Qk1	Qk1y	Qkld1		3,000 - 5,000
	Qkc1o		Qk1o			5,000 - 11,000
Qkc		Qk				>11,000

Qkh **Kahuku Basalt (Pleistocene)**—Lava flows and minor interbedded tephra deposits of tholeiitic basalt [p. 12]. Lithologically similar to overlying Ka‘ū Basalt, but the two units are separated by a widespread sequence of fallout tephra (unit Qt), the Pāhala Ash of previous workers

Qn **Nīnole Basalt (Pleistocene)**—Thin ‘a‘ā and pāhoehoe lava flows, minor interbedded tuff, and sparse dikes exposed as erosional remnants on scattered hills in the southern part of Mauna Loa’s southwest flank. Age poorly determined but in the range 100–300 ka on basis of K–Ar geochronology. Thought to be eruptive products of early southwest rift zone of Mauna Loa that were isolated by massive landsliding of the volcano’s west flank [p. 12]

HUALĀLAI VOLCANO

Hualālai Volcanics (Holocene and Pleistocene)—Lava flows and vent deposits of transitional and alkali basalt and trachyte [p. 12]. The basaltic units are divided on basis of lithology and age according to the following matrix; whereas the trachyte belongs to a separately named member.

Hualālai Volcanics, basaltic rocks

Spatter or scoria cones	Lava flows	Tephra deposits	Age, years
Qhc5	Qh5		0 - 200
Qhc4	Qh4	Qha4	200 - 750
Qhc3	Qh3		750 - 1,500
Qhc2	Qh2		1,500 - 3,000
Qhc1y	Qh1y		3,000 - 5,000
Qhc1o	Qh1o		5,000 - 11,000
Qhc	Qh		>11,000

Wa‘awa‘a Trachyte Member (Pleistocene)—Lava flow and vent deposits. Slightly porphyritic, containing fewer than 1 percent phenocrysts of biotite, plagioclase, and pyroxene. Widespread in subsurface, on basis of water-well data, xenolith inclusions elsewhere in Hualālai lava flows, and trachytic blocks in ejecta (unit Qha4) adjacent to a cinder cone south of Hualālai’s summit. Emplaced across a span of about 20 kyr, on basis of radiometric ages ranging from about 114 to 92 ka (Clague 1987b; Cousens and others, 2003). Divided into:

Qw **Lava flow**—Light gray trachyte, altered to light brown where sheared [p. 13]. Blocky scoriaceous top grades downward into dense lava. Crescentic flow ridges 3–18 m high increase in height toward terminus of flow (Stearns and Macdonald, 1946). Terraces on its slopes suggest it is composed of several flow units

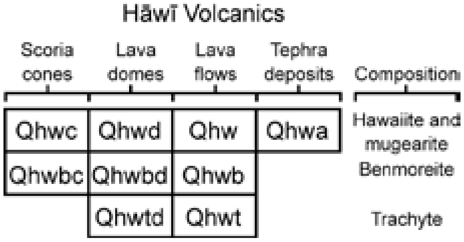
	80–150 m thick (Stearns and Macdonald, 1946). Total thickness exceeds 275 m; base not exposed (Clague and Bohrson, 1991). Cuttings from water well indicate two flow lobes, each at least 70 m thick, separated by about 40 m of pumice (Clague and Bohrson, 1991). Radiometric ages from lava flow and cone and from similar trachyte from water wells and disgorged blocks indicate eruption occurred during span of time from 114 to 92 ka (Cousens and others, 2003)
Qwc	**Scoria cone**—Generally loose fragments of pumice, obsidian, and massive, flow-banded trachyte [p. 13]. Other vents buried but required to explain subsurface distribution

MAUNA KEA VOLCANO

	Laupāhoehoe Volcanics (Holocene and Pleistocene)—Volcanic rocks, composed of hawaiite, mugearite, and benmoreite, and associated glacial deposits [p. 13]. Divided into two informally named volcanic members and an intervening formally named glacial member, thus:
	Younger volcanic rocks member (Holocene and Pleistocene)—Lava flows, scoria cones, and tephra-fall deposits of hawaiite and mugearite. Postdates the Mākanaka Glacial Member (units Qlmt, Qlmo). Where glacial deposits are lacking, may be distinguished from older volcanic rocks on basis of youthful physiographic aspect and absence of mantling surficial deposits. Divided into:
Qlcy	**Scoria cones**—Vesicular lapilli with lesser amounts of ash and bombs; some spatter
Qly	**Lava flows**—Predominantly ‘a‘ā and blocky ‘a‘ā. Pāhoehoe found locally
Qlay	**Tephra-fall deposits**—Lapilli and ash. Distributed downwind from pyroclastic eruption columns. Shown only on east half of Mauna Kea, where deposits are found on leeward side of scoria cones (in unit Qlcy). On west half, stratigraphically equivalent tephra are dispersed more widely and mapped as part of tephra-fall deposits of the older volcanic rocks member (unit Qla)
	Older volcanic rocks member (Holocene and Pleistocene)—Lava flows, scoria cones, and tephra-fall deposits of hawaiite, mugearite, and benmoreite. Divided into:
Qla	**Tephra-fall deposits (Holocene and Pleistocene)**—Lapilli and ash distributed downwind during eruptions of pyroclastic material at cinder cones. Chiefly Pleistocene in age but locally includes tephra stratigraphically equivalent to that in the younger volcanic rocks member (unit Qlay). On larger-scale geologic map, all tephra of Laupāhoehoe age are included in a single map unit (Wolfe and others, 1997, their air-fall deposits of the Laupāhoehoe Volcanics)
Qlc, Qlbc	**Scoria cones (Pleistocene)**—Two benmoreite cones (unit Qlbc) identified on basis of chemical composition and shown separately
Ql, Qlb	**Lava flows (Pleistocene)**—Benmoreite lava flows (unit Qlb) on northwest flank, identified on basis of chemical composition, shown separately
	Mākanaka Glacial Member (Pleistocene)—Glacial deposits. Divided into:
Qlmt	**Till**—Poorly sorted, poorly consolidated deposits containing subangular to subrounded pebbles, cobbles, and boulders in finer-grained matrix
Qlmo	**Outwash**—Subrounded to well rounded silt, sand, and cobbly to bouldery gravel. Moderately well sorted
	Hāmākua Volcanics (Pleistocene)—Basaltic volcanic rocks and associated glacial deposits. Volcanic member is divided to show lava flows separately from vent deposits. Consists of
	Basalt—Lava flows and cinder cones of alkalic and transitional basalt, minor hawaiite, tholeiitic basalt, and strongly undersaturated basalt. Variably porphyritic, with phenocrysts of olivine, plagioclase, and clinopyroxene. Divided into:
Qhm	**Lava flows**—‘A‘ā and pāhoehoe from vents distributed widely across the volcano
Qhmc	**Vent deposits**—Scoria cones
Qhmw	**Waihū Glacial Member**—Chiefly till; thin beds of gravel occur as lenses or tongues locally. Exposed only on southwest flank
Qhmp	**Pōhakuloa Glacial Member**—Chiefly till; thin beds of glaciofluvial gravel occur locally. Separated from Waihū Glacial Member by lava flows of the Hāmākua Volcanics

KOHALA VOLCANO

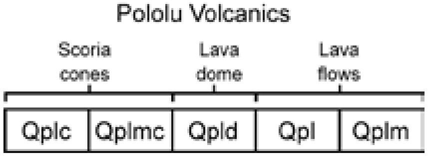
Hāwī Volcanics (Pleistocene)—Lava flows (unit Qhw), lava domes (unit Qhwd), vent deposits (unit Qhwc), and tephra-fall deposits (unit Qhwa) of hawaiite, mugearite, benmoreite (unit Qhwb), and trachyte (unit Qhwt) [p. 14]. Aphyric to sparsely porphyritic. Divided on basis of lithology and composition according to the following matrix. (No implication for age relations among parts of the unit)



Hāwī Volcanics

Scoria cones	Lava domes	Lava flows	Tephra deposits	Composition
Qhwc	Qhwd	Qhw	Qhwa	Hawaiite and mugearite
Qhwbc	Qhwbd	Qhwb		Benmoreite
	Qhwtd	Qhwt		Trachyte

Pololū Volcanics (Pleistocene)—Lava flows (unit Qpl), cinder cones (unit Qplc), and a lava dome (unit Qpld). Most lava is basaltic, ranging from tholeiite to alkalic basalt and rarely hawaiite. Sparse mugearite lava flows (unit Qplm) and the single identified mugearite cone (unit Qplmc) are mapped separately, according to the following matrix. The lava dome is basaltic.



Pololu Volcanics

Scoria cones		Lava dome	Lava flows	
Qplc	Qplmc	Qpld	Qpl	Qplm

Appendix 1. Information about the recalculating of radiometric ages for Hawai‘i State Geologic Map.

Data for radiometric ages were compiled from the published literature. Some additional data were obtained from unpublished sources and are newly presented here. To simplify the tabulation, we report the weighted mean age in those instances where multiple gas extractions led to multiple age determinations from single samples. Ages are weighted by the inverse of the variance (Taylor, 1982).

Decay standards and isotopic abundances used in calculating K-Ar ages were standardized in 1977 (Steiger and Jäger, 1977). For consistency, all ages were checked by recalculation, and revised ages are reported here. Consequently, our tabulation might appear discrepant if a reader makes only a casual comparison of previously published ages for specific samples. Described here, in chronologic order, are specific examples of changes made for those publications that preceded the complete adoption of the new standards.

After 1980, the next publication describing K-Ar ages was issued in 1982 (Clague and others, 1982). It and all subsequent publications use modern decay standards for calculating ages.

Evernden and others, 1964

Data are insufficient to allow recalculation. Therefore, we used the method of Dalrymple (1979), which leads to ages about two percent older than originally reported by Evernden and colleagues.

McDougall, 1964

All ages were recalculated using data originally published. No analytical error was assigned to specific ages in the original document, but an estimation for 2σ error was provided—(1) about 3 percent of the reported age where the proportion of radiogenic to atmospheric argon exceeds 15 percent and (2) 5-10 percent for radiogenic argon less than 15 percent (McDougall, 1964, p. 111). We used 3 percent and 10 percent for the two cases, respectively.

Gramlich and others, 1971

Recalculated using modern decay constants. Weighted mean ages were estimated for those samples that had multiple gas extractions.

McDougall and Aziz-ur-Rahman, 1972

Ages recalculated here using the data originally published. Samples had multiple gas extractions; therefore we assigned the original 1σ error to our newly recalculated age and then determined the weighted mean age reported in our database. Additionally, some earlier ages, which were first reported without analytical error (McDougall, 1964), appeared in the 1972 report with 1σ analytical error, which we adopted.

McDougall and Swanson, 1972

Recalculated using modern decay constants. Weighted mean ages were estimated for the three samples that had multiple gas extractions.

Doell and Dalrymple, 1973

Recalculated using modern decay constants. Weighted mean ages were estimated for those samples that had multiple gas extractions.

Bonhommet and others, 1977

Recalculated using modern decay constants. Weighted mean ages were estimated for those samples that had multiple gas extractions.

Stearns and Dalrymple, 1978

Used modern decay constants. No changes reported here.

McDougall, 1979

Used modern decay constants. No changes reported here.

Lanphere and Dalrymple, 1980

The reported decay constants reported therein differ from modern values, but the data are unchanged by our efforts at recalculating.

Naughton and others, 1980

Used modern decay constants. No changes reported here.