Keanakākoʻi Tephra produced by 300 years of explosive eruptions following collapse of Kīlauea's caldera in about 1500 CE

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A B S T R A C T

The Keanakākoʻi Tephra at Kīlauea Volcano has previously been interpreted by some as the product of a caldera-forming eruption in 1790 CE. Our study, however, finds stratigraphic and 14C evidence that the tephra instead results from numerous eruptions throughout a 300-year period between about 1500 and 1800. The stratigraphic evidence includes: (1) as many as six pure lithic ash beds interleaved in sand dunes made of earlier Keanakākoʻi vitric ash, (2) three lava flows from Kīlauea and Mauna Loa interbedded with the tephra, (3) buried syneruptive cultural structures, (4) numerous intraformational water-cut gullies, and (5) abundant organic layers rich in charcoal within the tephra section. Interpretation of 97 new accelerator mass spectrometry (AMS) 14C ages and 4 previous conventional ages suggests that explosive eruptions began in 1470–1510 CE, and that explosive activity continued episodically until the early 1800s, probably with two periods of quiescence lasting several decades. Kīlauea’s caldera, rather than forming in 1790, predates the first eruption of the Keanakākoʻi and collapsed in 1470–1510, immediately following, and perhaps causing, the end of the 60-year-long, 4–6 km3 Ailāʻau eruption from the east side of Kīlauea’s summit area. The caldera was several hundred meters deep when the Keanakākoʻi began erupting, consistent with oral tradition, and probably had a volume of 4–6 km3. The caldera formed by collapse, but no eruption of lava coincided with its formation. A large volume of magma may have quickly drained from the summit reservoir and intruded into the east rift zone, perhaps in response to a major south-flank slip event, leading to summit collapse. Alternatively, magma may have slowly drained from the reservoir during the prolonged Ailāʻau eruption, causing episodic collapses before the final, largest downdrop took place. Two prolonged periods of episodic explosive eruptions are known at Kīlauea, the Keanakākoʻi and the Uwēkahuna Tephra (Fiske et al., 2009), and both occurred when a deep caldera existed, probably with a floor at or below the water table, and external water could readily interact with the magmatic system. The next period of intense explosive activity will probably have to await the drastic deepening of the present caldera (or Halemaʻumaʻu Crater) or the formation of a new caldera.

1. Introduction

“Kīlauea...has not always been the tame creature of today.” (Hitchcock, 1909, p. 167)

The caldera atop Kīlauea Volcano, and the conspicuous tephra blanket that surrounds it, have been linked temporally and genetically by volcanologists for the past several decades. Both were commonly interpreted to have formed in November 1790 (Fornander, 1996, p. 241; Cahill, 1999, p. 69), when an explosive eruption killed a large number of people (Swanson and Christiansen, 1973), variously reported as about 80 (Ellis, 1825), approaching 400 (Desha, 2000, p. 279), almost 800 (Desha, 2000, p. 280), and 5405 (Douglas, 1834). Geologic and radiometric evidence presented here shows that the caldera and tephra are not linked as closely as was once assumed. The caldera formed nonexplosively in about 1470–1510 CE. Explosive eruptions began shortly thereafter and continued intermittently for the next 300 years to produce the Keanakākoʻi Tephra. The stratigraphic relation of the oldest tephra to the caldera faults, the 14C age of that tephra, and the physical characteristics of reticulite near the base of the tephra provide the evidence that constrains the age and depth of collapse.

2. Definition and general characteristics of Keanakākoʻi Tephra

The surface tephra deposit surrounding Kīlauea’s caldera is formally named the Keanakākoʻi Ash Member of the Puna Basalt (Easton, 1987). The Keanakākoʻi contains prominent deposits coarser than ash, however,
so we modify its formal name to the Keanakākoʻi Tephra Member, or Keanakākoʻi for short.

Various workers have defined the Keanakākoʻi somewhat differently. This paper follows the Decker and Christiansen (1984) and Easton (1987) definition that includes a bed of reticulite below, and of pumice (the “golden pumice” of Sharp et al., 1987) above, the rest of the section, which consists of well-bedded vitric and lithic ash, scoria, and lithic lapilli and block deposits. These deposits were mostly formed by tephra falls, but some result from surges and other pyroclastic density currents (PDCs; Fig. 1).

McPhie et al. (1990) give the most detailed field description of the Keanakākoʻi, dividing it into 16 subunits termed layers, and we mostly follow their terminology. They focused attention on the products of explosive eruptions rather than of lava fountains and so did not describe the upper pumice and lower reticulite layers. A gray to pink lithic ash underlies the reticulite in most places northwest, north, and northeast of the caldera (Fig. 1; Stone, 1926, p. 29; Finch, 1942). Though nowhere more than a few centimeters thick, this ash nonetheless indicates that explosive activity (possibly a surge and accompanying fall) began a little earlier than the reticulite, and we see no reason to exclude it from the Keanakākoʻi. Consideration of 14C ages later in the paper supports this decision.

We agree with past workers that the Keanakākoʻi is the product of phreatomagmatic eruptions (McPhie et al., 1990; Mastin, 1997; Mastin et al., 2004), except for the reticulite and “golden pumice,” which are clearly fallout from high lava fountains. The reticulite occurs completely around the caldera and is an important marker unit. On the west, north, and east sides of the caldera, it is sandwiched between two lithic units, the underlying gray to pink ash and the overlying pink Housing Area block and ash fall (described below; equivalent to layers 0 and 5 of McPhie et al., 1990). The bulk of the Keanakākoʻi consists of well-bedded vitric ash (Fig. 1), generally less vesicular than pumice, which contains several percent of wallrock clasts in all grain sizes. In general, the lithic content is nearly constant from bed to bed, but it increases in the upper part of the vitric section. Within the vitric section (Fig. 1) is a single bed of crystal-rich scoria less than 50 cm thick, layer 6 of McPhie et al. (1990), that may be the product of a relatively dry explosive eruption, with some involvement of groundwater. Layer 6 is an important marker bed, as shown below. Above a major erosional unconformity are lithic fall and PDC deposits, including definite surges, ranging in grain size from ash to blocks tens of centimeters in diameter. Ballistic blocks dot the ground surface, some reaching more than 2 m in diameter (Swanson et al., 2010). The “golden pumice” caps the lithic part of the section along the western and southwestern sides of the caldera.

Near the caldera, the thickness of the Keanakākoʻi section ranges from about 11 m to only a few tens of centimeters, reflecting the prevailing NE wind direction, the inferred locations of vents within the caldera, and the height of the caldera wall. Most deposits are primary, resulting from pyroclastic falls and PDCs, but some deposits were reworked in places by water and wind, and erosional unconformities are common. In fact, erosion during Keanakākoʻi time removed several meters of section along master drainages.

The only pyroclastic deposits overlying the Keanakākoʻi are lithic ejecta of the 1924 phreatic eruptions from Halemaumau Crater (Jagger and Finch, 1924; Decker and Christiansen, 1984) and several thin or local deposits of vitric ash and Pele’s hair from fissure eruptions, mainly in 1959, 1971, and 1974 (Neal and Lockwood, 2002).

3. Previous interpretations of age

Interpretations of the age of the Keanakākoʻi have a long and complicated history. Dana (1890, p. 43–45) more or less assumed that its entire thickness was produced by the 1790 eruption, as did Brigham (1909, p. 36), but Hitchcock (1909, p. 167–169) clearly had reservations. Sidney Powers (1916) divided the section into a younger, blocky 1790 deposit and one or more older, finer ash deposits on the basis of a large erosional unconformity (Fig. 1) and possible buried soils. Finch (1925, 1942), Stone (1926), Stearns and Clark (1930), and Wentworth (1938) agreed that deposits of several pre-1790 explosive eruptions dominated the Keanakākoʻi, finding carbonaceous material and soils as well as other physical differences below the erosional break at the base of their 1790 deposits. Finch (1925) even reported molds of trees rooted in ash near the base of the tephra section and buried by younger ash. Finally, Howard Powers (1948) interpreted several “humus” layers and small unconformities to suggest at least 9 phreatic and 11 magmatic explosive eruptions older than the 1790 deposit.

With the development of the base surge concept in the late 1960s, interpretations swung back to assigning all, or almost all, of the Keanakākoʻi to the 1790 eruption. Deposits interpreted to have been produced by surges were noted in the youngest lithic deposits (Swanson and Christiansen, 1973), which all previous workers had assigned to the Keanakākoʻi. Thereafter, the entire tephra section was reinterpreted to be of 1790 vintage; most of its internal unconformities were ascribed to surge erosion, and the overall upward change in componentry of the deposits—from vitric low in the section to almost completely lithic in the upper part of the section—was interpreted as the general evolution of a single eruption (Christiansen, 1979; Malin et al., 1983; Decker and Christiansen, 1984; McPhie et al., 1990; Mastin, 1997; Neal and Lockwood, 2002). Uncertainty remained, however, as to whether the eruption lasted only a few days or as long as several months in 1790, primarily because of buried erosion surfaces and different dispersal directions of single layers (McPhie et al., 1990).
Thus the interpretations came full circle in 100 years. Late 20th-century workers once again agreed with Dana’s late 19th-century view that most or all of the Keanakākī was produced in 1790.

We reach a different conclusion, mostly on the basis of new evidence. We confirm the early and mid-20th-century view that only the relatively thin lithic deposits above a major erosional unconformity—and probably only a part of those—belong to the 1790 event, and we find that the rest of the Keanakākī was produced during 300 years of sporadic explosive eruptions following the formation of the caldera. The rest of this paper discusses the evidence for these interpretations and how they bear on the timing and mechanism of caldera collapse.

4. Field evidence for breaks in deposition of the Keanakākī

None of the physical evidence presented below requires long periods of quiet. The evidence is so abundant and varied, however, that it provides strong circumstantial evidence against all or even most of the Keanakākī being of 1790 age and the product of one eruption.

4.1. Ash beds in sand dunes

At least 6 thin beds of light gray, very fine-grained, dominantly lithic ash are interbedded with olive-colored, windblown, vitric sand in numerous dunes 10–15 km southwest of the summit (Fig. 2). The ash beds, typically 2–3 cm thick, are separated from one another by 20 cm to more than 1 m of cross-beded sand, derived by wind erosion of medium- and coarse-grained vitric ash in the Keanakākī Tephra (Fig. 1, layers 1–4). The fine lithic ash in each bed is not mixed with the coarser, vitric dune sand, and the youngest ash contains numerous unbroken accretionary lapilli. Less than 10% of juvenile material (pumice, dense black glass) is included in the otherwise lithic ash. These features suggest that the ash beds are primary deposits, not reworked, although the beds are discontinuous across an outcrop and truncated by vitric sand, probably owing to subsequent dune activity such as continues today at some dunes. The evidence indicates that each ash bed is a separate fall deposit, probably corresponding to eruptions that created some or all of layers 11–15 of McPhie et al. (1990). It is difficult to account for the primary lithic fall deposits within sand dunes made of coarser, reworked Keanakākī vitric ash if all of the Keanakākī had been erupted in only a few days to weeks.

4.2. Interbedded lava flows

Three lava flows are interbedded with the Keanakākī, one erupted from Kilauea and two from Mauna Loa. The Kilauea pāhoehoe flow issued from an arcuate fissure with associated spatter rampart along the southern margin of the caldera (Jaggar, 1926; Stearns and Clark, 1930, p. 150; Finch, 1942). This flow, unit 1790f of Neal and Lockwood (2002), spread down a broad, shallow drainage and several smaller, vertically walled gullies eroded into vitric ash containing accretionary lapilli (Figs. 3, 4). It underlies lithic lapilli and ash in erosional contact with the vitric tephra. McPhie et al. (1990) place it between layers 10 and 11.

One Mauna Loa flow, not previously reported as interbedded in the Keanakākī, occurs on Kapāpala Ranch near ʻŌhaʻika (Fig. 3, OH), 6 km west of Halemaumau. Here, the Kipuka Maunaʻai pāhoehoe flow rests on 10–15 cm of fine ash in the Keanakākī, some bearing accretionary lapilli, and underlies several centimeters of similar ash, also containing accretionary lapilli. The base of the Keanakākī at this location rests on the older Kulanaokuakiai Tephra (Fiske et al., 2009). At a nearby locality lacking the lava flow, a 49-cm-thick section of Keanakākī overlies Kulanaokuakiai and contains accretionary lapilli near its top and bottom and an organic-rich brown weathered zone 16 cm below the top; the lava flow may have erupted during the period of weathering. Charcoal along the base of the flow has been dated and is discussed in a later section.

Sidney Powers (1916, p. 232, 238) indicated that another Mauna Loa lava flow, the young Keʻamoku ‘ā‘ā flow (unit m4y of Neal and Lockwood, 2002), overlies “the largest part” of the Keanakākī Tephra at an unspecified locality northwest of the caldera. Howard Powers (1948, p. 284) reported that the reticulite unit low in the Keanakākī underlies the flow, again without giving a locality. Subsequent workers failed to find the reticulite under the flow but did identify younger Keanakākī ash on top (Neal and Lockwood, 2002). From this they inferred that the Keʻamoku flow predated the entire Keanakākī and interpreted the reticulite lapilli to have trickled out of sight between the rubble blocks on the ‘ā‘ā flow top.

To resolve this disagreement, we searched for reticulite along the poorly exposed base of the flow. One place near Kipuka Puauulu (Fig. 3, KP), 4 km northwest of Halemaumau, revealed a 5–6-cm-thick pocket of reticulite and an overlying 0–2-cm-thick bed of gray to olive vitric ash (equivalent to layers 1–3 of McPhie et al., 1990) unequivocally sandwiched between the rubby base of the Keʻamoku and the underlying pāhoehoe flow. The reticulite rests directly on the pāhoehoe, and the gray to olive vitric ash overlies and filters into the loose reticulite deposit. This discovery confirms the early observations of Sidney and Howard Powers, although “the largest part” of the Keanakākī is probably younger than the flow. The young Keʻamoku flow, dated at another location, has a $^{14}C$ age consistent with its stratigraphic position (see later section).

4.3. Stone structures built during Keanakākī time

Remnants of several small stone structures made by humans occur several kilometers south of Halemaumau; locations are not given here to protect the sites. With archaeologists from Hawaiʻi Volcanoes National Park, the best-preserved structure was excavated in 1998 and found to have been built on a faintly orange ash bed resting on scoria of layer 6 (Fig. 1; McPhie et al., 1990), a prominent marker bed discussed in more detail below. All younger ash fell onto the structure, probably starting with layer 12. The orange color of this particular ash, not reported by McPhie et al. (1990), is widespread in this area and is unrelated to fumaroles or other local sources of hot gas. It probably developed on layer 7 (Fig. 1) during a period of weathering when soil began to form and people felt they could return safely to the area. By comparison, the surface of the nearby 1959 Kilauea Iki fall deposit is showing faint oxidation in places, some
50 years after the eruption. Perhaps several decades of weathering were needed to produce the weak oxidation of layer 7.

The other structures have not been excavated, but two are so disrupted by faulting that it is possible to see beneath them and confirm that each was built at the same stratigraphic level as the excavated structure.

4.4. Water-cut gullies and preserved master drainages

Narrow, steep-sided (locally undercut) channels partly filled by water-worked detritus and capped by primary tephra are fairly common in the Keanakākoʻi in the southern part of the caldera (Figs. 5, 6). Many are small and easily overlooked, but several are as deep as 1 m. They are clustered along, but not confined to, the three erosion surfaces recognized and clearly described by McPhie et al. (1990): below layer 6, above layer 7, and above layer 10. These gullies were probably eroded by running water.

Most of the gullies intersect present-day master drainages at high angles, though today they hang on the sides well above the incised modern drainages. Excellent examples are visible along the southwest side of Sand Wash (Figs. 3, 7, 8). The gullies were probably rills draining into master streams that have not changed location (except for bank erosion) since that time. In other words, today’s drainage system was largely developed at the time such gullies were cut. This implies sufficient time between explosive eruptions for gullies to be eroded.

Fig. 3. Map showing features mentioned in text and locations of all dated charcoal samples listed by number in Table 1, col. 1. Some locations have two or more samples from different beds containing charcoal. Note how all charcoal locations are in areas that are vegetated today (shaded areas on map); vegetated areas during Keanakākoʻi time were apparently similar. Features mentioned in text: AS, summit of A’ilau shield; HM, Halemaʻumaʻu; HVO, Hawaiian Volcano Observatory; KC, Keanakākoʻi Crater; KF, Kilauea lava flow interbedded in Keanakākoʻi; Ki, Kilauea Iki tephra deposit; KK, Kipuka Ki; KMC, Kilauea Military Camp; KP, Kipuka Puaulu; MLE, Mauna Loa Estates; OH, ʻōhaikea; SW, Sand dunes with ash layers; SD, Sand Wash; TM, Tree Molds; VV, Volcano Village. Base map from USGS 7 ½-minute quadrangles Kīlauea Crater, Kāʻū Desert, Volcano, and Makaopuhi Crater. Small-scale map shows location of larger map and the 5 volcanoes on the Island of Hawai’i.
Some of the gullies have been modified into U-shapes, possibly by lithic PDCs. Fig. 4a in McPhie et al. (1990) shows an example of this process. In some places, remnants of vertical walls, probably cut by water, are preserved at the bottom of the otherwise scoured and filled gully (Fig. 7).

The axes of other gully fills capped by primary tephra parallel today’s master drainages and occur as remnants against the steep sides of those streams. Such relations are well exposed just west of Sand Wash (Fig. 9) and are shown in Fig. 4b in McPhie et al. (1990). They testify to periods of master stream erosion, partial filling, draping by later tephra, and renewed stream cutting.

A prominent erosional unconformity in Sand Wash (Fig. 3) apparently separates layers 10 and 11. At least the upper part of the lithic tephra above the unconformity was erupted in 1790. The unconformity extends nearly to the modern floor of the wash and has relief of about 6 m (Fig. 10). The filled paleorills mentioned above mostly occur along the unconformity (Fig. 7, 8). These relations indicate that Sand Wash was cut before the lithic tephra was deposited. Such relief seems far too great to ascribe to PDC erosion. Moreover, the orientation of the wash, nearly concentric to the caldera and at high angles to PDCs originating at the summit, makes it an unlikely candidate for deep PDC erosion. This unconformity is striking physical evidence of a hiatus in deposition before the upper lithic part of the Keanakākoʻi was erupted. Sand Wash is one of the main drainages in the southern part of the caldera and may follow an arcuate caldera fault buried by tephra.

4.5. Other erosion surfaces

Many small-scale erosion surfaces occur within the Keanakākoʻi. Some are probably surge-related, for they occur in discontinuous ash beds with antidune structures and large-wavelength, undulatory upper surfaces. Good examples are in the vitric part of the section in Sand Wash, probably equivalent to layers 1–4 of McPhie et al. (1990). Many of the small-scale erosion surfaces are not clearly caused by surges, however, and may well record minor water and wind erosion—not unexpected in the rainy environment of the caldera. Such small features probably have little time significance.

4.6. Organic-rich layers and soil

On the wet, heavily vegetated north side of the caldera, Stone (1926, p. 34) found at least four black, carbonaceous layers, each about 1 cm thick, within the Keanakākoʻi, some containing “remains and impressions of ferns and other plants.” Finch (1925) noted molds of small trees and branches completely within the tephra during excavation at the current site of the national park’s visitor center,
and Stearns and Clark (1930, p. 151) reported that T.A. Jaggar had seen six “vegetable” layers in the same hole. The organic-rich layers and trees in growth position within the Keanakākoʻi indicate times during which either plants returned following tephra falls or litter accumulated on the ground surface from plants that survived an eruption. Finally, Howard Powers (1948) interpreted “not less than seven” levels of revegetation in the Keanakākoʻi, the lower two of which are at stratigraphic positions recognized by our work.

Those early workers were present during a period of road and building construction on the wet, north side of the caldera and observed many exposures unavailable to us today in the protected confines of the national park. Most modern tephra studies have concentrated on the drier, barren south and southwest sides of the caldera, where organic-rich layers would not be expected and indeed have not been found (Fig. 3).

We found charcoal and other carbonaceous layers exposed in pits and along cracks at many places east and southeast of the caldera, and in road cuts and building excavations in Volcano Village (Fig. 3) north of the caldera. One cut along Kalanikoa Road in the village, and several pits east of the caldera, expose at least three such layers, and two are common (Fig. 11).

In some places, the ash directly under an organic-rich layer is slightly oxidized and apparently reflects the early stage in development of a soil in which plants were growing (Fig. 11). The current surface of the 1959 Kīlauea Iki tephra deposit (Fig. 3, KI) has a similar, vaguely orange hue in the wet forest. Several decades may be a reasonable time for soils to start forming in this temperate, wet environment lacking much seasonality.

One level of common charcoal occurrence is at the base of the Keanakākoʻi section, associated with the gray lithic ash (Fig. 1). Another is in and overlying the reticulite above the gray ash. Still other charcoal comes from a pink, lithic block and lapilli fall on the northeast side of the caldera (layer 5 of McPhie et al., 1990). Another charcoal-bearing level is just above layers 6 (and 7, if present). Still another occurs higher in the section, along the erosional break between layers 10 and 11. Finally, large pieces of charcoal have been found in the youngest lithic block deposit at Kīlauea Military Camp (Fig. 3) in the northern part of the caldera.

A challenge in correlating specific charcoal-rich layers with the stratigraphy of McPhie et al. (1990) is that the layers occur in a thickly forested, poorly exposed area that was also vegetated during Keanakākoʻi time, whereas the stratigraphy was mostly defined in well exposed areas with little vegetation then and now (Fig. 3). The

*Fig. 8.* Narrow, subvertical slot or pocket (arrows) eroded into bedded vitric–lithic ash, filled by lithic ash, and overlain by coarser lithic ash and lapilli in vertical exposure just west of Sand Wash. Such erosional pockets are common at the bottom of modern gullies cut into fine ash in this area.

*Fig. 9.* Beds of lithic ash and lapilli (layers 11–16) unconformably overlying vitric ash and draping into, and partly filling, an old drainage. The old drainage parallels the modern drainage. Lithic stratigraphy in the fill is the same as that capping the ridge at left, including a primary bed of accretionary lapilli ash 3–5 cm thick. This shows that the old drainage was in about the same location as today’s, and that it had relief of several meters. Later erosion beveled off the fill in the channel, forming a terrace. About 2.2 km south–southeast of center of Halemaʻumaʻu.
The charcoal-rich layers indicate breaks in tephra deposition long enough for vegetation to return or for litter to form distinct layers. They obviously minimize the possibility that the Keanakākoʻi was entirely erupted in 1790 or even within a few years at any time. They also provide a means to quantify the age of various parts of the section through 14C dating.

5. 14C ages of Keanakākoʻi tephra

Since 1998, 97 new 14C ages have been obtained on Keanakākoʻi tephra and related deposits (Table 1; Fig. 3). These ages have proven crucial for quantifying the age relations within the tephra and between the tephra and its underlying deposits. A large number of analyses is necessary to define the age relations, owing to the youth of the deposits and the consequent large uncertainties in calibrated calendar ages (Guilderson et al., 2005). Four conventional ages from Rubin et al. (1987, Table 10.1, lab numbers W3871, W4006, W4919, and W5106) help to define the ages of the two Mauna Loa flows interbedded in the Keanakākoʻi. Most of the charcoal formed from small twigs, leaves, and roots; this minimizes the chance of “old wood” contamination. A few pieces of charcoal, however, came from larger pieces of wood, whose 14C age could significantly predate the time of fire (Wilmshurst et al., 2011).

5.1. Techniques

Charcoal was the only material dated. It was hand picked from field samples dried for several hours at low temperature within 2 days of collection. The samples selected for radiocarbon dating were converted to pure carbon in the form of graphite at the USGS Radiocarbon Laboratory in Reston, Virginia. Radiocarbon dating of graphite was done by accelerator mass spectrometry (AMS) at the Center for Accelerator Mass Spectrometry (CAMs) at Lawrence Livermore National Laboratory (CAMS/LNL) in Livermore, California or the NSF-Arizona AMS facility at the University of Arizona in Tucson.

Raw sample material was chemically treated to remove contaminant carbon using successive acid and alkali washes: 1 M HCl (2 h at 60 °C), 0.1 M NaOH (overnight at 60 °C), 1 M HCl (2 h at 60 °C). The neutralized sample was dried in an oven at 50 °C. Each sample was then combusted in air-free, sealed 6-mm Vycor tubes with CuO and
Table 1
Reported \(^{14}C\) ages, with 1 sigma error, referenced to stratigraphic unit, and figure in which calibrated age is plotted. Latitude and longitude referred to Old Hawaiian datum. WW, AMS age; W, conventional age.

<table>
<thead>
<tr>
<th>No.</th>
<th>Lab no.</th>
<th>Field no.</th>
<th>N Lat</th>
<th>W Long</th>
<th>(^{14}C) age BP</th>
<th>Unit</th>
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</thead>
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<td>1</td>
<td>WW5901</td>
<td>S06-53Z</td>
<td>19.43973</td>
<td>155.23837</td>
<td>495±45</td>
<td>Reticule on All'ai or other young flow</td>
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<td>2</td>
<td>WW5891</td>
<td>S02-23</td>
<td>19.44754</td>
<td>155.27539</td>
<td>305±35</td>
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<td>WW5892</td>
<td>S03-2-1</td>
<td>19.43553</td>
<td>155.24218</td>
<td>370±35</td>
<td>Do.</td>
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<td>WW2997</td>
<td>S0-25B</td>
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<td>155.24795</td>
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<tr>
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<tr>
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<td>155.23737</td>
<td>305±30</td>
<td>Do.</td>
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<td>155.24582</td>
<td>330±40</td>
<td>Do.</td>
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<td>155.24148</td>
<td>680±40</td>
<td>Do.</td>
</tr>
<tr>
<td>13</td>
<td>WW5403</td>
<td>S02-21A</td>
<td>19.44432</td>
<td>155.25185</td>
<td>390±40</td>
<td>Do.</td>
</tr>
<tr>
<td>14</td>
<td>WW3905</td>
<td>F01-1-4-C</td>
<td>19.47188</td>
<td>155.26202</td>
<td>358±41</td>
<td>Do.</td>
</tr>
<tr>
<td>15</td>
<td>WW2246</td>
<td>10-16-98-1</td>
<td>19.46133</td>
<td>155.24859</td>
<td>360±40</td>
<td>Do.</td>
</tr>
<tr>
<td>16</td>
<td>WW2255</td>
<td>S9-28-6-C</td>
<td>19.46528</td>
<td>155.25694</td>
<td>550±50</td>
<td>Do.</td>
</tr>
<tr>
<td>17</td>
<td>WW3540</td>
<td>F01-1-48</td>
<td>19.47188</td>
<td>155.26202</td>
<td>390±50</td>
<td>Basal ash, under reticule and on Kulanakuaiki</td>
</tr>
<tr>
<td>20</td>
<td>WW3909</td>
<td>S01-51</td>
<td>19.43152</td>
<td>155.35732</td>
<td>558±38</td>
<td>Housing Age area fall on reticule</td>
</tr>
<tr>
<td>21</td>
<td>WW3900</td>
<td>S01-60</td>
<td>19.43185</td>
<td>155.23837</td>
<td>342±44</td>
<td>Do.</td>
</tr>
<tr>
<td>22</td>
<td>WW5900</td>
<td>S06-53-C</td>
<td>19.43973</td>
<td>155.23837</td>
<td>345±35</td>
<td>Do.</td>
</tr>
<tr>
<td>23</td>
<td>WW3902</td>
<td>S01-13A</td>
<td>19.41920</td>
<td>155.24522</td>
<td>239±37</td>
<td>Do.</td>
</tr>
<tr>
<td>24</td>
<td>WW5409</td>
<td>S04-211</td>
<td>19.39642</td>
<td>155.22736</td>
<td>190±35</td>
<td>Layer 61 within Keanakakii</td>
</tr>
<tr>
<td>26</td>
<td>WW5902</td>
<td>S06-68-C</td>
<td>19.33373</td>
<td>155.20897</td>
<td>220±35</td>
<td>Do.</td>
</tr>
<tr>
<td>27</td>
<td>WW4097</td>
<td>F02-20-2-C</td>
<td>19.35209</td>
<td>155.11133</td>
<td>260±40</td>
<td>Do.</td>
</tr>
<tr>
<td>29</td>
<td>WW3538</td>
<td>S7-103-12A</td>
<td>19.35209</td>
<td>155.21133</td>
<td>320±50</td>
<td>Do.</td>
</tr>
<tr>
<td>30</td>
<td>WW2959</td>
<td>S05-75A-C</td>
<td>19.38057</td>
<td>155.18736</td>
<td>215±35</td>
<td>Layer 6 on All’ai flow</td>
</tr>
<tr>
<td>31</td>
<td>WW3091</td>
<td>S0-28-C</td>
<td>19.38264</td>
<td>155.22222</td>
<td>230±40</td>
<td>Do.</td>
</tr>
<tr>
<td>32</td>
<td>WW3000</td>
<td>F0-11-2</td>
<td>19.34083</td>
<td>155.22715</td>
<td>550±40</td>
<td>Layer 6 resting on Kulanakuaiki Tephra</td>
</tr>
<tr>
<td>33</td>
<td>WW2882</td>
<td>S0-7-2</td>
<td>19.32731</td>
<td>155.25546</td>
<td>510±40</td>
<td>Do.</td>
</tr>
<tr>
<td>34</td>
<td>WW5893</td>
<td>S04-118B</td>
<td>19.35209</td>
<td>155.21133</td>
<td>395±35</td>
<td>Do.</td>
</tr>
<tr>
<td>35</td>
<td>WW2640</td>
<td>S9-49-5-C</td>
<td>19.34683</td>
<td>155.23294</td>
<td>320±50</td>
<td>Do.</td>
</tr>
<tr>
<td>36</td>
<td>WW2922</td>
<td>F0-14-1</td>
<td>19.32733</td>
<td>155.22285</td>
<td>340±50</td>
<td>Do.</td>
</tr>
<tr>
<td>37</td>
<td>WW2970</td>
<td>S0-9-1</td>
<td>19.34700</td>
<td>155.26504</td>
<td>320±40</td>
<td>Do.</td>
</tr>
<tr>
<td>38</td>
<td>WW2957</td>
<td>S0-8-2A-X</td>
<td>19.32281</td>
<td>155.25257</td>
<td>420±40</td>
<td>Do.</td>
</tr>
<tr>
<td>39</td>
<td>WW2956</td>
<td>S0-8-2X</td>
<td>19.32281</td>
<td>155.25257</td>
<td>330±40</td>
<td>Do.</td>
</tr>
<tr>
<td>40</td>
<td>WW3871</td>
<td>None</td>
<td>19.44626</td>
<td>155.31895</td>
<td>230±60</td>
<td>Young Ke‘amoku flow in Kipuka KI</td>
</tr>
<tr>
<td>41</td>
<td>WW4919</td>
<td>None</td>
<td>19.44626</td>
<td>155.31895</td>
<td>350±70</td>
<td>Do.</td>
</tr>
</tbody>
</table>

(continued on next page)
Ag at 900 °C to produce CO2. The CO2 for each sample was cryogenically isolated from volatile gases and H2O in a high-vacuum manifold. Finally, sample CO2 was reduced to 1 mg carbon as graphite precipitated on 63 mesh Fe powder in the presence of hydrogen at 575 °C (Vogel et al., 1984). The resultant graphite was pressed into an aluminum target and shipped to one of the AMS labs for dating.

Radiocarbon ages were determined with an assumed $\delta^{13}C$ of $-25%o$, using the Libby half life of 5568 years. The $\delta^{13}C$ value was measured for 6 samples (Table 1) at the University of California at Davis (UC-D) Stable Isotope Laboratory. Ages were reported with 1$\sigma$ error, and the following discussion uses these 2 sigma calendar ages as meaningful to Keanakākoʻi history. Ages from sites that are best defined stratigraphically are examined first, followed by those less certain.

5.2. What started the fires?

Charcoal associated with a tephr‐fall deposit can have several origins. When erupted, basaltic tephra is hot, about 1165 °C at Kilauea, and falling lapilli can start fires away from vents. For example, pumice lapilli from a 300‐m‐high lava fountain at Mauna Ulu (Kilauea) in October 1969 set fire to several trees 2.5 km from the vent (Swanson et al., 1979). Radiant heat from high fountains caused dry grass and small shrubs to burst into flame on exposed slopes 700 m away (Swanson et al., 1971).

Another syneruption origin of charcoal is by fire generated near the vent by spatter, hot blocks, or small flows and moves downwind just before, during, or just after tephra is deposited. Fire can also be started by lightning during the eruption.

In addition, fires unrelated to an eruption could have been started by natural causes or human activity some time before or after the tephra fall. Charcoal made by syneruption fire records the age of the tephra; other charcoal generally does not. We know of no way to distinguish with certainty these two possibilities. This means that every charcoal‐tephra pair must be evaluated carefully; context and consistency among multiple samples are important, and every relation is interpretative, not obvious.

In the following sections, several charcoal ages are interpreted as either the products of fires predating the Keanakākoʻi or of Keanakākoʻi‐age fire burning old wood. Vegetation grew on the older Kulanakauiki Tephra, a good substrate for plant growth, particularly given the 500–600‐year interval since the latest Kulanakauiki eruption (in about 900–1000 CE; Fiske et al., 2009). We tried, wherever possible, to avoid this problem by dating deposits resting on lava flows emplaced only a few years to a few decades before the start of the Keanakākoʻi eruptions, using the map of Neal and Lockwood (2002) as a guide.

The following sections present the ages in relation to observed stratigraphic relations and outline the reasons for accepting or rejecting specific ages as meaningful to Keanakākoʻi history. Ages from sites that are best defined stratigraphically are examined first, followed by those less certain.

5.3. Lower part of Keanakākoʻi

Charcoal derived from small leaves, roots, and stems occurs at the base of, in, and along the top of the reticulite (Fig. 1) at many places in the summit area (Fig. 3, nos. 1–16). The mingling of charcoal with the reticulite, and the continuation of the internal charcoal with that both directly below and above the reticulite, suggest that fires were burning as the reticulite fell. They were likely started by the reticulite itself, given the widespread occurrence of the charcoal. None of the charcoal comes from the centers of large pieces of wood; this helps minimize the chance of “old” charcoal.

The 10 most robust dated sites are those where the reticulite rests directly on pāhoehoe (Table 1, nos. 2–10; Fig. 12, nos. 7–15) or on a 0.1–2.0‐cm‐thick gray lithic ash—the oldest Keanakākoʻi Tephra—deposited directly on the pāhoehoe (Table 1, no. 1; Fig. 12, no. 6). The underlying flows range in calendar age from about 1470 CE (younger ‘Ailawau flow of Clague et al., 1999) to about 1350 CE (some of the youngest flows from the Observatory shield, the edifice that existed before its summit collapsed to form today’s caldera; Neal and...
The lack of Kulanaokuaiki Tephra minimizes the chance of old charcoal, because vegetation returns more readily to weathered ash than to bare lava flows at Kīlauea. Ages from 6 localities where the reticulite rests on top of Kulanaokuaiki Tephra (Table 1, nos. 11–16) illustrate the possible pitfalls of old charcoal. Four of the ages (Fig. 12, nos. 16–19) are consistent with that of the reticulite on bare lava flows, but two (Fig. 12, nos. 4–5) are older and suggest either previous fires on the vegetated Kulanaokuaiki surface or old wood.

Fig. 14 shows that all of the radiocarbon ages have a wide range of possible calendar dates. This is because the calibration curve has a low slope from about 1450 to 1600 CE, leading to multiple solutions for a single 14C age (Reimer et al., 2004). In an attempt to improve the resolution, we combined the reticulite ages for four groups to evaluate a single “best” age for the deposit, using OxCal version 4 (Bronk Ramsey, 2009). Group R10 includes the ten ages obtained on bare lava flows or thin ash (Table 1, nos. 1–10); group R11, the 11 youngest ages, which may form a coherent cluster (Table 1, nos. 2–3, 6–11, 13–15); group R14, all ages except the two oldest (Table 1, nos. 1–11, 13–15); and group R16, all 16 ages.

The results (Table 2) show that the late 1400s and early 1500s is a credible time for the reticulite to have been erupted. The late 1500s or early 1600s is another possible range, though generally at lesser probability. Group R16 is of questionable validity, given the two old ages (Table 1, nos. 12 and 16) obtained for charcoal on the surface of the Kulanaokuaiki Tephra. Group R11 is only marginally defendable, but supported by the sequence analysis shown in Fig. 13. Vertical line indicates 1790, year when Keanakāko‘i was previously thought to have been erupted.

Sample numbers are cross-correlated in Table 1 with the original reported ages. One age (Table 1, no. 96) is not plotted, because it is from charcoal poorly constrained stratigraphically and clearly older than Keanakāko‘i.
because it specifically excludes 3 ages of only slightly older $^{14}$C age. On balance, we favor group R14, because it includes all ages except the two oldest, and a generalized calendar age of 1500 CE for the reticulite eruption, allowing for 2–3 decades on either side of that year. A later discussion, utilizing dated units in stratigraphic sequence, also favors a generalized date of about 1500 and shows that the late 1500s–early 1600s period is unlikely. The ages clearly show that the reticulite was not erupted in 1790.

5.4. Units directly below and above the reticulite

Charcoal occurs at the base of the 1–2-cm-thick, gray-pink lithic ash underly ing the reticulite (Fig. 1). Of three ages with Kulanakuaii underneath, one (Table 1, no. 17) has a geologically reasonable age similar to that of the reticulite (Fig. 12, no. 2), and one (Table 1, no. 18) is too old and probably the product of an earlier fire or old wood. The third age (Table 1, no. 19), from charcoal at the contact of the gray-pink lithic ash and the ‘Ahulau flow, is anomalously young for an unknown reason.

A coarse, pink, lithic fall and PDC deposit occurs in a limited area northeast of the caldera, where it rests directly on the reticulite (Fig. 1). This deposit, equivalent to layer 5 of McPhie et al. (1990) and called the Housing Area block fall by us, forms an excellent stratigraphic marker. Its finer-grained marginal facies, pink to tan lithic ash (layer 0 of McPhie et al., 1990) a few centimeters thick, occurs on all sides of the caldera except the south.

The Housing Area block-fall deposit was hot, as its pink color indicates, and produced charcoal that was dated at four localities. Three ages (Table 1, nos. 21–23; Fig. 12, nos. 21–23) are consistent with that of the underlying reticulite, and we combined them to yield an age of 307 ± 23 radiocarbon years BP (Table 3) that we use later in the sequence analysis. The fourth age (Table 1, no. 20) is too old by at least 50 years (Fig. 4, no. 20). This anomalous locality is on top of a young flow of the Observatory shield (the lava flows of Volcano village; unit k4ov of Neal and Lockwood, 2002) that pre dates the ‘Ahulau flow. Possibly an old tree was burned by the Housing Area block fall, or some pre-existing charcoal was incorporated in the deposit.

5.5. Layer 6 scoria fall (McPhie et al., 1990)

A widespread, easily recognizable scoria fall blankets the area southeastward from Kilauea’s caldera to the seacoast, 20 km distant. This deposit is one of the most intriguing in the Keanakakoi eruption, allowing for 2–3 decades on either side of that year. A later discussion, utilizing dated units in stratigraphic sequence, also favors a generalized date of about 1500 and shows that the late 1500s–early 1600s period is unlikely. The ages clearly show that the reticulite was not erupted in 1790.

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Table 2

<table>
<thead>
<tr>
<th>Group</th>
<th>Combined $^{14}$C age</th>
<th>Calendar age (CE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95.4% (2 sigma)</td>
<td>99.7% (3 sigma)</td>
</tr>
<tr>
<td>R10</td>
<td>373 ± 12</td>
<td>1453–1515 (72.1%); 1447–1524 (73.4%); 1522–1627 (26.3%)</td>
</tr>
<tr>
<td>R11</td>
<td>350 ± 11</td>
<td>1471–1524 (46.5%); 1458–1530 (48.3%); 1551–1635 (51.4%)</td>
</tr>
<tr>
<td>R14</td>
<td>371 ± 10</td>
<td>1454–1515 (70.4%); 1448–1524 (72.1%); 1573–1624 (27.6%)</td>
</tr>
<tr>
<td>R16</td>
<td>395 ± 10</td>
<td>1446–1488 (55.4%); 1442–1510 (56.8%); 1601–1614 (2.9%)</td>
</tr>
</tbody>
</table>

5.6. Interbedded lava flows

Both $^{14}$C-dated lava flows interbedded with the Keanakakoi eruption, and thin vitric ash above the Housing Area deposit and underlies lithic ash and lapilli. Charcoal collected beneath the flow in Kipuka Ki (Fig. 3) was dated by conventional methods and later rerun (Table 1 and Fig. 3, nos. 40–41; W3871 and W4919, respectively, in Rubin et al., 1987, table 10.1). Later, an AMS age was obtained on different charcoal from the same locality (Table 1 and Fig. 3, no. 42). The three ages combine to 338 ± 31 BP (Table 3).

The Kipuka Mauna’iu flow overlies Keanakakoi vitric ash and thus is younger than both the reticulite and Housing Area deposits. It underlies lithic ash capped by an accretionary lapilli ash of probable 1790 age. Three ages are available for charcoal at the base of the flow. Two were previously determined by conventional methods (Table 1 and Fig. 3, no. 43–44; W5106 and W4006 in Rubin et al., 1987, table 10.1). An AMS age was later measured on a different sample (Table 1 and Fig. 3, no. 45). A combined age is 323 ± 32 BP (Table 3), remarkably similar to that for the young Ke‘amoku flow. Each has a calendar age range in the 2-sigma range of 1470–1640; sequence analysis narrows this range to early 1500s–mid 1600s (Fig. 13).

5.7. Lithic part of the section (layers 11–16 of McPhie et al., 1990)

Most of the lithic deposits lie above the largest erosional unconformity in the Keanakakoi (Figs. 1, 7, 10). This part of the section is dominated by lithic PDCs, including surges, and fall deposits, many with a small juvenile component. The lithic beds include the deposits of 1790 as well as probably older falls and PDCs, and a thin, possibly
younger ash-fall bed associated with emplacement of ballistic blocks and lapilli (Swanson et al., 2010).

The erosional unconformity is muted or absent in areas of low relief on the western, northern, and eastern sides of the caldera. Here, a normally graded lithic–vitric ash bed less than 5 cm thick, overlain by accretionary lapilli ash of similar thickness, lies along the vitric–lithic contact. This doublet, and in particular the normally graded mixed ash, serves as a useful marker bed in the field. Charcoal was collected and dated from 7 proximal or medial localities in, or at the base of, the lithic section. All of the samples come from sections containing the reticulite and Housing Area block fall or ash, but none contains layer 6. Consequently, the only stratigraphic constraint on the dated samples is imposed by units low in the Keanakākī section (Fig. 1). However, where layer 6 is present near the caldera, several centimeters to 3.5 m of mixed vitric–lithic ash separate it from the lithic section. Barring complications, the age of charcoal from the lithic section or the unconformity at its base should therefore be younger than about 1650.

Two ages are from charcoal along an unconformity between the vitric and lithic parts of the section (Table 1, nos. 48–49; Fig. 12, nos. 91–92), exposed during excavations near the national park’s entrance station. The unconformity in this area is on nearly flat ground not subject to water erosion and was probably formed by PDCs scouring into unconsolidated vitric ash. Strictly interpreted, the charcoal ages suggest a surge or other PDC event in about 1660, though the age could be much younger if the older of the two ages is on old wood.

Another age from this area is on charcoal at the base of a surge deposit high in the lithic section (Table 1, no. 50) and calibrates at 2 sigma to the 1680–1760 time frame (Fig. 12, no. 97). Four ages are for charcoal collected in temporary excavations at Kīlauea Military Camp (KMC) in 1998 and 2007. Two of these come from small pieces of charcoal in a 13-cm-thick surge deposit 94 cm above the top of the Housing Area deposit and 36 cm above the base of the lithic section; its top is 10 cm below the top of the Keanakākī (Table 1, nos. 51–52; Fig. 12, nos. 95–96). The two ages yield a combined 171 ± 36 BP for the young surge and are consistent with a date from the mid 1600s to 1790 (Table 3). The age of the young surge can be narrowed to the mid to late 1700s when the ages of vitric and lithic ash beds below it are considered later in the paper (Fig. 14).

A third KMC age is from a small plant in growth position, rooted in a probable surge deposit and overlain by a coarse ash-fine lapilli fall deposit (Table 1, no. 53), 63 cm above the Housing Area deposit, 18 cm above the base of the lithic section, and 32 cm below the bulldozed ground surface. It has a 2-sigma calendar date of 1688–1730 (Fig. 12, no. 94; not plotted is the stratigraphically inconsistent range of 1809–1926).

The fourth age from KMC is for charcoal at the base of the normally graded mixed ash bed, exposed in a temporary trench, 18 cm above the top of the Housing Area deposit and 71 cm below the top of the Keanakākī (Table 1, no. 54; Fig. 12, no. 93). Its calibrated range at 2 sigma is 1694–1727 (24%; the other calendar ages are younger than 1812).

The distal part of the lithic section is represented by thin beds of ash, some with accretionary lapilli, as in the sand dunes described above (Fig. 2). Charcoal in lithic ash above prominent accretionary lapilli-rich beds was recovered and dated from three distal localities lacking any stratigraphic constraint other than that of the lithic unit itself (Table 1 and Fig. 3, nos. 55–57). They calibrate to calendar dates that could record eruptions from the late 17th century to the early 19th century (Fig. 12, nos. 98–100).

### 5.8. Parts of the section constrained by marker units

Charcoal at four localities was collected from vitric ash several centimeters above the reticulite and below layer 6, with the Housing Area deposit missing. The four ages (Table 1, nos. 58–61) have 2-sigma calendar ranges consistent with, though not unique to, their stratigraphic position between the two marker beds (Fig. 12, nos. 24–27).

Fourteen ages (Table 1, nos. 62–75) come from vitric and mixed vitric–lithic ash in sections above the reticulite and below the lithic part of the section but lacking the Housing Area deposit. The four ages (Table 1, nos. 58–61) have 2-sigma calendar ranges consistent with, though not unique to, their stratigraphic position between the two marker beds (Fig. 12, nos. 24–27).

Twenty ages were obtained above observed layer 6 and below the observed lithic part of the section. Nineteen of those ages (Table 1 and Fig. 3, nos. 77–95) allow, and most require, a 2-sigma calendar age younger than that of layer 6, consistent with the stratigraphy (Fig. 12, nos. 68–86). The one inconsistent result (Table 1 and Fig. 3, no. 76; Fig. 12, no. 67) has a youngest 2-sigma calendar age that is slightly older than that of layer 6. The ash containing this charcoal comes from 10 cm above the top of layer 6 and rests on a slightly red surface, possibly an incipient soil at the top of layer 7 of McPhie et al. (1990). This age is marginally too old for an unknown reason.

---

**Table 3**

Combined radiocarbon ages and calendar years using only the marker units, our best estimate for the age of those units except the young surge (see text). For layer 6, two alternatives shown in italics are also given but are not preferred. See text.

<table>
<thead>
<tr>
<th>Stratigraphic unit</th>
<th>Combined</th>
<th>Calendar age (CE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14C age</td>
<td></td>
</tr>
<tr>
<td>Young surge</td>
<td>171 ± 36</td>
<td>1655–1706 (18.5%); 1647–1895 (80.8%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1720–1820 (47.9%)</td>
</tr>
<tr>
<td></td>
<td>1906–1907</td>
<td>1647–1895 (80.8%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1720–1820 (47.9%)</td>
</tr>
<tr>
<td>Layer 6 (best 8)</td>
<td>239 ± 14</td>
<td>1646–1668 (71.6%); 1641–1670 (72.9%); 1688–1700 (74.2%); 1690–1700 (74.5%)</td>
</tr>
<tr>
<td>Layer 6</td>
<td>349 ± 20</td>
<td>1643–1529 (41.6%); 1454–1640 (99.7%)</td>
</tr>
<tr>
<td>(on Kulanaokouki)</td>
<td></td>
<td>1544–1634 (53.8%)</td>
</tr>
<tr>
<td>Layer 6 (all 14)</td>
<td>288 ± 11</td>
<td>1525–1558 (49.4%); 1520–1592 (52.7%); 1554–1589 (55.6%); 1631–1650 (46.0%); 1622–1655 (47.0%)</td>
</tr>
<tr>
<td>Kipuka Mauna’i’u</td>
<td>323 ± 32</td>
<td>1475–1645 (95.4%); 1451–1656 (99.7%)</td>
</tr>
<tr>
<td>Young Ke’a’omoku</td>
<td>338 ± 31</td>
<td>1471–1641 (95.4%); 1450–1648 (99.7%)</td>
</tr>
<tr>
<td>Housing Area</td>
<td>307 ± 23</td>
<td>1494–1602 (72.6%); 1471–1655 (99.7%)</td>
</tr>
<tr>
<td>Reticulite (best 14)</td>
<td>371 ± 10</td>
<td>1454–1515 (70.4%); 1448–1524 (72.1%); 1600–1619 (25.0%); 1573–1624 (27.6%)</td>
</tr>
</tbody>
</table>

![Fig. 13](image-url)  
**Fig. 13.** Distributions of ages for charcoal associated with 6 marker units, calculated by combining several ages for each unit (see text) and then placing them in sequence using OxCal v. 4.1.6 (Bronk Ramsey, 2009). Relative ages of units Kipuka Mauna’i’u, Ke’a’omoku, and Layer 6 best 8 are not known, but plot shows that layer 6 is almost certainly younger than the two lava flows. Bars show 68.2% and 95.4% probabilities. The date 1790 is assumed to be the youngest possible date.
5.9. Stratigraphically unconstrained or poorly constrained ages

Keanakākoʻi Tephra directly overlies Kulanaokuaiki Tephra across broad areas away from the summit where no marker bed occurs. In such areas, the base of the Keanakākoʻi is defined by a thin deposit of fresh vitric ash resting on the weathered Kulanaokuaiki. One example is in Kpuka KI (Fig. 3, KK), 6 km northwest of the caldera, where glassy Pele’s tears and hair of the Keanakākoʻi rest on weathered ash; charcoal along the contact yields a pre-Keanakākoʻi 2-sigma calendar age of 1299–1441 CE (Table 1 and Fig. 3, no. 96); this age is not plotted in Fig. 12.

Charcoal was dated from the top of the vitric section under lithic ash at three distal localities (Table 1 and Fig. 3, no. 99–101). The vitric ash is only 1–2 cm thick and lies directly on Kulanaokuaiki Tephra. Given the stratigraphic context, the 2-sigma calibrated ages (Fig. 12, nos. 87–89) suggest a fire in the mid-late 1600s to early 1700s, possibly associated with the fall of layer 6, the western margin of which is just east of the charcoal sites. One pair of samples straddles the vitric–lithic contact; the 2-sigma calibrated ages of the two (Table 1, nos. 55 and 100) are indistinguishable (Fig. 12, nos. 98 and 88). At another locality in the same area (Table 1 and Fig. 3, no. 98), charcoal along the contact of the Keanakākoʻi vitric ash and the underlying weathered Kulanaokuaiki has a calibrated age (Fig. 12, no. 66) most likely from the time between the reticulite and layer 6, once again possibly related to a fire associated with layer 6.

Two samples of charcoal from near or at the base of the lithic part of the Keanakākoʻi were collected near, but not in the same section as, the Kpuka Maunaʻiu flow at ʻŌhaikea (Fig. 3) southwest of the summit. The samples may be at about the same stratigraphic level as the flow, to judge from the local ash stratigraphy. The calibrated ages (Table 1 and Fig. 3, no. 46–47; Fig. 12, nos. 34–35) range from early 16th century to early 19th century; they confirm that the ash is Keanakākoʻi, not Kulanaokuaiki, but do not constrain the ages of any units within the Keanakākoʻi.

Finally, charcoal from the lower half of a 9-cm-thick, coarse to fine lithic ash resting on the ʻAilāʻau flow in Mauna Loa Estates (Table 1 and Fig. 3, no. 97) was calibrated as late 17th century to early 19th century (Fig. 12, no. 90). No marker bed occurs in the section, but
reticulate crops out nearby and was probably eroded away from the charcoal site before the dated lithic tephra was deposited.

5.10. Ages in stratigraphic sequence

The combined calibrated ages for the six dated marker units are consistent with their stratigraphic position. Fig. 13 was constructed using the “Sequence” model in OxCal (Bronk Ramsey, 2009), with a boundary condition of 1790 for the youngest eruption. The relative stratigraphic order among the two lava flows and layer 6 is not known, but all three are younger than the Housing Area and older than the Young Surge, and the combined ages make it very likely that layer 6 is younger than the two flows. The reticulate is unlikely to have been erupted in the early 1600s, a possibility permitted by the combined R14 age; taking into account younger tephra (Fig. 14B), the reticulate could not have been erupted so late. Fig. 13 shows clearly that the Keanakākoʻi Tephra was erupted over an approximately 300-year period from about 1500 to 1790 CE.

Charcoal ages for other tephra deposits can be constrained by their stratigraphic position between the marker units. For example, Fig. 14A shows 16 ages for vitric ash above layer 6 and below the lithic part of the section, represented by the young surge. Many of the ages overlap with that for layer 6 and are for charcoal in or downwind of the layer 6 dispersal. This raises the possibility that the large layer 6 scoria fall generated fires that spread downwind, forming small charcoal fragments that became incorporated in the immediately overlying ash. This idea is not testable but is appealing in that it minimizes the number of fires needed to form the charcoal.

Fig. 14B plots some ages for vitric ash without layer 6 in the section and shows that some of the ages almost certainly predate layer 6 and others are about the same age or younger. This is consistent with the stratigraphic position of layer 6, interbedded with vitric ash in the wall of the caldera (Fig. 1).

Ages for lithic ash above layer 6 (Fig. 14C) show the expected range, ranging from only a little younger than layer 6 up to about 1790.

Fig. 12 shows all the calibrated ages arranged according to our preferred interpretation and constrained by their stratigraphic position relative to the marker units. No sequence analysis was performed on the entire data set, as was done for Figs. 13 and 14. Instead, just the raw calibrated ages are shown; they generally decrease upsection and make our point with minimal statistics. Younger vitric units, and possibly some of the older lithic units as well, have ages suggesting late 17th and 18th century eruptions. Most of the lithic unit, particularly where it lies above the well-defined erosional unconformity, was likely deposited in the 18th century. Explosive eruptions dominated by lithic debris may have continued until at least February 12, 1794, when Archibald Menzies reported “smoke, dust, and ashes arising from [the caldera]” some 20–25 km upwind of his location, though this has often been interpreted as a dust storm (Hitchcock, 1909, p. 72, 161). The youngest eruption produced the golden pumice, deposited “possibly around 1820” (Sharp et al., 1987).

It is notable that the 14C ages of such young deposits can be placed in a reasonable stratigraphic order consistent with the physical stratigraphy. Many ages, however, were needed to construct this figure; only a few would have been inadequate, given the wide uncertainty in assigning calendar ages to such young 14C ages and the poorly constrained nature of some samples.

Our summary interpretation of the ages, in the context of the physical stratigraphy, is that the Keanakākoʻi eruptions began in about 1470–1510 CE and continued sporadically into the early 19th century. They could have started a little earlier if the 1470 age for the end of the Ailāʻau eruption is too young. Oxidized horizons, particularly the one probably at the top of layer 7, may record periods of quiet lasting several decades, enough time for soil to begin forming. The deep erosional unconformity at the base of the lithic section likewise implies eruptive quiet, perhaps lasting several decades. Clearly the 14C ages do not support previous interpretations that all Keanakākoʻi eruptions took place in 1790. The ages are about as consistent with the physical relations as can be expected, given the difficulty in calibrating such young ages to calendar years. Most of the “too old” ages likely document either old fires or old vegetation growing on the Kulanauokuaiki Tephra. One age—the young age for the gray lithic ash under the reticulate (Table 1, no. 19)—remains enigmatic.

6. Age of Kilauea’s caldera

Caldera subsidence has often been tied to the date of the Keanakākoʻi Tephra (Decker and Christiansen, 1984; Holcomb, 1987). This paper shows that the Keanakākoʻi was erupted over a 300-year period. Where does the caldera fit into this time frame? This question can be answered from key stratigraphic relations in the summit area.

The outermost fault bounding the eastern margin of the caldera (Neal and Lockwood, 2002) cuts across the shield (Figs. 3, 16) built during the Ailāʻau eruption, which lasted for about 60 years and ended in about 1470 CE (Clague et al., 1999). The older Observatory eruptive center or shield (Holcomb, 1987), which collapsed to form most of the caldera, existed during the Ailāʻau eruption, because Ailāʻau flows advanced only a short distance west from their vent, blocked by the Observatory edifice (Neal and Lockwood, 2002). Thus the caldera postdates the Ailāʻau eruption and is younger than about 1470 CE. How much younger?

The nature of the Keanakākoʻi reticulate helps answer this question. Reticulate typically forms only in high lava fountains (consistent with very rapid ascent rates, according to Rust and Cashman, 2006) and has seldom if ever been noted at Kilauea from fountains less than 300 m high, more often 400 m or more. In tephras deposits from such high modern fountains (1959 Kilauea Iki, 1969 Mauna Ulu, and 1983–86 Pu’u O’o), reticulate is mostly found only several kilometers downwind from the vent. Near the vent, its place is taken by denser pumice and vitric scoria, products with much greater fall velocities.

The Keanakākoʻi reticulate is nearly pure, containing only small amounts of pumice and Pele’s tears or achneliths (Fig. 17). It encircles the caldera, with changes in grain size and componentry (May et al., 2009) consistent with eruption from several vents within the caldera (along a ring fracture?). Moreover, it is as thick as 65 cm in places along the western caldera rim and 20–30 cm along the northern and eastern rims. Thus the reticulate is almost certainly not a distal deposit several kilometers from the vent and must have had a source in the caldera. Why, then, is it so pure?

This can be explained by eruption of high fountains on the floor of a deep caldera—so deep that most of the pumice and denser pyroclasts were trapped within the caldera. The depth of the caldera was probably greater than 300 m and perhaps 200–300 m deeper. There is no evidence of external water influencing the reticulate eruption, so one limit on the depth of the caldera might be the water table, today a little more than 600 m below the high point on the caldera rim and about 500 m below the present caldera floor (Mastin, 1997). However, one can envision scenarios whereby caldera collapse and eruption took place too rapidly for external water to play a role, even below the water table. Whatever the depth, this reasoning suggests that the caldera was already deep when the reticulate was erupted.

The preceding discussion indicates that the caldera formed between about 1470 and 1510 CE. Other evidence supports such an early caldera. Small remnants of the two oldest deposits in the Keanakākoʻi, the gray lithic ash and the reticulate, are plastered against the nearly vertical walls of the caldera in several places, most notably just above the northeastern floor of the modern caldera. Thin veneers of vitric ash that correlate with deposits just above the reticulate cling to, and
occupy niches in, the vertical caldera wall 800 m west-southwest of Keanakākoʻi Crater (Figs. 3, 15). Such plastering relations indicate that the wall existed when this ash was erupted, pointing toward early formation of the caldera.

In 1823, William Ellis, the first European visitor to the caldera, was told that lava erupted at the summit previously flowed over the surrounding countryside but that “for many kings’ reigns past” it had been confined to what is today called the caldera (Ellis, 1825; Swanson, 2008). This agrees with the known eruptive history at Kilauea’s summit, where the most recent eruption outside the caldera was from the 15th century ‘Ailāau shield (Figs. 3 (AS), 16; Neal and Lockwood, 2002; Clague et al., 1999). Thus the oral tradition is consistent with the geologic record in suggesting an old caldera, not one formed entirely in 1790.

The evidence presented here suggests that the caldera was already deep when the Keanakākoʻi eruptions began. A depth of several hundred meters, required by the reticulate deposit, is far greater than the modern depth of about 120 m but comparable to the measured depth of about 400 m in 1825 (Byron, 1827, p. 184 [corrected by Mastin, 1997]) and the estimated depth of at least 540 m in 1823 (Mastin, 1997). Mastin (1997; Mastin et al., 2004) makes the point that the texture and volatile content of the vitric tephra (Fig. 1, layers 1–4) above the reticulate suggest that vents were near or at the depth of the water table, about 515 m below today’s caldera floor and attainable if the caldera were about 600 m deep. These observations and interpretations make it clear that a deep caldera existed in the early 19th century and probably in the early-mid 16th century, consistent with our independent interpretations.

Finally, Hawaiian chants suggest that a sister of Pele, the volcano deity, dug the caldera so deeply soon after the ‘Ailāau eruption that there were warnings about water coming in and drowning the “fires of Pele” (Emerson, 1915; Swanson, 2008). This oral tradition suggests a great initial depth of the caldera, perhaps close to or even intersecting the water table. It also suggests that a major collapse took place, but whether it was the final event in a series of incremental collapses or a single collapse is not clear from the chants.

There could have been smaller, nested collapses of the caldera floor between 1500 and the late 18th century; in fact, such collapses are likely to have occurred as caldera filling took place episodically, possibly including the large eruption in 1790. Nonetheless, the boundary faults created during the initial, main collapse persist today, and the caldera was deep very early in its history.

7. What caused the caldera to form?

The evidence just presented shows that the caldera formed just after the ‘Ailāau eruption ended and before the Keanakākoʻi eruptions began. It is possible that the collapse caused the long-lived eruption to end. In any case, no explosive ejecta were projected over the rim, except for the thin gray-pink lithic ash at the base of the Keanakākoʻi. Hawaiian chants suggest that rocks were “flying” as the caldera formed (Swanson, 2008), but apparently these were confined to within the down-dropping caldera and could well have been rock falls.

We estimate the caldera collapse volume to have been 4–6 km$^3$, assuming a depth of 600 m, diameters of 3.5 km by 3 km (about the diameters of the modern summit depression), and various shapes of collapse. This volume likely represents the amount of magma evacuated from the summit reservoir. In keeping with most models for caldera formation, this evacuation would have been rapid. It should be a simple field exercise to identify such a huge lava flow that gushed onto Kilauea’s surface only 500 years ago, but no such flow has been recognized anywhere on the volcano—including the Puna Ridge, the submarine extension of the east rift zone (Smith et al., 2002), though rapid sedimentation there might partly obscure such a flow.

Alternatively, a volume of 4–6 km$^3$ may have been intruded into one of Kilauea’s rift zones. In this scenario, the east rift zone (Fig. 16)—much larger than the southwest rift zone—would have been the most likely site of intrusion, possibly enabled by a large slip event that displaced the volcano’s south flank many meters seaward and dilated the rift zone. A dike 40–60 km long, 5 km high, and 20 m wide could accommodate such a volume. A dike 10 km high, reaching down to the base of the volcano, would still require a 10-m-wide dike, about an order of magnitude wider than most measured dikes in Hawaiian shields (Walker, 1986). Such an event might account for much of the displacement in the Ko‘ere fault system (Fig. 18), which connects the east and southwest rift zones and forms part of the boundary of the mobile south flank (Duffield, 1975; Fiske and Swanson, 1992). More than 30 m of extension have accumulated across the 2.5-km-wide fault system since it was covered by a lava flow about 700 years ago. The extension probably resulted from several large slip events, one of which could reasonably relate to caldera formation.

The volume of the ‘Ailāau flow (Fig. 16) and shield, 4–6 km$^3$ (Clague et al., 1999), is similar to that assumed for the early caldera. Is that only a coincidence? Possibly its slow eruption, lasting for about 60 years at a rate comparable to that of the current Pu‘u‘O‘o eruption, gradually withdrew magma from the summit reservoir complex, eventually draining it to the point where its roof could no longer be supported. Probably more likely, caldera formation could have been incremental, beginning during the eruption and ending with a large collapse described by the oral tradition.

Another way to relate the large ‘Ailāau eruption to caldera formation is to consider the mass of the lava flow and shield, about 10$^{10}$ tonnes. Perhaps this mass, added over 60 years to the surface of the volcano, weakened it to the point where the edifice failed and the south flank (Fig. 16) slipped seaward, splitting open the east rift zone, draining the summit reservoir, and causing collapse as well as
ending the eruption. Incremental collapse might be favored if the magma reservoir consisted of separate bodies (Fiske and Kinoshita, 1969), as in a sill-like complex, rather than a single balloon-like chamber often used in modeling.

We are left with an unsatisfactory explanation for the origin of the caldera. Yet understanding the cause(s) of caldera formation at Kīlauea takes on more relevance than might first appear, for the ongoing Pūʻōʻō eruption is in its 29th year (in 2011), about half the duration of the ʻAilāʻau eruption. What will happen if the current activity persists for as long as that eruption? The caldera was subsiding for the first 20 years of the Pūʻōʻō eruption and by 2004 had dropped about 2 m. This could be interpreted as sagging above an emptying reservoir. The subsidence ended in 2004, however, and has not resumed at this writing.

8. Relation of explosive activity to calderas at Kīlauea

Two prolonged periods of episodic explosive activity are now reasonably well defined at Kīlauea, represented by the Keanakākoʻi Tephra and the Uwēkahuna Tephra, including its best studied member, the Kulanaokuaiki Tephra (Fiske et al., 2009). The Keanakākoʻi lasted about 300 y, and the Uwēkahuna perhaps 1000–1200 y, ending in about 900–1000 CE.

Both units formed when a caldera existed at Kīlauea’s summit. This paper describes the Keanakākoʻi situation. The Uwēkahuna was erupted from the Powers caldera of Holcomb (1987), the forerunner of the modern caldera. The Uwēkahuna is present on the northwest wall of today’s caldera below the Hawaiian Volcano Observatory (Fig. 3, HVO) and is described by Fiske et al. (2009) in two stratigraphic sections, the mid-Bluff and Bluff-base sections. The two sections are about 100 m and 130 m, respectively, below the rim of the Powers caldera as defined at nearby Tree Molds (Fig. 3, TM; Fiske et al., 2009). These relations indicate that the Powers caldera was at least 130 m deep when the Uwēkahuna was erupted. The two sections are overlain by lava flows that built the Observatory shield (Holcomb, 1987) between about 1000 and 1400 CE and later collapsed to form the modern caldera.

A caldera setting probably facilitates the potential for phreatomagmatic eruptions, as suggested for Kīlauea by Mastin (1997; Mastin et al., 2004). Both the Uwēkahuna and Keanakākoʻi record numerous phreatomagmatic eruptions, particularly early in their history, consistent with vents in a deep caldera where magma and external water could interact. Each unit had explosive eruptions later in its development that may not have involved much external water (Keanakākoʻi layer 6, Kulanaokuaiki units 1, 3, and 5)—perhaps as the caldera fill became thick enough to minimize phreatomagmatic activity.

The two examples of prolonged explosive periods suggest that a caldera may be necessary at Kīlauea to enable such periods. If so, the rapid filling of the modern caldera following the 1750 explosive eruption (Mastin, 1997) may have sharply minimized the chance for explosive eruptions to resume. The latest Keanakākoʻi eruption, in the early 1800s (Sharp et al., 1987) produced “dry” pumice from a tuff fountain; by that time the caldera had possibly thickened enough to inhibit external water involvement.

Minor explosive eruptions can take place at Kīlauea’s summit under specific circumstances, even with a full caldera. The phreatic eruptions in 1924 resulted from draining of a lava lake in Halemaʻumaʻu to below the water table (Jaggard and Finch, 1924; Decker and Christiansen, 1984), and one tiny explosive eruption at Halemaʻumaʻu in 2008 was apparently caused by choking of a gas vent (Houghton et al., 2011; others in 2008 and 2011 were triggered by rock falls into lava). But it seems to us that another prolonged period of major explosive activity will have to await the formation of a new caldera. From a short-term hazards perspective, this may be reassuring. In the long term, however, caldera collapse is likely to occur.

9. Conclusions

The Keanakākoʻi Tephra was produced by multiple eruptions throughout a 300-year period starting in about 1470–1510 CE. This conclusion, supported by several characteristics of the physical stratigraphy and by 97 new AMS 14C ages, differs from the previous view that the Keanakākoʻi was formed during a single eruption in 1790. A challenge being tackled by on-going work is relating single depositional units or packages to changing vent locations and eruption styles during the 300 years of explosive activity.

Kīlauea’s caldera formed between the end of the 60-yr-long ʻAilāʻau eruption in about 1470 CE and the start of the Keanakākoʻi eruptions. This is consistent with oral tradition but 300 years older than commonly assumed. Caldera formation took place during essentially the same time period as the initiation of Keanakākoʻi eruptions, but stratigraphic relations indicate that the caldera formed first by collapse.

Physical characteristics of the Keanakākoʻi reticulate, and veneers of early ash plastered against today’s caldera walls, indicate a depth of at least a few hundred meters for the caldera soon after it formed.
Thus the caldera reached its great depth quickly, likely in days to weeks, not slowly over decades.

Caldera collapse was neither explosive nor related to the rapid effusion of a huge lava flow. A better explanation is a massive intrusion of some 4–6 km$^3$ of magma into the east rift zone from the summit reservoir. Another hypothesis relates the slow eruption of the 4–6-km$^3$ A’i’au flow to the caldera of similar volume by postulating incremental collapses as the reservoir gradually emptied, eventually leading to the final large collapse as conveyed in oral tradition.

Prolonged periods of explosive eruptions at Kilauea may require the presence of a caldera to sustain them. The current situation does not favor resumption of major explosive activity, though this could change overnight with the development of a new caldera.

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Fig. 18. Map showing that the Koae fault system (KFS) and most of the east and southwest rift zones form the landward boundary of the mobile south flank. The east rift zone trends southeastward from the caldera to its intersection with the Koae fault system, where it bends east-northeastward. The Koae fault system is a noneruptive extension of the east rift zone and blends into the southwest rift zone. The Hilina fault system is a series of normal faults in the south flank. Lines are ground cracks and faults north of the south flank, simplified from Neal and Lockwood (2002) and Wolfe and Morris (1996).

References

Finch, R.H., 1925. The ash deposits at Kilauea Volcano. The Volcano Letter 17, 1.