Cycles of explosive and effusive eruptions at Kīlauea Volcano, Hawaiʻi

Donald A. Swanson[1], Timothy R. Rose[2], Adonara E. Mucek[3], Michael O. Garcia[3], Richard S. Fiske[2], and Larry G. Mastin[4]
[1]U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii National Park, Hawaii 96718, USA
[2]Department of Mineral Sciences, Museum of Natural History, Smithsonian Institution, Washington, D.C. 20013, USA
[3]Department of Geology and Geophysics, SOEST (School of Ocean and Earth Science and Technology), University of Hawaiʻi, Honolulu, Hawaiʻi 96822, USA
[4]U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington 98683, USA

ABSTRACT

The subaerial eruptive activity at Kīlauea Volcano (Hawaiʻi) for the past 2500 yr can be divided into 3 dominantly effusive and 2 dominantly explosive periods, each lasting several centuries. The prevailing style of eruption for 60% of this time was explosive, manifested by repeated phreatic and phreatomagmatic activity in a deep summit caldera. During dominantly explosive periods, the magma supply rate to the shallow storage volume beneath the summit dropped to only a few percent of that during mainly effusive periods. The frequency and duration of explosive activity are contrary to the popular impression that Kīlauea is almost unceasingly effusive. Explosive activity apparently correlates with the presence of a caldera intersecting the water table. The decrease in magma supply rate may result in caldera collapse, because erupted or intruded magma is not replaced. Glasses with unusually high MgO, TiO_2, and K_2O compositions occur only in explosive tephra (and one related lava flow) and are consistent with disruption of the shallow reservoir complex during caldera formation. Kīlauea is a complex, modulated system in which melting rate, supply rate, conduit stability (in both mantle and crust), reservoir geometry, water table, and many other factors interact with one another. The hazards associated with explosive activity at Kīlauea's summit would have major impact on local society if a future dominantly explosive period were to last several centuries. The association of lowered magma supply, caldera formation, and explosive activity might characterize other basaltic volcanoes, but has not been recognized.

INTRODUCTION

Kīlauea (Hawaiʻi) is an iconic effusive volcano, known for its lava flows and high fountains. Approximately 17% (250 km^2) of the volcano's subaerial flanks has been resurfaced by lava flows in the past 200 yr (Fig. 1), and the ongoing Puʻu ʻŌʻō eruption on the east rift zone, nearly continuous since 1983, covered >125 km^2 with >4 km^3 of lava by 2014.

Our analysis of Kīlauea's past 2500 yr shows, however, that explosive eruptions were dominant for periods lasting several centuries, not just brief diversions at an otherwise effusive volcano. We find that Kīlauea has been in a dominantly explosive mode ~60% of the past 2500 yr. The effusive style of the past 200 yr is, from that perspective, misleading.

For this paper we distinguish lava fountains, which at Kīlauea invariably feed lava flows and contain only juvenile components, from explosive eruptions, which do not feed lava flows and have at least some lithic components. In this usage, most of Kīlauea's explosive eruptions are phreatomagmatic or phreatic, though some may be products of overpressurized magmatic gas.

Kīlauea had many explosive eruptions older than those discussed here (Easton, 1987), but details are lacking. We deal with only the past 2500 yr, for which many ages and stratigraphic controls are available, and examine only periods lasting centuries, not short-term events of several years or less.

TWO DOMINANTLY EXPLOSIVE PERIODS

Recent studies indicate two long periods of time during which explosive activity dominated the summit region and adjacent south slope of Kīlauea (Fig. 2A). More than 140 calendar-calibrated ^{14}C ages (Tables DR2 and DR3 in the GSA Data Repository[1]; Stuiver and Reimer, 1993; Reimer et al., 2004) define the length of each explosive period, as interpreted in Fiske et al. (2009) and Swanson et al. (2012a).

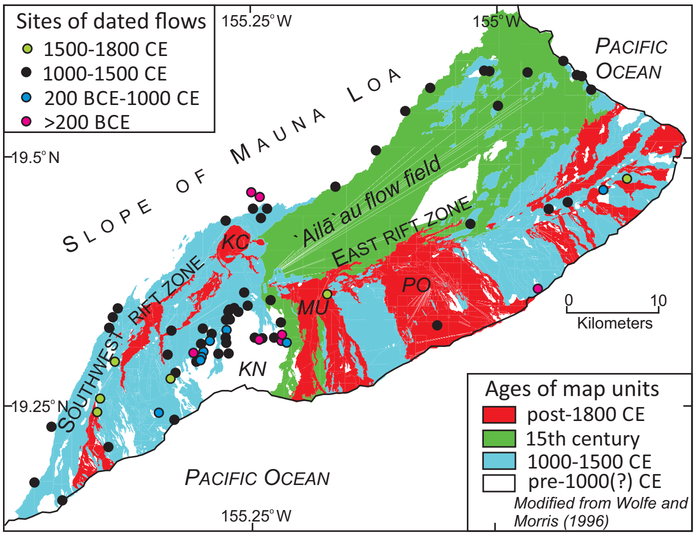

Figure 1. Locations of all ^{14}C-dated lava flow samples on Kīlauea Volcano (Hawaiʻi), color coded by time periods discussed in text. Data are available in Table DR1 (see footnote 1). Two sample locations north of Kīlauea Caldera (KC) with ages older than 200 BCE are shown beyond the limit of Kīlauea, because the dated flows are in the subsurface overlain by tephra. Map colors indicate general ages of lava flows compiled from map units of Wolfe and Morris (1996), assuming that their unit p4o is entirely younger than 1000 CE. All flows younger than 1800 CE were recorded during or shortly after the eruption. The 15th century ʻAilāʻau flow field is shown separately to emphasize its large size; samples along its margin date the flow field (Clague et al., 1999). Other flow fields: PO—Puʻu ʻŌʻō flow field (1983–present), which has enlarged somewhat from depiction of Wolfe and Morris (1996) used here; MU—Mauna Ulu flow field (1969–74); KN—Kīpuka Nēnē flow field (200–300 BCE).

The Uwēkahuna Ash contains deposits of explosive eruptions between ca. 200 BCE and 1000 CE (Fiske et al., 2009). Only three lava flows have been found interbedded with the Uwēkahuna Ash. Two are south of Kīlauea Caldera; a third is interleaved with tephra low on the caldera wall and may correlate paleomagnetically with one of the other flows (Fiske et al., 2009). The Keanakākoʻi Tephra Member was produced between ca. 1500 and 1800 CE (Swanson et al., 2012a). Only one lava flow was erupted at Kīlauea's summit during that time, from the outermost ring fault bounding the south caldera. Thus, for 2 periods of time lasting 1200 yr and 300 yr, Kīlauea's summit, normally the site of frequent lava flows (Holcomb, 1987; Neal and Lockwood, 2003), had little effusive ac-

[1]GSA Data Repository item 2014233, Tables DR1–DR3 and Figure DR1, showing all ^{14}C ages of lava flows and tephra and their calendar-calibrated ages, and Tables DR4 and DR5, presenting chemical data, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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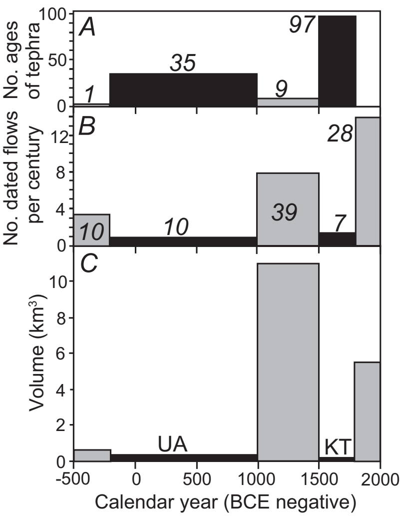

Figure 2. A: Histogram showing number (No.) of tephra ages, prepared from Tables DR2 and DR3 (see footnote 1). B: Histogram showing number of different dated lava flows per century in each eruptive period. Numbers indicate how many different flows were dated per period. From 1800 CE, only flows outside the caldera are counted, because intracaldera flows are not recognizable for earlier periods. Analytical data and original figure from which histogram was prepared are in Table DR1 and Figure DR1; entire calendar ranges were used except where constrained by stratigraphy. C: Histogram of estimated volume (not corrected for pore space) erupted subaerially during each eruptive period. Gray is dominantly effusive period. Black is dominantly explosive period. UA—Uwēkahuna Ash; KT—Keanakākoʻi Tephra Member.

tivity. Instead, almost all summit eruptions were explosive: sporadic, violent, and brief. In contrast, most eruptions during the intervening periods were frequent, effusive, and sometimes lasted for decades. This suggests a cyclicity in summit activity, shifting from mostly effusive to mostly explosive and back again.

DISTRIBUTION OF LAVA FLOW AGES

Did the rest of the volcano, beyond the extent of marker ash beds for the two dominantly explosive periods, behave similarly? To address this question, we compiled and calendar-calibrated all 93 known ^{14}C ages of Kīlauea lava flows younger than ca. 500 BCE (only a few ages are older than that; Table DR1). Figure 2B and Figure DR1 show the distribution of the calendar-calibrated flow ages with time for the past 2500 yr, with the two periods of major tephra production indicated. Lava flow ages cluster in periods between explosive eruptions. This is best shown for the past 1000 yr. Numerous ages plot in the 1000–1500 CE time interval, when the present summit shield was under construction (Holcomb, 1987; Neal and Lockwood, 2003); few are within the 1500–1800 CE period, when the Keanakākoʻi tephra was deposited, and numerous lava flows have been observed to form since 1800 (1823 CE is the actual age of the oldest known post-Keanakākoʻi flow). The number of flow ages is small before 1000 CE, but there appears to be an increase in the period 200–500 BCE (Fig. 2A), from 0.8 flows/100 yr to 3.3 flows/100 yr, bracketing the 200 BCE–1000 CE age of the Uwēkahuna Ash.

Three factors could weaken this pattern. The spatial distribution of lava flow ages is uneven (Fig. 1). The lower east rift zone is underrepresented. For example, flows from Heiheiahulu (Holcomb, 1987) and the so-called 1790 flow (Moore and Trusdell, 1991), both ascribed to the 18th century, are not dated.

Second, young flows cover old ones, so the temporal record becomes obscured with age. Few ages, however, plot in the 1200-yr-long period of tephra production, in contrast to the many flow ages in the following, much briefer, 500-yr-long period.

Third, flows along the Puna Ridge, the 75-km-long submarine extension of the east rift zone, are not dated well enough for our analysis (Smith et al., 2002). Palagonite rind thicknesses suggest ages for dredged samples of 700–24,000 yr, mostly 2000–7000 yr (Clague et al., 1995). This suggests relatively little eruptive activity during the past 2500 yr. The large flows at the base of the ridge are not young, based on sediment cover (Clague et al., 1995). We discuss only the subaerial edifice in this paper, but suspect that our conclusions apply to the Puna Ridge.

Acknowledging these caveats, we think that the clear pattern for the summit area holds for the entire subaerial edifice. We interpret the subaerial volcano to have undergone alternating periods of mostly explosive and mostly effusive eruptions for the past 2500 yr. Successive periods constitute explosive-effusive cycles of varying duration.

MAGMA SUPPLY DROPS DURING PERIODS OF MAINLY EXPLOSIVE ACTIVITY

How do eruptive volumes and rates of magma supply compare between the explosive and effusive periods? The volume of magma erupted during periods of dominantly explosive activity is far less than that during effusive periods (Fig. 2C), and the calculated magma supply rate is correspondingly lower, only 1%–2% of the effusive rate (Table 1). Our estimates of flow volumes (Table 1; Fig. 2C) are compromised by variable flow thickness and coverage by later flows. A simple comparison of tephra and flow thickness at the summit area, however, illustrates the disparity between effusive and explosive volumes.

TABLE 1. ESTIMATED VOLUME OF LAVA ERUPTED ON SUBAERIAL KĪLAUEA DURING DOMINANTLY EFFUSIVE AND DOMINANTLY EXPLOSIVE PERIODS

Calendar age range	Volume (km^3)	Magma supply rate (km^3/yr*)	Dominant style
500–200 BCE	>0.6	not calculated	Effusive
200 BCE–1000 CE	0.3	2.5×10^{-4}	Explosive
1000–1500 CE	11	2.2×10^{-2}	Effusive
1500–1800 CE	0.15	5×10^{-4}	Explosive
1800–present	5.5	2.6×10^{-2}	Effusive

Note: Effusive volumes estimated using mapped areas of flows and areas projected beneath younger flows, as shown on geologic maps (Wolfe and Morris, 1996; Neal and Lockwood, 2003), assuming an age consistent with ^{14}C data and unit label; thickness was estimated from field observations and topographic gradient. Explosive volumes were estimated from area and average thickness of juvenile tephra. Volumes were not adjusted for vesicularity (lava flows) or pore space (tephra).

*Average supply rate to ground surface for entire period. Not calculated for earliest period, which began before 500 BCE and so is incomplete.

The 140-m-high wall of Kīlauea Caldera is made almost entirely of flows erupted between 1000 and 1500 CE (Neal and Lockwood, 2003), when the Observatory shield was built (Holcomb, 1987); its total thickness is more, because the base of the shield is covered by caldera fill. In contrast, the maximum exposed thickness of the Keanakākoʻi tephra is only ~11 m (McPhie et al., 1990; Swanson et al., 2012a). The flow thickness is several meters thick 5 km southwest (downwind) of the summit, and the tephra is only several centimeters.

A similar comparison can be made for the Uwēkahuna Ash on Kīlauea's south flank. It is at most a few tens of centimeters thick, thinning to only a few centimeters at the coastline (Fiske et al., 2009), but the overlying and underlying flows are each at least several meters thick.

The striking difference in erupted volume between periods dominated by effusive and explosive activity must reflect a major disruption to the supply system that lasts for centuries. The disruption could take place anywhere between the point of melt accumulation in the mantle and the shallow storage system beneath Kīlauea's summit. Perhaps increased magma supply to Mauna Loa volcano causes a drop in supply to Kīlauea (Gonnermann et al., 2012). Once magma enters the Kīlauea plume, it could be diverted away from the shallow reservoir, perhaps as intrusions into the crust or lower shield (Lin et al., 2014). A subhorizontal mantle pathway of magma transport at ~30 km depth, interpreted by Wright and Klein (2006; see also Wolfe et al., 2003), might be a zone within which magma could stall or be diverted. Magma probably did not bypass the summit reservoir system and immediately erupt on the Puna Ridge, because lava compositions on the ridge are highly fractionated, reflecting shallow storage (Clague et al., 1995). Whatever the cause, a major change in the dynamics of Kīlauea's magma supply system is needed to explain the effusive-explosive cyclic behavior.

RELATION OF CALDERA TO CYCLES

Both explosive periods occurred when a deep caldera indented Kīlauea's summit. The Powers caldera existed during the time of deposition of the Uwēkahuna Ash (Powers, 1948; Holcomb, 1987) and only began filling ca. 1000 CE, as estimated from the age of the oldest flow overlying the Uwēkahuna Ash south of the caldera (Fiske et al., 2009). The modern caldera formed ca. 1500 CE, when the Keanakākoʻi explosive period started, and began to fill ca. 1800 CE (Swanson et al., 2012a). The phreatomagmatic and phreatic nature of most of the explosive eruptions suggests that the two calderas were often deep, at or below the water table (Mastin, 1997; Mastin et al., 2004). Today the water table is ~615 m below the highest point on the caldera rim, ~490 m below the caldera floor (Keller et al., 1979). We think it likely that parts of the floor were at least that deep during the dominantly explosive periods. The water table is unlikely to have been higher during the past few hundred years, to judge from the presence of fresh basalt above, and altered basalt below, today's water table (Hurwitz et al., 2002, 2003).

The cause of caldera formation at Kīlauea is uncertain. If the caldera collapsed because a large volume of magma was rapidly erupted or intruded into the east rift zone, as conventionally thought (Holcomb et al., 1988), then why did the average magma supply rate drop by almost two orders of magnitude and stay low for centuries? No relatively shallow, top-down process in the edifice is likely to cause such a long-term change in behavior.

Recognition of eruption cycles at Kīlauea raises a new possibility. Perhaps caldera formation results from reduction in magma supply to the shallow storage reservoir, a term we use for a configuration of multiple magma storage volumes (Fiske and Kinoshita, 1969; Dawson et al., 2004; Baker and Amelung, 2012; Poland et al., 2014). If magma supply dropped significantly, eruptions or intrusions might deplete the shallow reservoir, eventually leading to collapse of the overlying edifice. This bottom-up model seems best suited to explain the linked formation of the caldera and the ensuing decline in magma supply.

Before each explosive period, an effusive eruption took place that could have depleted the storage reservoir if magma supply were low. Extrusion of the 4–6 km^3 ʻAilāʻau flow field (Fig. 1) during an ~60 yr period (Clague et al., 1999) immediately preceded collapse of the modern caldera. The Kīpuka Nēnē flow field (Fig. 1; Holcomb, 1987) covers more than 130 km^2 (extrapolating back to its summit source) on Kīlauea's south flank and immediately underlies the Uwēkahuna Ash. Much of its volume could have flowed into the ocean, given its coastline width of ~7 km (Fig. 1). We estimate that at least 0.5 km^3 remains on land, and the total volume erupted could be several times larger.

An alternative bottom-up model is that an increase in mantle melting rate supplied the large flow fields preceding caldera formation. The increase could have depleted a relatively large volume of its melt components, so that little magma was available to enter the volcano for several centuries.

Both alternatives are at odds with the ongoing eruption of Puʻu ʻŌʻō, during which the supply rate has generally been ~0.12 km^3 yr^{-1}except for a temporary increase in 2003–2007 (Poland et al., 2012).

MgO-RICH AND FRACTIONATED VITRIC TEPHRA

Small volumes of MgO-rich juvenile ash occur in both the Uwēkahuna Ash and Keanakākoʻi tephra. Microprobe glass analyses show that vitric ash with MgO to 11 wt% occurs at several levels in the Keanakākoʻi tephra (Mastin et al., 2004; Table DR4), and one thin vitric ash in the Uwēkahuna Ash (Fiske et al., 2009) contains MgO values of 12.5 wt% (Table DR5A; Helz et al., 2014). Such high MgO contents in erupted melt are unprecedented among summit lava flows at Kīlauea; the highest published amount in glass is 10.2 wt% (Helz et al., 2014). The normal summit glass compositions (6–9 wt% MgO; Garcia et al., 2003) indicate storage in the shallow reservoir and crystallization of mainly olivine before eruption (Powers, 1955; Wright, 1971).

We think it significant that the highest MgO melts were erupted during explosive, not effusive, periods. We interpret these high MgO values to record brief or no storage in a disrupted shallow reservoir not fully recovered following caldera collapse. Helz et al. (2014) reached a similar interpretation for the Kulanaokuaiki tephra and for the much older Pāhala Ash.

The most highly fractionated compositions known at Kīlauea's summit also occur in vitric tephra. For example, in the Keanakākoʻi tephra, thin vitric ash just above layer 6 (McPhie et al., 1990; Swanson et al., 2012a) has only 4.0 wt% MgO and as much as 4.5 wt% TiO_2 and 1.0 wt% K_2O (Table DR4). We interpret such unusual compositions to reflect isolated storage and advanced fractionation of small pockets of magma undisturbed by fresh, mantle-derived magma during low magma supply.

A marker bed in the Kulanaokuaiki tephra (unit 2 of Fiske et al., 2009) contains glass with unusually high values of TiO_2 (>3 wt%) and K_2O (>0.7 wt%) for its moderately low MgO value (6.7 wt%; Table DR5B). A temporally associated lava flow, one of two interbedded with the Kulanaokuaiki tephra south of the caldera, has a similar composition (Wolfe and Morris, 1996). This composition does not plot along the typical Kīlauea fractionation trend during effusive periods, although similar compositions occur in lava flows earlier in Kīlauea's history (Chen et al., 1996; Lipman et al., 2006).

HAZARD IMPLICATIONS

Previous studies indicate that hazards of explosive eruptions at Kīlauea are substantial, including pyroclastic density currents as well as tephra falls and ballistic showers (Decker and Christiansen, 1984; McPhie et al., 1990; Dzurisin et al., 1995; Fiske et al., 2009; Swanson et al., 2012a, 2012b). Our work shows that the hazardous periods last much longer than previously thought. When the next dominantly explosive period begins, society may have to deal with centuries of repeated explosive activity at Kīlauea's summit.

CONCLUSIONS

Recognition of the explosive-effusive cycle raises far-reaching questions about the dynamics of Kīlauea volcano. Rather than erupting lava flows almost continuously, Kīlauea is instead a more complex, modulated system in which melting rate, supply rate, conduit stability (in both mantle and crust), reservoir geometry, water table, and many other factors interact. The explosive-effusive cycle is the net result of this interaction. Future studies approaching Kīlauea from a broad perspective are necessary to significantly advance our understanding of one of Earth's most studied volcanoes. Whether unrecognized explosive-effusive cycles occur on other basaltic volcanoes is a topic for future research.

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