Two Hundred Years of Magma Transport and Storage at Kīlauea Volcano, Hawai‘i, 1790–2008

Professional Paper 1806

U.S. Department of the Interior
U.S. Geological Survey
Railroad tracks twisted during the lower east rift intrusion of April 1924. Image courtesy of Bishop Museum.
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By Thomas L. Wright and Fred W. Klein

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Acknowledgments

We are grateful for a broad range of support during the preparation of this long and difficult manuscript. A three-year (2007–2009) U.S. Geological Survey (USGS) Bradley scholarship to the senior author funded completion of the research and initial writing. Our ideas were refined by dialogues developed over many years with present and former staff members of the Hawaiian Volcano Observatory (HVO). Many concepts about how Kīlauea works were developed in the authors’ brains during staff discussions while working at HVO. Both authors appreciate in particular discussions over many years with Bob Koyanagi, who impressed on us the importance of earthquake sequences in interpreting Kīlauea’s history. During preparation of the manuscript, Asta Miklius has been particularly helpful in providing information about HVO’s computer database (VALVE) and in clarifying for us information obtained from VALVE. Jennifer Nakata helped develop our earthquake classification and has facilitated acquisition of the seismic data from the HVO catalog. Jerry Eaton, Don Swanson, and Dick Fiske (Smithsonian Natural History Museum Mineral Sciences Department) have been sounding boards for discussion of many of our ideas in the formative stages of producing this manuscript. Among non-USGS sources, Emily Montgomery-Brown (Stanford University, University of Wisconsin, and presently Mendenhall fellow at the USGS in Menlo Park) has been particularly helpful in providing and discussing data that clarified our association of suspected deep intrusions with silent earthquakes. The ideas not specifically attributed to published and unpublished sources are our own syntheses of events described in those sources. We greatly appreciate reviews from Dan Dzurisin, John Power, and an exceptionally thorough and incisive review by Jim Kauahikaua, all of which resulted in significant revisions of many parts of the manuscript. Jim Kauahikaua also checked all Hawaiian place names in the manuscript and ensured that their spelling was in conformance with the Geographic Names Information System (GNIS) as of 2010. Finally, we greatly benefitted from Peter Stauffer’s thorough editing and appreciate Jeanne DiLeo’s design of the book.
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Two Hundred Years of Magma Transport and Storage at Kilauea Volcano, Hawai‘i, 1790–2008

By Thomas L. Wright¹ and Fred W. Klein²

Abstract

This publication summarizes the evolution of the internal plumbing of Kilauea Volcano on the Island of Hawai‘i from the first documented eruption in 1790 to the explosive eruption of March 2008 in Halema‘uma‘u Crater. For the period before the founding of the Hawaiian Volcano Observatory in 1912, we rely on written observations of eruptive activity, earthquake swarms, and periodic draining of magma from the lava lake present in Kilauea Caldera. After 1912 the written observations are supplemented by continuous measurement of tilting of the ground at Kilauea’s summit and by a continuous instrumental record of earthquakes, both measurements made during 1912–56 by a single pendulum seismometer housed on the northeast edge of Kilauea’s summit. Interpretations become more robust following the installation of seismic and deformation networks in the 1960s. A major advance in the 1990s was the ability to continuously record and telemeter ground deformation to allow its precise correlation with seismic activity before and after eruptions, intrusions, and large earthquakes.

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We interpret specific events in Kilauea’s 200-year written history as steps in a broad transition from summit lava-lake activity in Kilauea Caldera to shield building on the east rift zone. The ability of the magmatic plumbing to deliver magma to eruption is critical to the history of eruption and intrusion. When the rate of magma supply equals the rate of eruption, there is little ground deformation or intrusion. When the magma supply rate is greater than the rate of eruption, then the edifice responds through any or all of summit inflation, intrusion, increased spreading rate, and large flank earthquakes.

In Kilauea’s 200-year history we identify three regions of the volcano in which magma is stored and supplied from below. Source 1 is at 1-km depth or less beneath Kilauea’s summit and fed Kilauea’s summit lava lakes throughout most of the 19th century and again from 1907 to 1924. Source 1 was used up in the series of small Halema‘uma‘u eruptions following the end of lava-lake activity in the summit collapse of 1924. Source 2 is the magma reservoir at a depth of 2–6 km beneath Kilauea’s summit that has been imaged by seismic and deformation measurements beginning in the 1960s. This source was first identified in the summit collapses of 1922 and 1924. Source 3 is a diffuse volume of magma-permeated rock between 5 and 11 km depth beneath the east rift zone and above the near-horizontal decollement at the base of the Kilauea edifice.

Magma distribution within source 2 has been derived by combining petrologic study of the three chemically uniform summit eruptions of 1952, 1961, and 1967–68 and the east rift eruptions within this interval with both observation of migrating centers of inflation determined from leveling surveys conducted before the 1967–68 eruption and with published models of expected deformation from different source geometries. We adopt a model of concatenated magmatic plugs with nodes beneath the inflation centers. Addition of erupted and intruded volumes of the three summit magma batches yields a liquid magma volume of about 0.2 km³, with dimensions of ~1 km by 1 km by 200 m centered at about 3-km depth within source 2. Following the Halema‘uma‘u eruption of 1967–68, the chemistry of magma coming into Kilauea’s summit reservoir has changed frequently, and during the eruption that began in 1983, chemical changes have been subtle and continuous. In this period we interpret changes in chemistry as related to an increase in magma supply resulting from increased partial melting in an expanding mantle source volume.

We know from instrumental recording of eruptions since the long Halema‘uma‘u eruption in 1952 that stress in the edifice accumulates as magma is added underground and is relieved by eruption and by dilation of the rift zones associated with seaward movement (spreading) of Kilauea’s south flank. During
and after the last half of the 20th century, magma transfer to the rift zone has dominantly occurred from source 2. High rates of flank motion have been correlated with high rates of endogenous growth; alternatively, lower rates of motion have characterized periods when the underground magmatic plumbing was being refilled following lateral removal of magma, as well as periods when a more open magmatic plumbing favored continuous eruption.

Since at least 1952, source 3 has not drained during deflations, which was apparently not the case before 1924. Triangulation and leveling conducted in 1912, 1921, and 1926, combined with post-1912 tilt measurements, identified a broad regional uplift in 1918–19 and an equally broad collapse in 1924, neither of which has been seen since. We associate these elevation changes with addition or subtraction of magma from all three magma sources, dominantly source 3. We interpret the intrusion beneath the east rift zone during the 1924 collapse to have stabilized the rift zone-south flank relationship, preventing loss of magma from source 3 in subsequent collapses. Rates of seaward spreading were low until 1952, when earthquakes in 1950 and 1951 associated with surges of magma from the hotspot triggered a large offshore south flank earthquake swarm that unlocked the south flank and enabled a greatly increased rate of seaward spreading.

Magma supply rates have been derived for the entire period of study. Between 1823 and 1840, magma was supplied from source 1 at a very high rate of more than 0.2 km$^3$/yr, which we interpret as recovery from a substantial draining of magma from beneath Kilauea in 1790. Inferred magma supply rates diminished to one-tenth of that value after 1840, in part because of increase in the activity of Mauna Loa beginning in 1843. Magma supply rates between 1918 and 1924 were about 0.024 km$^3$/yr, matching that of the period from 1840 to 1894. During 1950–52 the magma supply rate increased to about 0.06 km$^3$/yr, in part because of the great reduction in Mauna Loa activity following its large eruption in June 1950. Following the summit eruption of 1967–68, magma supply increased further to ~0.1 km$^3$/yr, and further increases to more than 0.2 km$^3$/yr occurred during the east rift eruption that began in 1983.

Eruption at Kilauea’s summit took place in 1952, and eruptive activity steadily increased as increased magma supply also drove increased spreading rates. The inability of magma supply to be accommodated by a combination of eruption and spreading during the 1969–74 Mauna Ulu period stressed Kilauea’s south flank. The stress was relieved in part by the M7.2 earthquake of 29 November 1975. That earthquake, in turn, dilated Kilauea’s east rift zone as the south flank moved seaward, producing a favorable condition for continuous east rift eruption, which began in 1983. The 1975 earthquake also resulted in the ability of the south flank to move independently under the influence of gravity, effectively decoupling the spreading rate from changes in the magma supply rate. The continuing increase in magma supply after 1983 was instead manifested in rift dilation, increased intrusion, and ultimately in the launching of a second eruption in Halema‘uma‘u in March 2008, the first instance in Kilauea’s recorded history of simultaneous eruption at the summit and on the east rift zone.

Kilauea’s history can be considered in cycles of equilibrium, crisis, and recovery. The approach of a crisis is driven by a magma supply rate that greatly exceeds the capacity of the plumbing to deliver magma to the surface. Crises can be anticipated by inflation measured at Kilauea’s summit coupled with an increase in overall seismicity, particularly manifest by intrusion and eruption in the southwest sector of the volcano. Unfortunately the nature of the crisis—for example, large earthquake, new eruption, or edifice-changing intrusion—cannot be specified ahead of time. We conclude that Kilauea’s cycles are controlled by nonlinear dynamics, which underscores the difficulty in predicting eruptions and earthquakes.