Geometry of the summit magma storage reservoir of Kilauea Volcano: A view from high-precision Pb isotopes

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Photo of Kīlauea Volcano courtesy of T. Orr (USGS-HVO)
Mantle-generated melt transported by primary conduit from >60 km depth

Summit magma reservoir 1-2 km SE of Halemaumau (2-4 km deep)

Storage prior to eruption at the summit or lateral intrusion into the rift zones (for further storage and/or eruption)

Model refined over the last 50 years by (1) continuous monitoring of deformation and seismicity and (2) studies of lava chemistry

Basic model first outlined by Eaton & Murata (1960) →

Kilauea’s magmatic plumbing system

Ryan (1988)
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Kilauea’s magmatic plumbing system

The summit magma storage reservoir is one of the most important components of the Kilauea’s magmatic plumbing system, but the geometry (size and shape) of this reservoir is poorly known!

Is this an accurate view?

Modified from Garcia et al. (1996)
Overview

Geometry (size and shape) of the summit magma storage reservoir

A review of recent geophysical studies (ground deformation, seismicity, and gravity)

A view from high-precision Pb isotopes

→ Two magma bodies beneath Kilauea’s summit?

Burning questions, new and old

→ Deeper magma chamber?
→ Current state of the plumbing system?

Or this?

Fiske & Kinoshita (1969)
Size of the summit magma reservoir

How much magma?

Maximum = 40 km$^3$
Minimum = 0.08 km$^3$

Volume of the aseismic zone (Klein et al., 1987)
Avg. eruption rate (km$^3$/yr) × repose period (yr)
Volume of largest short-duration eruptions (Klein, 1982)

Residence time analysis of historical fluctuations in summit lava chemistry (Pietruszka & Garcia, 1999)

Aseismic zone may include a crystal-mush zone and a hot, ductile region surrounding the magma reservoir!
Shape of the summit magma reservoir

Ground deformation

★ Inflation centers migrate over a large area (up to 16 km²)

★ Sequential pressurization of dikes and sills

Fiske & Kinoshita (1969)

Complex network of interconnected magma bodies?
Shape of the summit magma reservoir

**Ground deformation**

- Inflation centers migrate over a large area (up to 16 km²)
- Sequential pressurization of dikes and sills

**Fiske & Kinoshita (1969)**

- Complex network of interconnected magma bodies?

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**Main chamber?**

**Secondary HMM body?**
Shape of the summit magma reservoir

**Ground deformation**

- Rift zone intrusions may bias locations of summit inflation centers
- Inflation centers converge within ~1 km^2 if this effect is removed

Yang et al. (1992)

Simple, “spherical” magma body?
Review of recent geophysical studies
Ground deformation

Cervelli & Miklius (2003)

Long-term subsidence from 1996 to 2002 based on continuous GPS measurements and annual leveling surveys

Deflation of Kilauea’s summit magma storage reservoir

Data (mostly) consistent with a point-source centered over the SE edge of Kilauea caldera

Depth is <3.5 km (~3 km most likely)

Consistent with earlier studies of ground deformation
Ground deformation

*Cervelli & Miklius (2003)*

- Short-lived deformation episodes recorded by tiltmeters from 2000-2002, often associated with magma surges at Puʻu ʻŌʻō
- Inflation of a **magma reservoir** centered E of Halemaumau
- Depth is poorly constrained at ~130-450 m (**shallow!**)  
- Update from new tiltmeter data?

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#### EXPLANATION

- UWE N46°W
- SDH S38°W
- IKI N97°E
- POC N38°W

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**Sep. 24-26, 2000**
Long-period seismicity

*Almendros et al. (2001)*

Long-period (LP) events and volcanic tremor generated in the same region E/NE of Halemaumau (<400 m deep)

Dimensions = $0.6 \times 1.0 \times 0.5 \text{ km} = 0.3 \text{ km}^3$

Three clusters of LP events, but one source for volcanic tremor

Related to flow of magma and/or hydrothermal fluids through cracks

Hydrothermal fluid origin based on shallow depth of LP seismicity

*Experiment in Feb. 1997*
Long-period seismicity

Battaglia et al. (2003)

“Relocation” of LP events pinpoint two sources for seismicity

Deep LP events cluster below the eastern rim of Kilauea caldera (~5 km below sea level) \( \textbf{Upper ERZ?} \)

Shallow LP events cluster E/NE of Halemaumau at a shallow level (“resonance of fluid-filled volume” \( \rightarrow \text{magma or fluids?} \))

Experiment from Jan. 1997 to Dec. 1999
Comparison of residual gravity changes & ground deformation

**South caldera**

**Long-term** subsidence from 1975-2003

Negative residual gravity anomaly of <100 \( \mu \text{Gal} \) from 1975-2008

Mass decrease (small)
Microgravity
Johnson et al. (2010)

Comparison of residual gravity changes & ground deformation

Halemaumau

Long-term subsidence from 1975-2003

Unexpected positive residual gravity anomaly of ~450 µGal from 1975-2008

Mass increase due to magma accumulation
Microgravity
Johnson et al. (2010)

Comparison of residual gravity changes & ground deformation

Halemaumau

Long-term subsidence from 1975-2003

Unexpected positive residual gravity anomaly of \(~450 \ \mu\text{Gal}\) from 1975-2008

Mass increase due to magma

\(~0.02-0.12 \ \text{km}^3\) \rightarrow accumulation
Microgravity
Johnson et al. (2010)

🌟 Modeled source of deformation (mostly) located ~2 km below south caldera (squares)

🌟 Modeled source of mass change located ~1 km below E margin of Halemaumau (diamonds)

🌟 Filling of void space created by the M7.2 earthquake in 1975? 2008 HMM eruption triggered when full?

💎 Gravity centers
▪ Deformation centers
Microgravity

Johnson et al. (2010)

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Diamonds: Gravity centers
■: Deformation centers

Two magma bodies beneath Kilauea’s summit, and an active hydrothermal system above the HMM body!
A view from high-precision Pb isotopes
Geochemical time series of historical and prehistoric Kilauea lavas

Photo of Kīlauea Volcano courtesy of T. Orr (USGS-HVO)
Rapid variations in lava chemistry

**Kīlauea summit lavas**

- High-precision Pb isotope ratios by Tl-doping MC-ICPMS
- Fluctuation on a time scale of years to decades
- Sinusoidal variation of Pb isotope ratios over the last millennium
- Systematic changes in parental magma composition (due to source heterogeneity)
Changes in the melt pathway

Rapid variations of $^{206}\text{Pb}/^{204}\text{Pb}$ on a time scale of years to decades require:

- Small-scale compositional heterogeneities in the Hawaiian plume
- Short-term changes in the pathway that melt takes from “source to surface”

Upwelling of mantle heterogeneities is important on a longer time scale of centuries...
Changes in the melt pathway

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**Magma mixing trends!**
Pb isotopic variations in time & space

From 1971-1982, the $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of the lavas define two separate decreasing trends.

For each eruption, the lavas with lower Pb isotope ratios have higher MgO contents.

During the 1970s, these compositional differences correlate with vent location.
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Two magma bodies!

Deep chamber
(e.g., Fiske & Kinoshita, 1969; Klein et al., 1987)

Shallow chamber
(e.g., Cervelli & Miklius, 2003; Johnson et al., 2010)
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Consistent with recent geophysical studies!

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Geometry of the summit reservoir

Two magma bodies
Geometry of the summit reservoir

Two magma bodies

Low $^{206}\text{Pb}/^{204}\text{Pb}$, high MgO trend from deep chamber
Geometry of the summit reservoir

Two magma bodies

High $^{206}\text{Pb}/^{204}\text{Pb}$, low MgO trend from shallow chamber

Low $^{206}\text{Pb}/^{204}\text{Pb}$, high MgO trend from deep chamber
Magma residence time modeling

The time rate of change of Pb isotope ratios may be used to estimate the residence time and volume of magma in a reservoir.

**What?**

Define magma residence time, \( \tau_H = V/Q \)

Mass balance relationship from Albarède (2008)

\[
V \frac{dC_i}{dt} = Q C_{in} - Q C_i - P C_{xtals}^i
\]

\[
C_i(t) = C_0^i e^{-t/\tau^i} + \frac{C_{in}^i}{1 + \beta^i} \left( 1 - e^{-t/\tau^i} \right)
\]

\[
\tau^i = \tau_H/1 + \beta^i
\]

Modify for use with Pb isotope ratios

Since \( D^i \sim 0 \)

\[
\beta^i = PD^i/Q = 0
\]

\[
R(t) = R_{in} + [R_0 - R_{in}] e^{-t/\tau_H}
\]

\[
R = \frac{206\text{Pb}}{204\text{Pb}}
\]

**How?**

\[
\tau_H = -\Delta t / \ln \left( \frac{R(t) - R_{in}}{R_0 - R_{in}} \right)
\]
Geometry of the summit reservoir

Two magma bodies, and both are very small ($\leq 0.2 \text{ km}^3$)

- $\tau_H = 2.9 \text{ yr}$
  - $Q = 0.06 \text{ km}^3/\text{yr}$
  - $\sim 0.2 \text{ km}^3$

- $\tau_H = 4.0 \text{ yr}$
  - $Q > 0.01 \text{ km}^3/\text{yr}$
  - $> 0.04 \text{ km}^3$

- $\tau_H = 2.8 \text{ yr}$
  - $Q = 0.06 \text{ km}^3/\text{yr}$
  - $\sim 0.2 \text{ km}^3$

Avg. magma supply rate from 1959-1990 = 0.06 km$^3$/yr (Dvorak & Dzurisin, 1993)
Burning questions, new and old

Photo courtesy of USGS-HVO
A deeper magma chamber?

First suggested by Wright (1971)

Location for high-pressure crystal fractionation

Re-emphasized by Clague (1987)

Xenolith populations in Hawaiian lavas require a magma reservoir at the base of the oceanic crust
A deeper magma chamber?

Clague (1987)

Magma bodies filter xenoliths during magma ascent

Postshield xenolith population implies existence of only a deep magma reservoir

This deep reservoir probably exists during the shield stage
Hawaiites have unusually low CaO, Sc, and V abundances.

High-pressure clinopyroxene fractionation (cryptic) in the lower crust due to low magma supply rate (Frey et al., 1990).

Deeper magma chamber during the shield stage? High magma supply rate to prevent cooling and CPX fractionation?
A deeper magma chamber?

Magma mixing in a larger magma body (~0.7-0.8 km$^3$) on a time scale of decades to centuries

Avg. summit eruption rate from 1823-1912 = 0.03 km$^3$/yr
A deeper magma chamber?

Magma mixing in a larger magma body (~0.7-0.8 km$^3$) on a time scale of decades to centuries

Evidence from geophysics?

Average summit eruption rate from 1823-1912 = 0.03 km$^3$/yr
Current state of the plumbing system?

★ Do Puʻu ‘Ōʻō magmas partially bypass the summit magma reservoir? (Garcia et al., 1996, 2000; Marske et al., 2008)

★ Is Puʻu ‘Ōʻō connected to the shallow “Halemaumau” magma body (Cervelli & Miklius, 2003) or the deeper “SE caldera” magma body?
Current state of the plumbing system?

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★ Is Puʻu ʻŌʻō connected to the shallow “Halemaumau” magma body (Cervelli & Miklius, 2003) or the deeper “SE caldera” magma body?

…or something else?

Modified from Garcia et al. (1996)
The Halemaʻumaʻu summit eruption
(March 2008 to present)

Halemaʻumaʻu eruption glasses represent the first samples from Kilauea’s summit magma reservoir since 1982

Based on the vent location, the juvenile glasses are probably supplied from the shallow “Halemaʻumaʻu” magma body

Photo of Kīlauea Volcano courtesy of T. Orr (USGS-HVO)
Current state of the plumbing system?

Early period of compositional variation (<2 weeks), probably due to mixing with an older (late 20th century) “gabbroic” crystal mush (C. Thornber, personal communication, 2010; this study)

Later Halemaʻumaʻu glasses are similar to Puʻu ʻŌʻō lavas

Puʻu ʻŌʻō-like magma has now fully infiltrated the volcano’s summit magma reservoir, consistent with the prediction of Thornber (2003)
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Current state of the plumbing system?

Recent Halemaʻumaʻu glasses have lower Pb isotope ratios than contemporaneous (and older) Puʻu ʻŌʻō lavas.

Puʻu ʻŌʻō lavas are not being supplied rapidly from the summit magma reservoir (>1 year delay).

The buffering capacity (magma volume) of the ERZ is probably larger than the summit reservoir (at present).

We expect to see 2010 HMM-type Pb isotope ratios in future Puʻu ʻŌʻō lavas!
Discussion?

Two shallow magma bodies beneath Kilauea’s summit ($\leq 0.2 \text{ km}^3$)?

A deeper magma chamber in the lower oceanic crust ($\sim 0.7-0.8 \text{ km}^3$)?

Current state of the magmatic connection between the summit and ERZ?