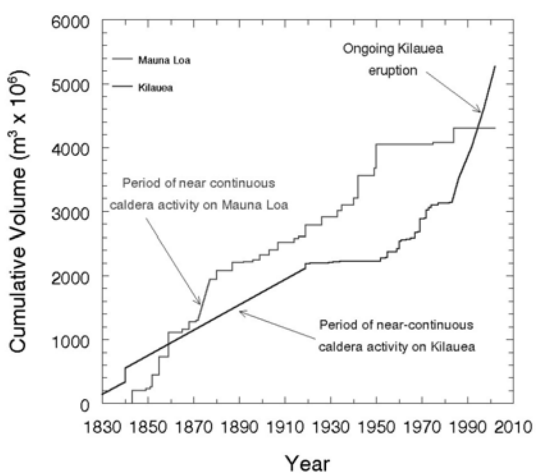
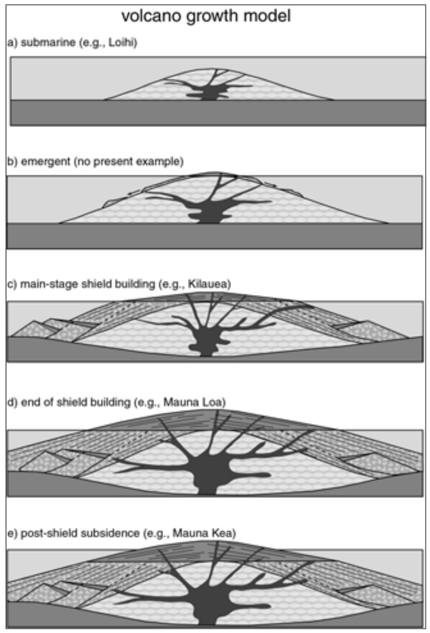
HAWAII

Lecture 3



Output from Mauna Loa and Kilauea have been very similar during historical times

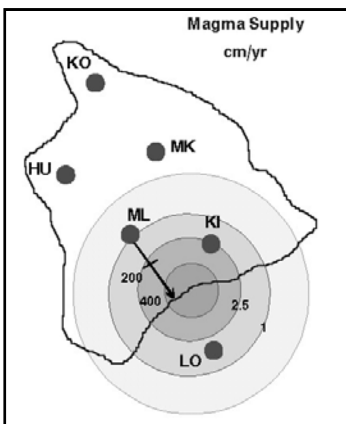


Submarine Stage

Emergent Stage

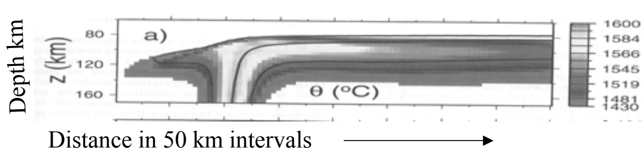
Shield Building Stage

Post-Shield Stage



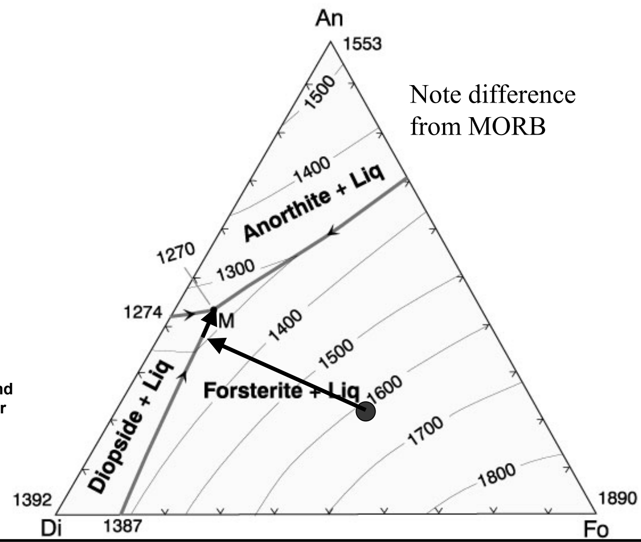
The evolutionary stages of Hawaiian volcanoes are consistent with a thermally zoned plume that is hotter and producing more melt in the plume center than at the margins.

Cartoon showing position of plume relative to volcanoes. Caution – we have no idea where it is actually located or what its shape and radius are!



Thermal model of a mantle plume
(Ribe & Christensen, 1991)

- The common crystallization sequence is: olivine (± Mg-Cr spinel), olivine + clinopyroxene (± Mg-Cr spinel), olivine + plagioclase + clinopyroxene



Note difference from MORB

Figure 7-2. After Bowen (1915), A. J. Sci., and Morse (1994), Basalts and Phase Diagrams. Krieger Publishers.

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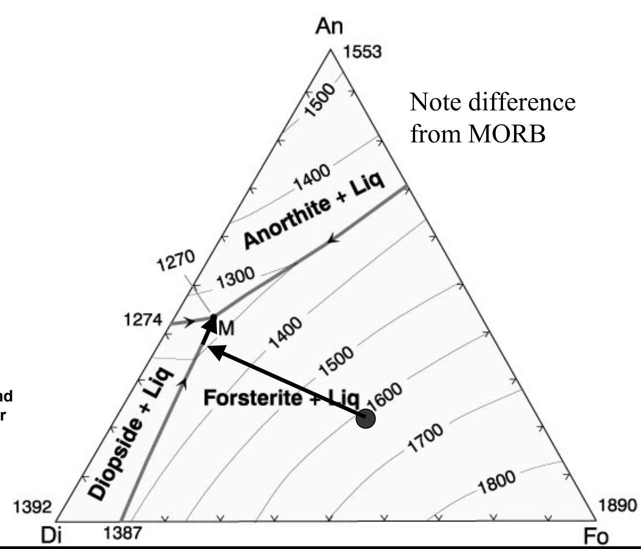
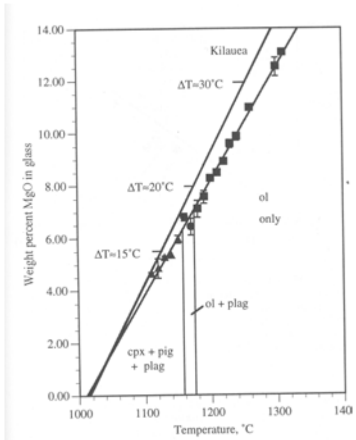


Note difference from MORB

Figure 7-2. After Bowen (1915), A. J. Sci., and Morse (1994), Basalts and Phase Diagrams. Krieger Publishers.



Relationship between MgO in glass and temperature for Mauna Loa (Montierth et al., 1995)

Note how quickly cpx follows plagioclase

$T(^oC) = 23.0(MgO) + 1012$

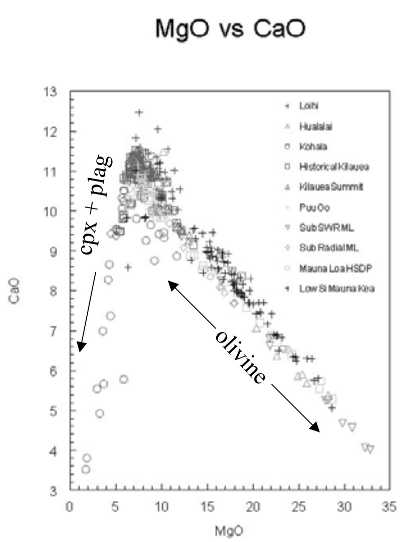
Therefore the temperature of a lava with 7% MgO will be:-

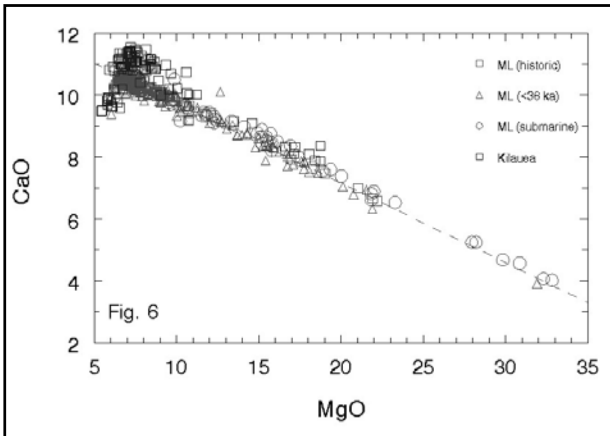
$23.0 \times 7.0 + 1012 = 1174\ ^oC$

Similarly for Kilauea
$T(^oC) = 20.1(MgO) + 1014$
(Helz and Thornber, 1987)

The crystallization sequence is clearly shown by the rock chemistry.

1. Extensive olivine crystallization (and accumulation)
2. Followed by clinopyroxene and plagioclase crystallization

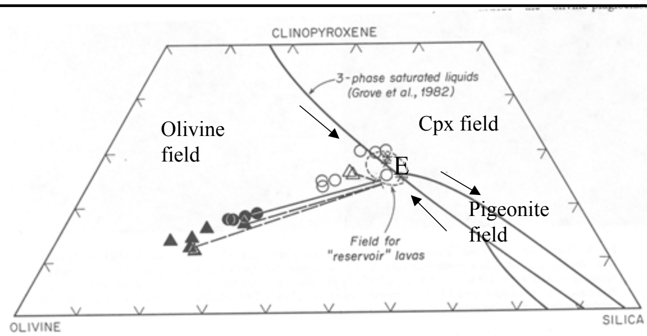




Data for Mauna Loa compared with Kilauea

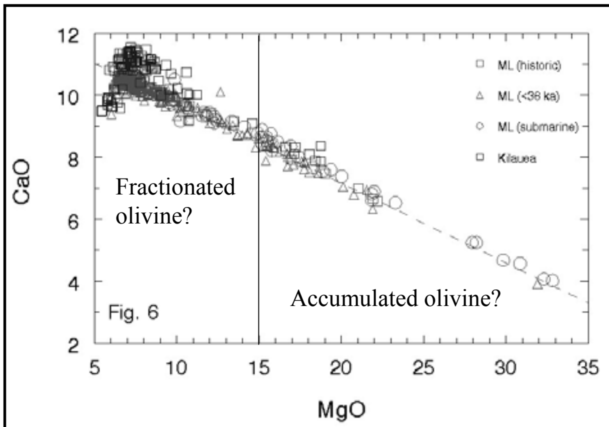
There are three problems:

1. Why does Mauna Loa differ from Kilauea?
2. Why do we only see an olivine fractionation trend for Mauna Loa? Why are there so few fractionated lavas showing cpx and plag crystallization?
3. What is the composition of the parental or primary magma (olivine fractionation vs accumulation)?



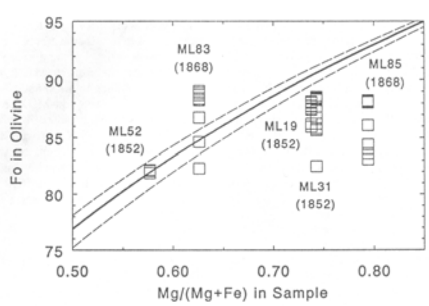
1. Mauna Loa lavas first crystallize olivine
2. At E olivine is joined by Cpx (+ Plag) and pigeonite
3. E is a reaction point where olivine reacts with the melt to produce pigeonite. The magma composition is fixed at E until all olivine is consumed. Only then can the melt evolve further.
4. Recharge and mixing with new parental magma drags the melt composition back into the olivine field
5. The process is repeated over and over again
6. Therefore Mauna Loa rarely erupts fractionated lavas

Note – all crystallization paths from the olivine field (red arrows) lead to E



Where does the parental (primary?) magma plot on this olivine-control line?

1. Most subaerial MgO-rich glassy lavas (true liquids) have a maximum MgO content around 10-11%
2. Submarine glass fragments have been found with MgO = 15%
3. Does this mean that lavas with > 15% MgO have accumulated olivine?

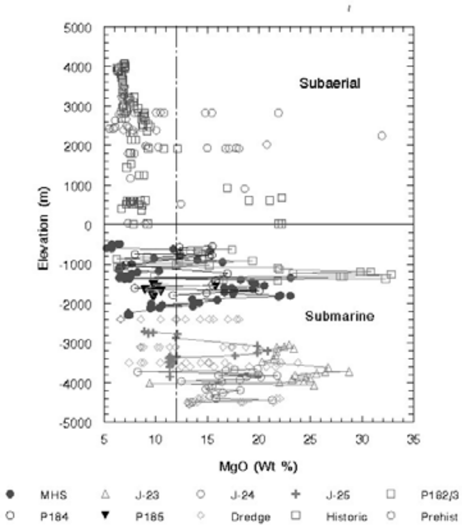


Fo content of olivine vs Mg/(Mg + Fe)

Curved lines give equilibrium compositions

1. Maximum Fo in Mauna Loa olivines is $Fo_{88\text{-}89}$
2. This corresponds to Mg/(Mg + Fe) around 0.70 and an equivalent MgO of 14-15%
3. This is the parental composition from which the most forsteritic olivines crystallized (it may not be primary)
4. Lava with > 15% MgO have accumulated olivine and are not liquid compositions

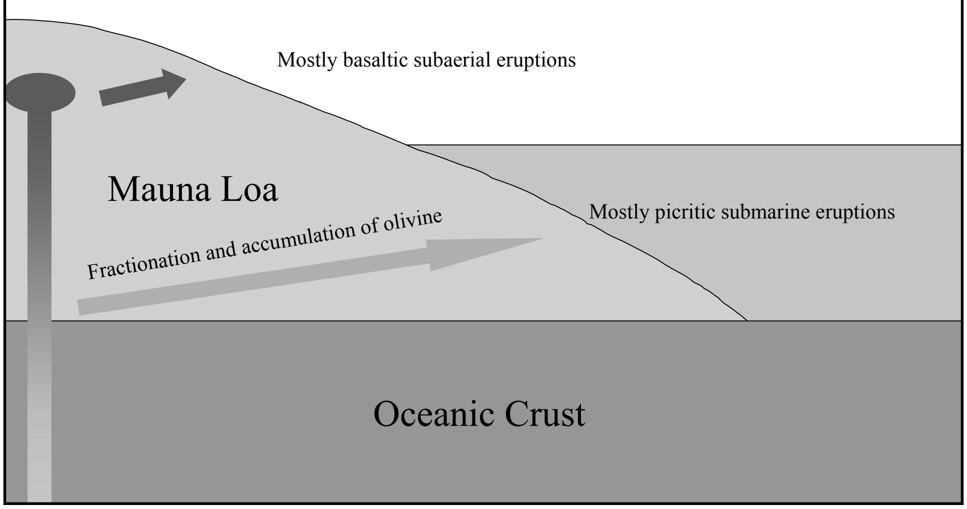
Variation of MgO with Elevation



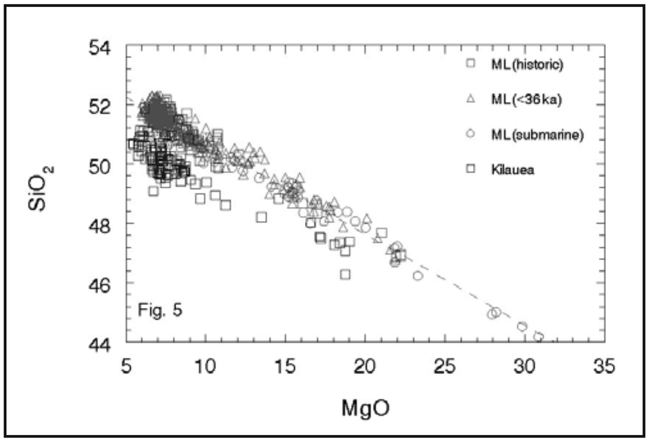
Mauna Loa’s SW Rift Zone

1. Picrites (>12% MgO) are rare among subaerial lavas, but very abundant among submarine lavas.
2. Low MgO lavas (7-8%) are common in subaerial lavas and submarine lavas down to 1200 m.
3. Evidence for a stratified magma column?

Consequences of a stratified magma column

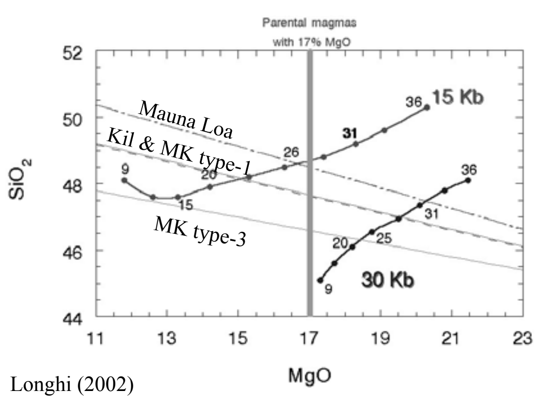


Why are Mauna Loa lavas different from those of Kilauea?



Lower SiO_2 at a given MgO content in Kilauea lavas relative to Mauna Loa lavas may reflect:

1. Lesser extent of melting
2. Melt segregation at greater depth



Longhi (2002)

Depth (P) and extent of melting influence both SiO_2 and MgO

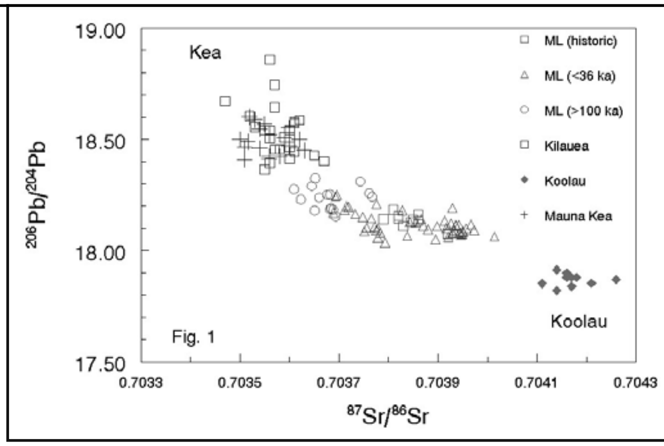
If parental magmas contain 17% Mgo (based on olivine) then depth of melting appears to be the dominant factor

There is a paradox!

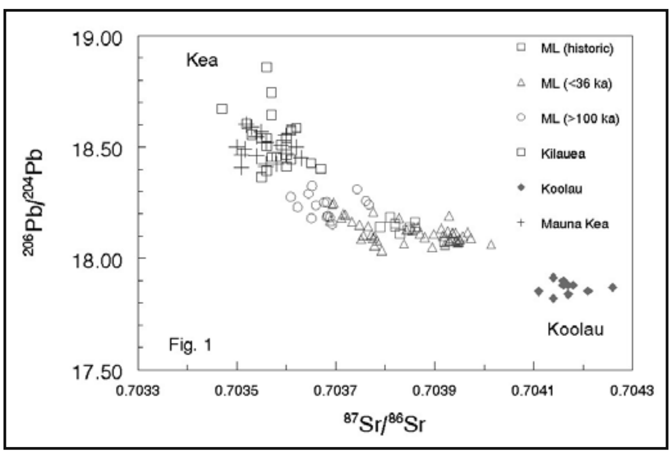
- ❑ Experiments indicate shallow melting in lithosphere
- ❑ Trace data require garnet residue in the source (deep melting)

Solution?

- ❑ Parental magmas contain 19-21 % MgO and we never see them
- ❑ Magmas re-equilibrate with mantle en-route to the surface



There are also differences in isotopic ratios between Hawaiian volcanoes. They plot on mixing lines between two mantle end-components:-
Kea – possibly primitive plume material (high $^3He/^4He$)
Koolau – possibly entrained lower mantle or recycled oceanic crust
(There is a lot of debate and uncertainty!)



Notice how old Mauna Loa (> 100 ka) is closer to Kilauea than young (< 36 ka) Mauna Loa
This implies the plume source for Mauna Loa has changed over time

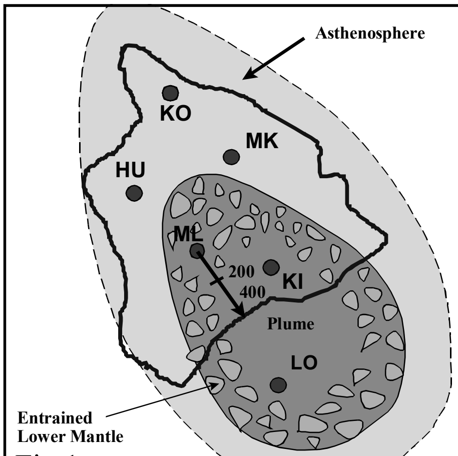


Fig.1

Current models suggest that the Hawaiian plume is zoned both compositionally and thermally

This cartoon illustrates how currently magmas for Mauna Loa may be being produced near the margins of the plume, whereas 200 – 400 ka ago its magmas may have come from closer to the plume center (as do Kilauea and Loihi today?)

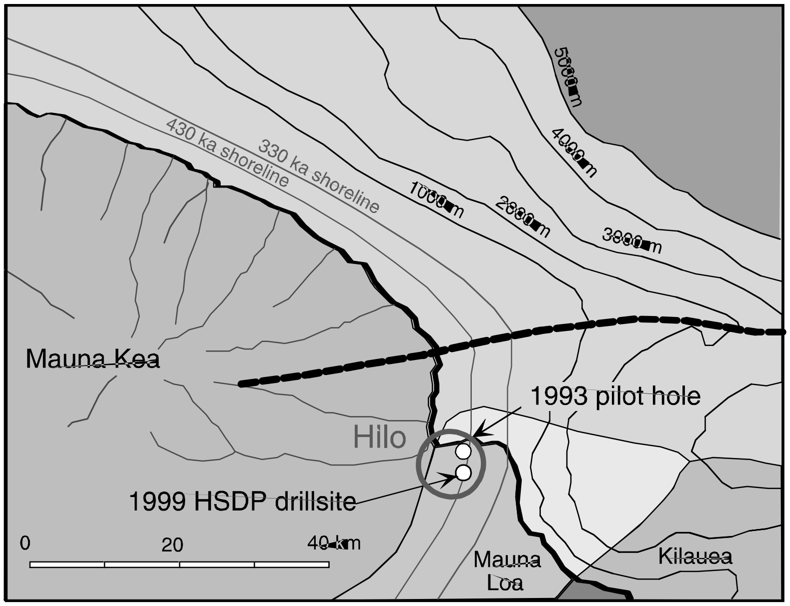
Plumbing the Hawaiian Plume: Geochemical Stratigraphy of Basalts from the Hawaii Scientific Drilling Project

Mike Rhodes

University of Massachusetts

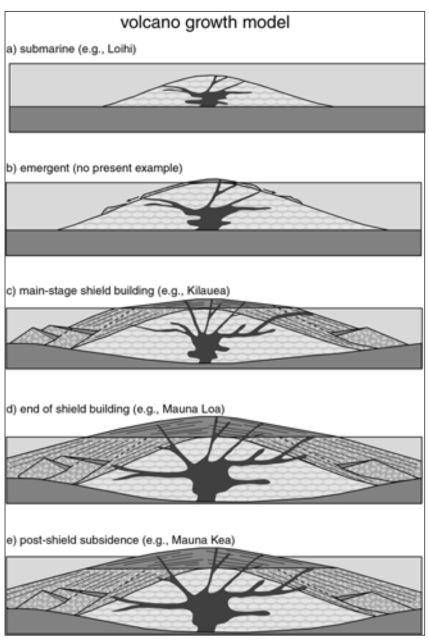
[redacted]

HSDP location map



HSDP Project Objectives

- Drill and core through a hot spot volcano to retrieve an order sequence of lavas that represent the volcanic output as the volcano drifts over the mantle plume
- Characterize the petrology, geochemistry, age and magnetic characteristics of the lavas
- Measure the temperature and fluid compositions at depth
- Study the fluid flow and alteration where present at depth
- Use the data to test models for the structure, dynamics, and source of the Hawaiian mantle plume



Submarine Stage

Emergent Stage

Shield Building Stage

Post-Shield Stage

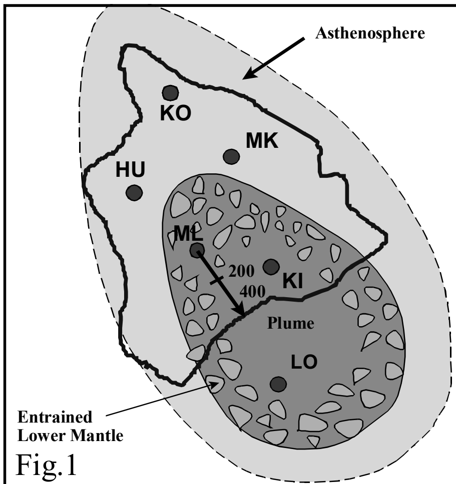
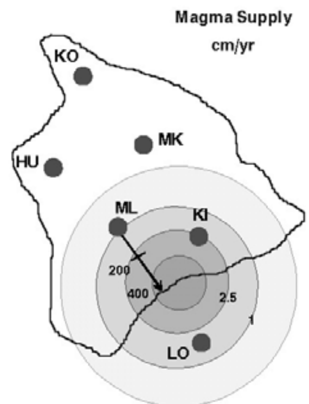
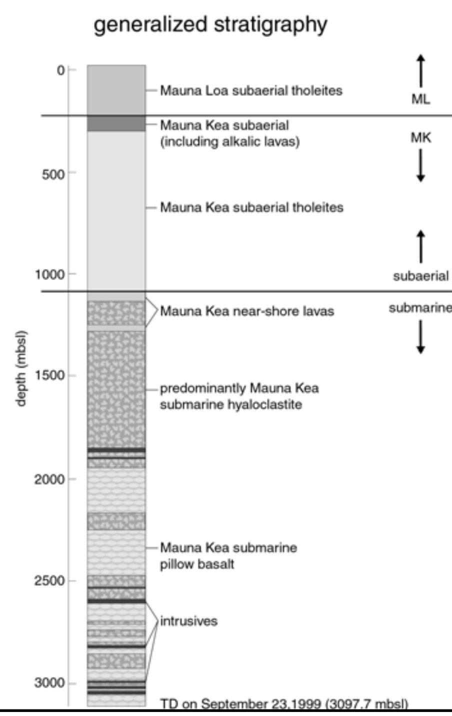
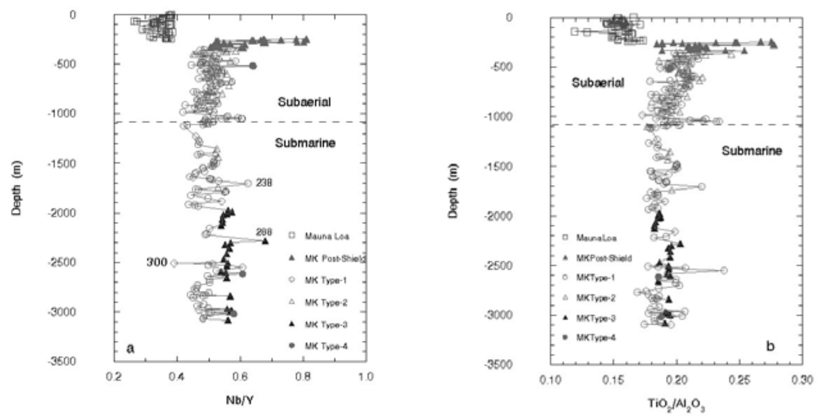


Fig.1

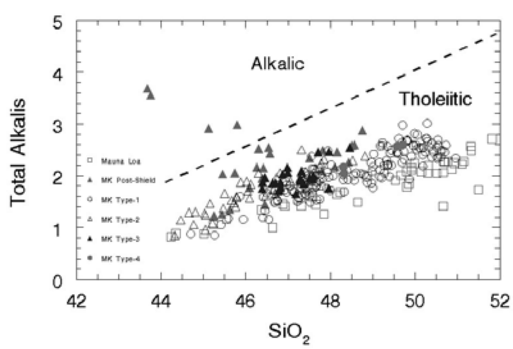
Current models suggest the Hawaiian plume is both compositionally and thermally zoned

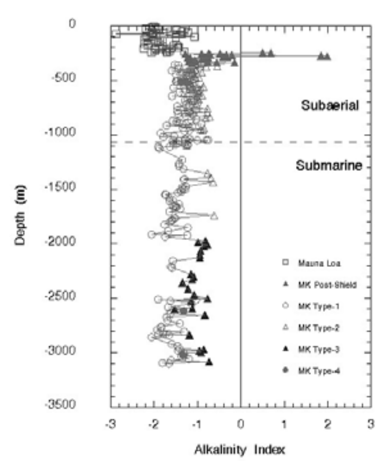


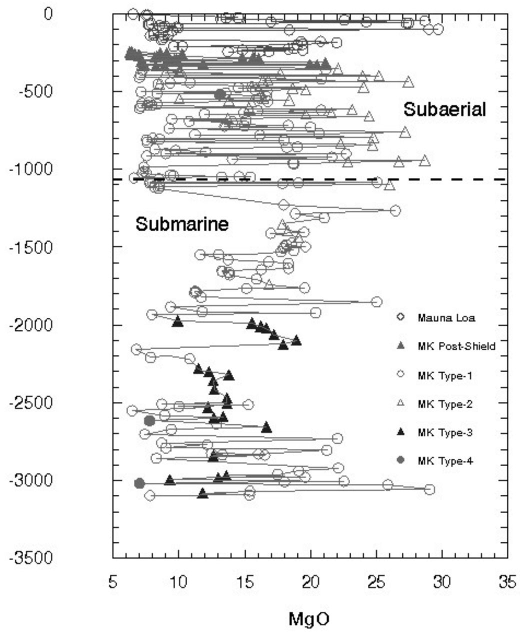




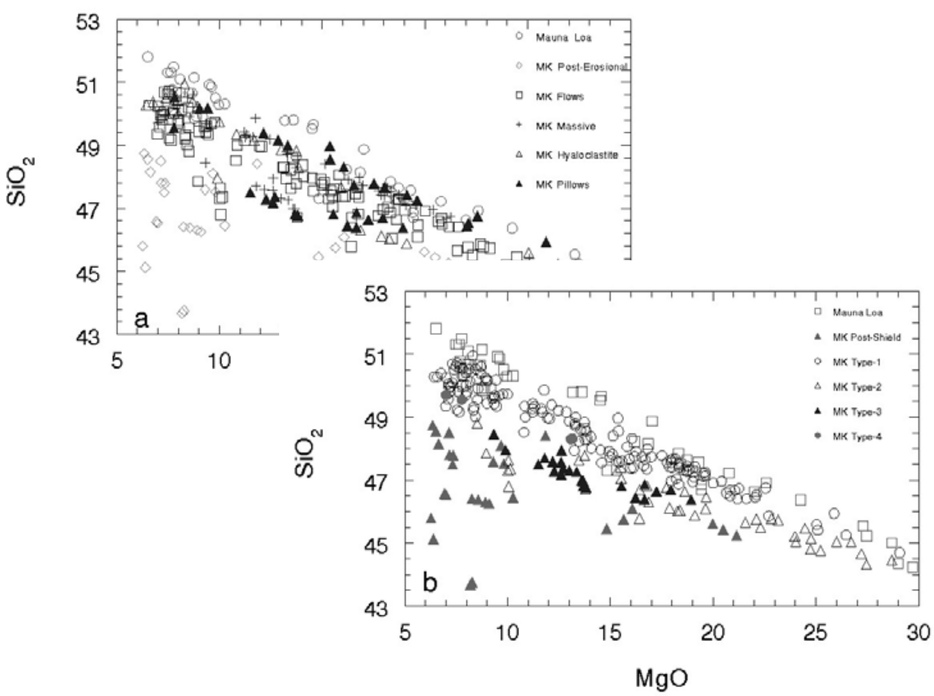
Mauna Loa lavas are readily distinguished chemically from Mauna Kea lavas. Transition occurs at 245 m

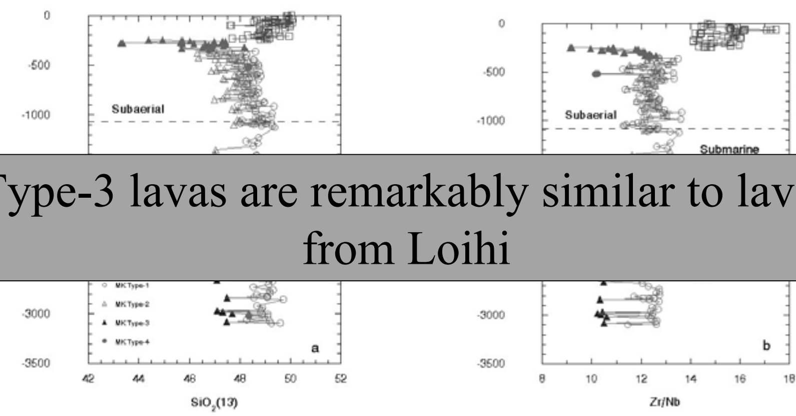






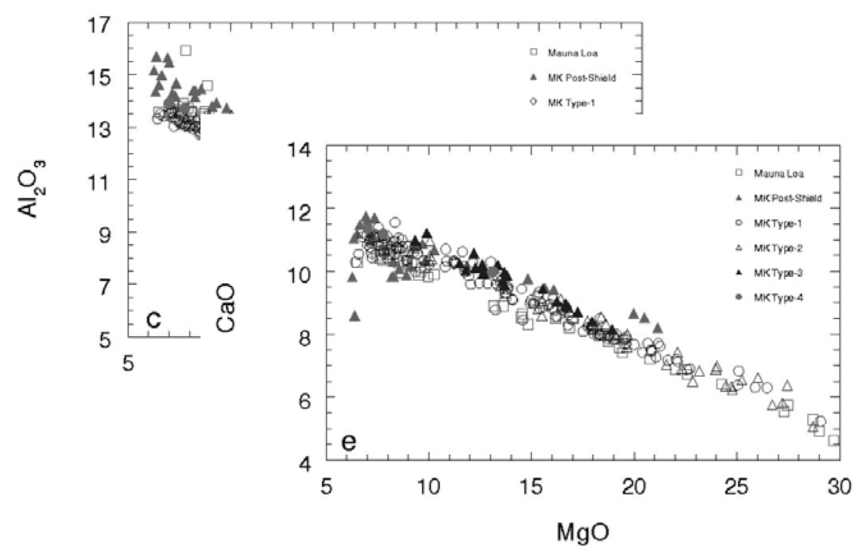
Note abundant picrites (>12% MgO) and scarcity of low-MgO (~7%) lavas in the submarine part of the section



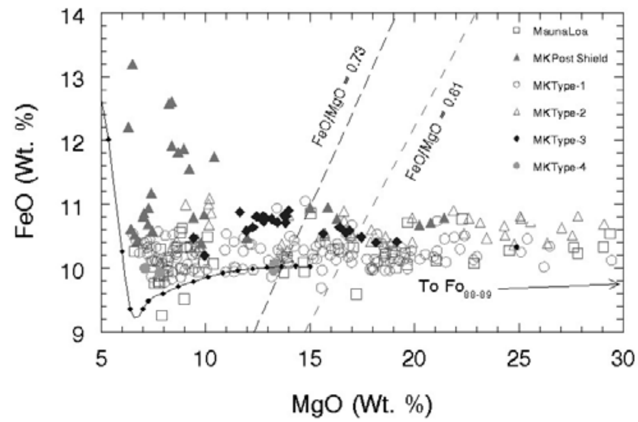


Type-3 lavas are remarkably similar to lavas from Loihi

Mauna Kea Magma Types
Post-Shield lavas
Type-1 (high SiO_2 and Zr/Nb)
Type-2 (low SiO_2 and high Zr/Nb)
Type-3 (low SiO_2 and low Zr/Nb)
Type-4 (high SiO_2 and low Zr/Nb

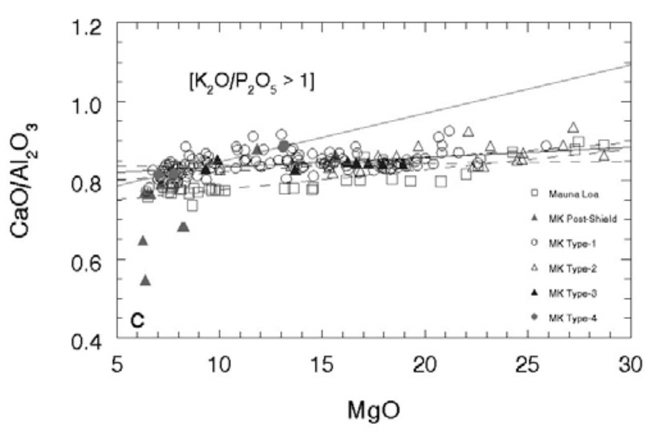


Strong linear trends are consistent with olivine accumulation and fractionation (note absence of evolved lavas)



Trend is towards Fo_{88-89} olivine
Parental magmas will have FeO/MgO = 0.73
MgO in parental magmas around 14 – 15 wt. %
MgO in primary magmas may be around 16-18 wt. %

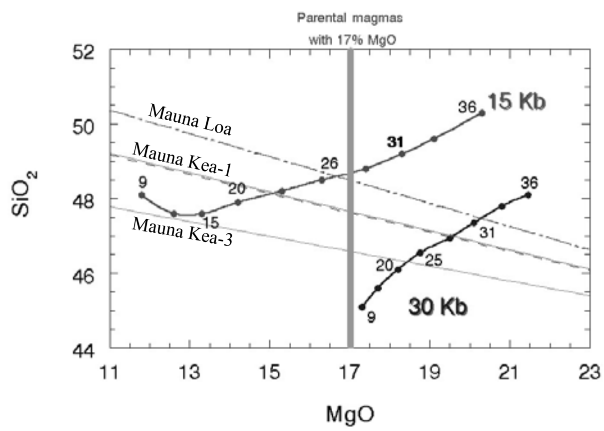
Not quite so simple!

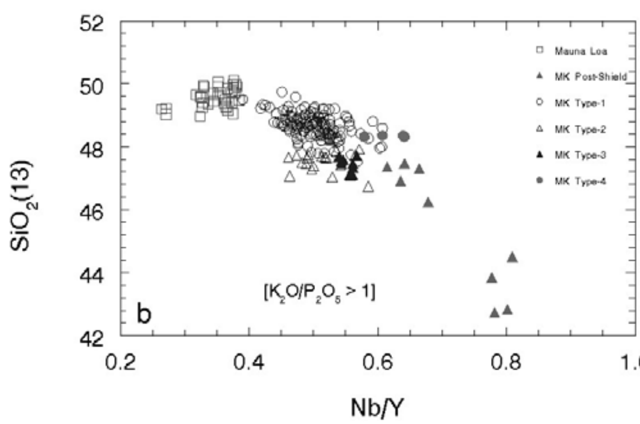


If trends are due solely to olivine accumulation and fractionation then there should be no change in CaO/Al_2O_3 with MgO. There is, so mixing must also be involved.

Experimental melting results show that SiO_2(13) is influenced by:-

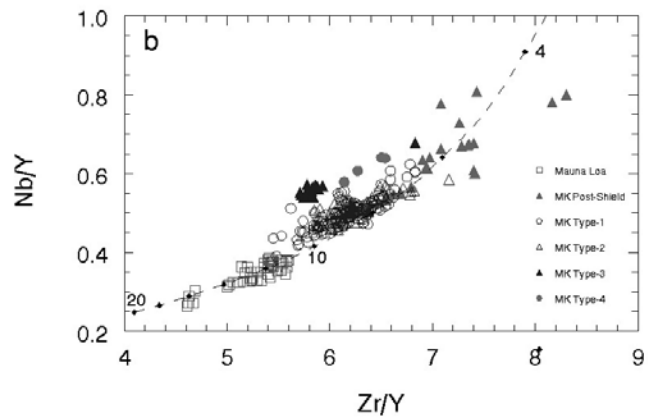
- The amount of melting
- The depth of melt segregation



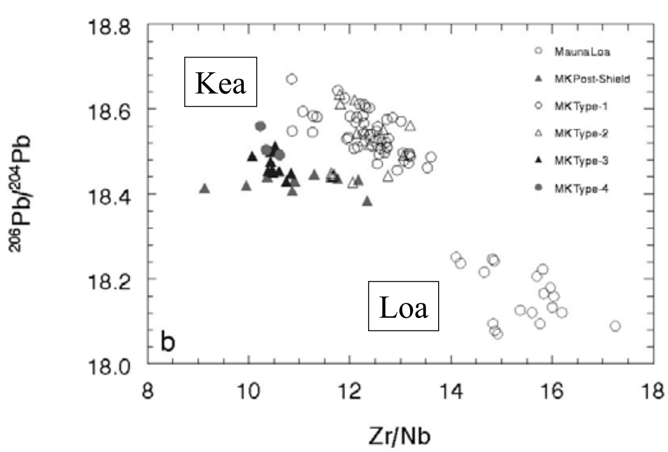


Thoughts on Melting:

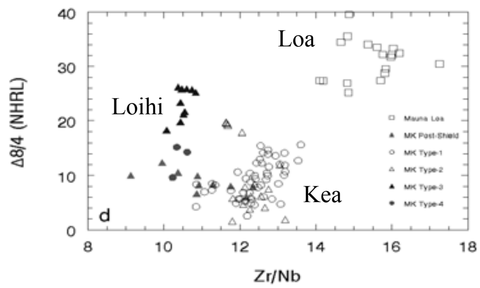
- Post-shield magmas are consistent with low degrees of melting, late in the volcanoes history
- Type-2 magmas were produced at greater depths than type-1 magmas
- Type-3 magmas may come from greater depth, but it could be a source factor



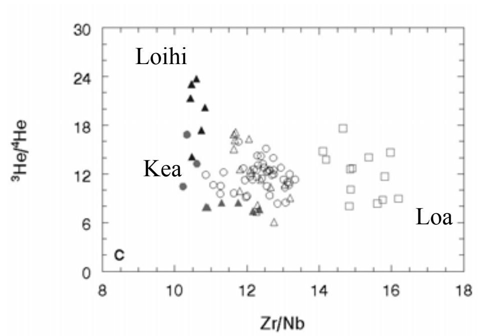
Trace data seem to imply that types 3 and 4 require different source components from types 1 and 2



This is not supported by Sr or Pb isotopic data
(data from Dominique Weis)



On the other hand delta 8/4 Pb and $^3He/^4He$ are higher in type 3 lavas and similar to values that are characteristic of Loihi



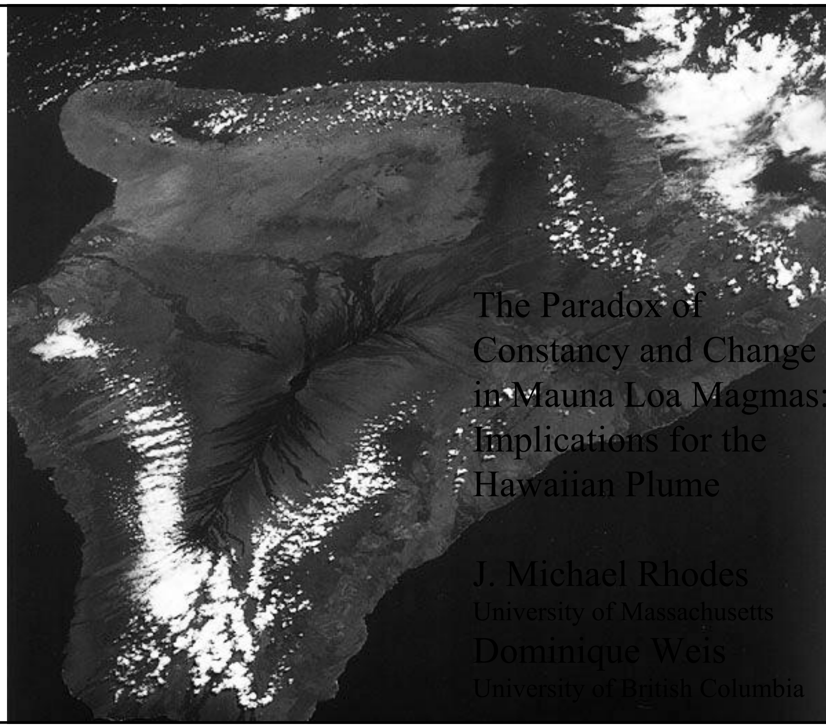
It appears then that type-3 lavas come from a source that is slightly different from other Mauna Kea lavas. What is this source?

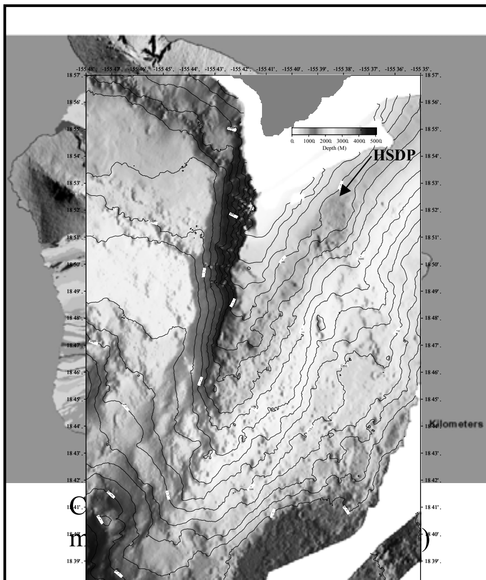
Isotopic data from Dominique Weis and Mark Kurz

Overview

Sampled around 400 ka of Mauna Kea's magmatic history. During this time it will have traversed about 40 km across the Hawaiian Plume.

280-150 ka	Low melting and magma supply rates - eruption of Post-Shield lavas
440-280 ka	Continued eruption of inter-layered type 1 and 2 lavas. Fundamental change in magmatic plumbing system; eruption of low MgO lavas (~7%); increase in incompatible element ratios; decrease in SiO_2(13) in both type 1 and 2 lavas; and in magma supply.
495-440 ka	Eruption of inter-layered type 1 and 2 lavas. Derived from a common source, but at different depths. High magma supply rates.
550-495 ka	Eruption of inter-layered type 1 and 3 lavas. Require different source components (possibly depths?). Early Mauna Kea or edge of plume? High magma supply rates.

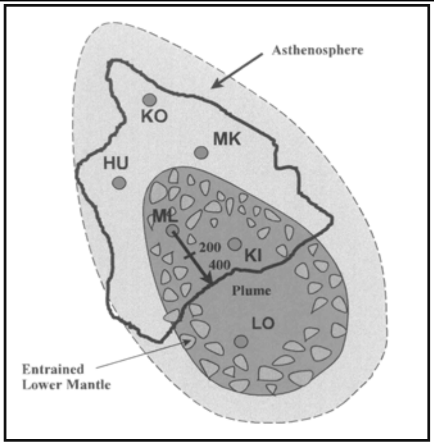




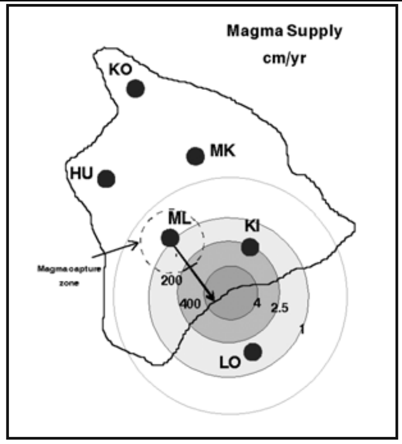
Source of Data

1. Historical lavas (1843 – 1984)
2. ^{14}C-dated Prehistoric lavas (0.2 – 36 ka). Ages from Jack Lockwood and Frank Trusdell (USGS).
3. HSDP-1 lavas (interpolated ages between 10 – 104 ka)
4. Submarine lavas from a landslide scarp on Mauna Loa's SW Rift Zone (ages interpolated from K/Ar dates of Herve Guillou - mostly > 100 to 300 ka)

In other words around 300 ka of magmatic history

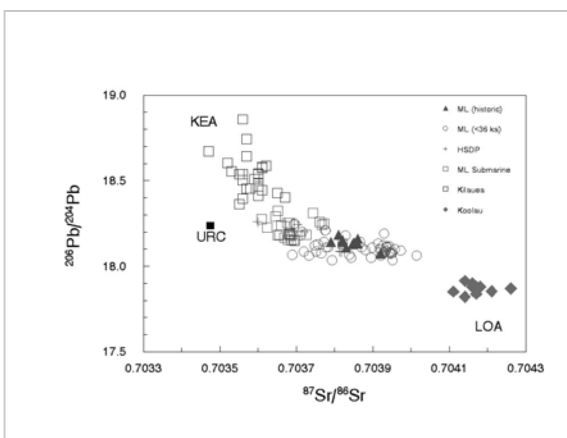


Rhodes and Hart (1995)

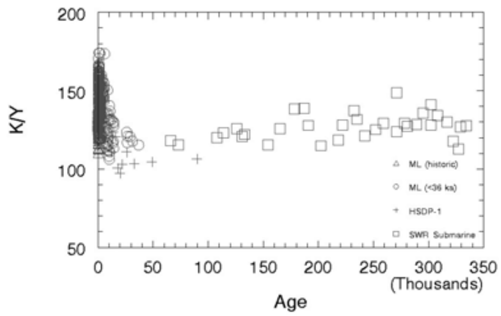


Modified from DePaulo et al., (2001)
and DePaolo and Stolper (1996)

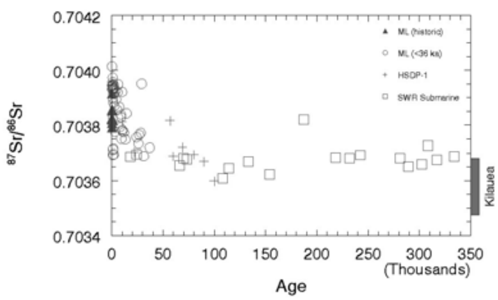
The Hawaiian plume is thought to be concentrically zoned in both temperature and composition. If so, then in 300 ka Mauna Loa will have traversed about 30 km of the plume. Over this time period we might expect to see changes in magma composition reflecting the extent of melting and changes in source components



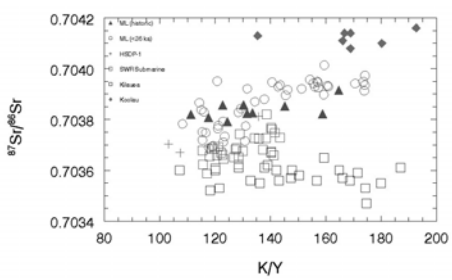
1. Mauna Loa lavas fall between the end-member “Kea” and “Loa” Hawaiian plume components
2. Prehistoric lavas (<36 ka) overlap historical lavas, but are more variable, especially in $^{87}Sr/^{86}Sr$
3. Older lavas (> 70 ka?) have more of a “Kea” component and tend to approach Kilauea values



In detail there is not much significant change until at about 20 – 30 ka ago when there are large fluctuations in incompatible element and isotopic ratios.

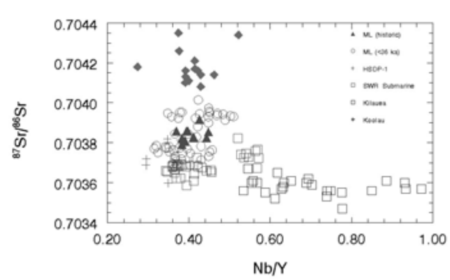


Historical lavas encompass much of this diversity in only 137 years!



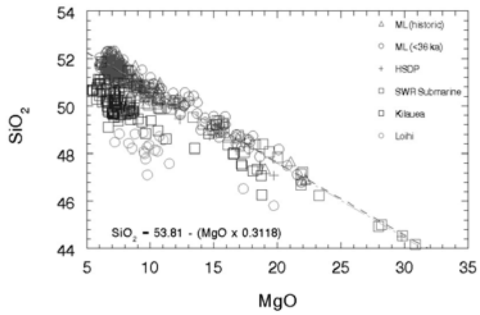
Temporal variations are related to:

1. Variations in the proportions of the "Loa" and "Kea" components.
2. Correlated changes in isotopic and incompatible element ratios associated with melting of a refractory plume component.

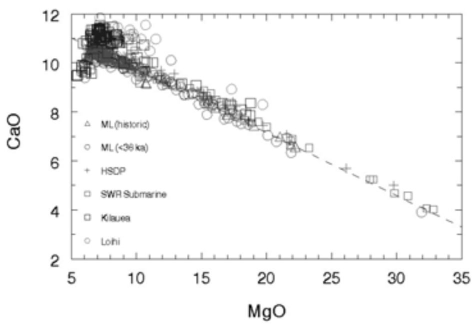


Note how the submarine SWR lavas converge or overlap with Kilauea lavas

What about major elements?

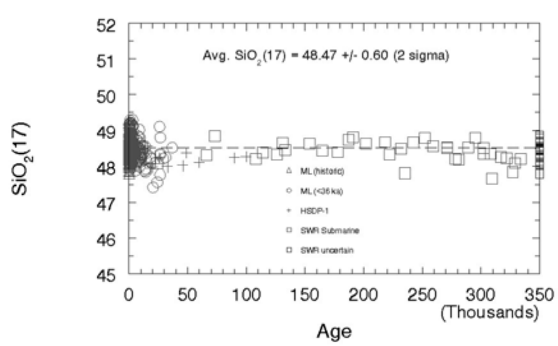


SiO_2 TiO_2 and CaO differ at a given value of MgO between Hawaiian volcanoes. This is presumably a consequence of differences in melting and melt segregation processes in different parts of the plume.



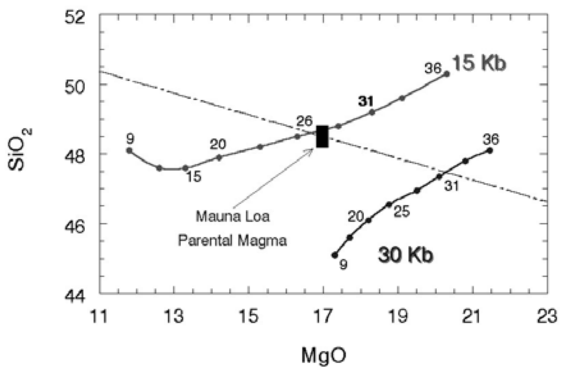
We might,therefore, expect to see changes in these values as Mauna Loa transits the Hawaiian plume.

This is not the case – they are remarkably constant over the entire 300 ka record!



Extrapolation of SiO_2 to 17% MgO (in equilibrium with Fo_{91}) using regression equation

Note how SiO_2(17) has remained essentially constant throughout Mauna Loa's recorded eruptive history.
The standard deviation for 438 analyses is only about 3 times the analytical error!

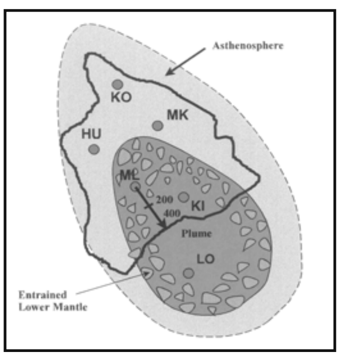


Peridotite melting parameterization curves at 15 and 30 kb from Longhi (2002) and Stolper et al., (submitted)

PROBLEMS:

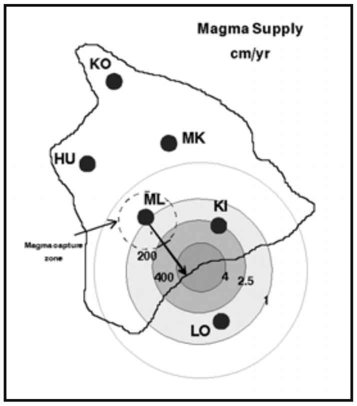
- Significant changes in the extent of melting, or the depth of melt segregation, should produce significant differences in SiO_2 content. These are not observed.
- Implied pressure (~15 kb) is much too shallow for garnet peridotite source (required by trace elements).
- Composition is appropriate for shallow melting of harzburgite.

CONCLUSIONS



1. Isotopic data are consistent with the notion that over 300 ka Mauna Loa has sampled a zoned plume.
2. For much of the 300 ka record the source of Mauna Loa magmas was intermediate between that of modern Mauna Loa and Kilauea.
3. Somewhere between 70 and 20 ka ago there was a substantial increase in the "Loa" component.
4. Over the last 20 ka the proportions of the "Loa" and "Kea" components have fluctuated wildly indicating marked heterogeneity in the source.

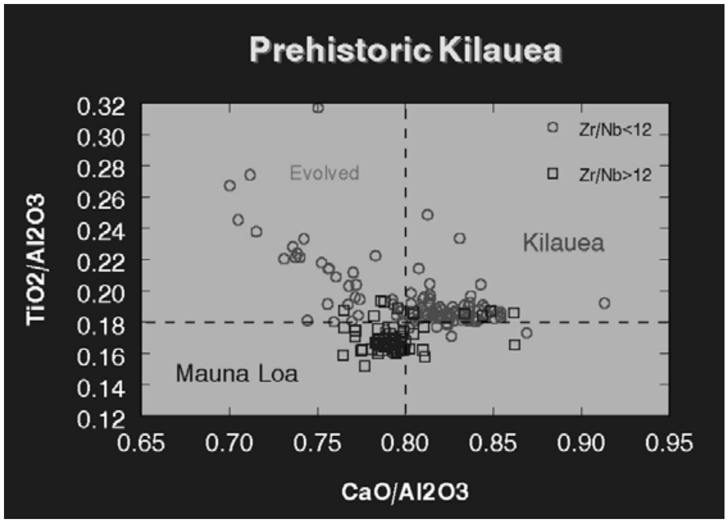
CONCLUSIONS

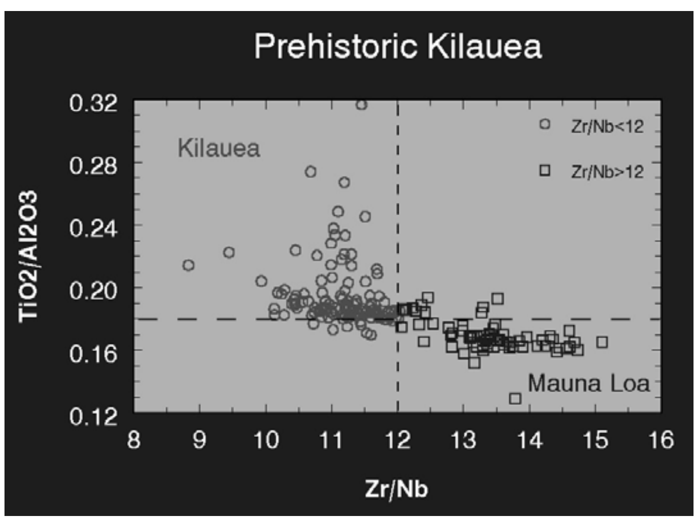


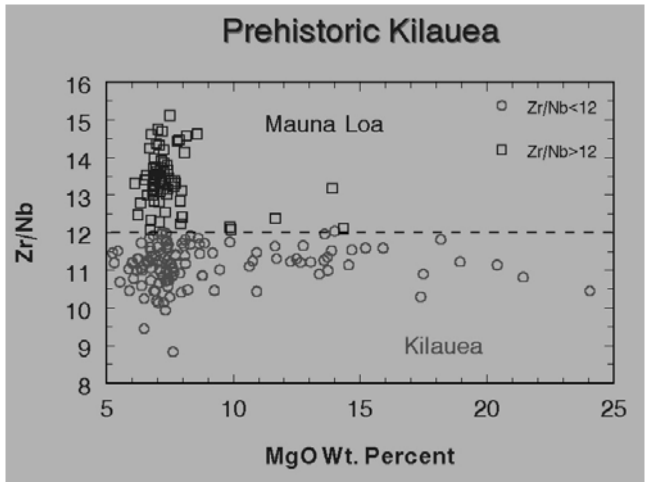
4. There are no significant changes in major elements over 300 ka.
5. This is inconsistent with the idea of a thermally zoned plume.
6. Either the thermal gradients are much wider than the models predict, perhaps reflecting lithospheric drag on the plume……
7. Or, magma compositions are determined by processes other than melting and melt segregation.
8. Re-equilibration with barren harzburgite at shallower levels in the plume (Eggins, 1992; Wagoner and Grove, 1998) appears to be a plausible explanation.

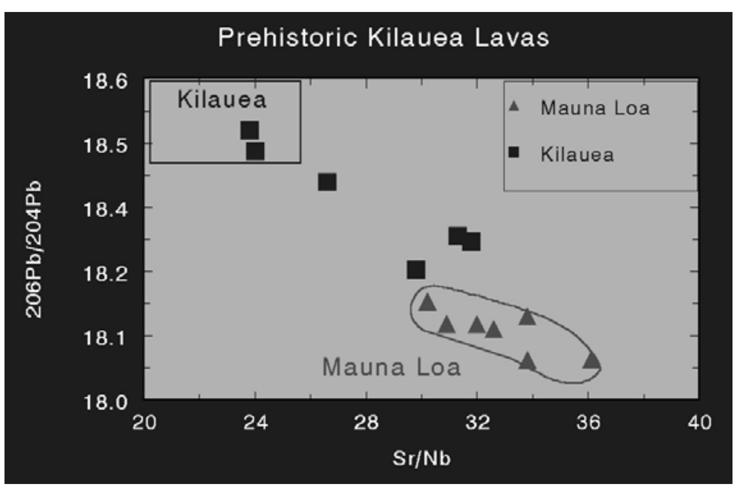
Magmatic Intercourse Between Mauna Loa and Kilauea Volcanoes?

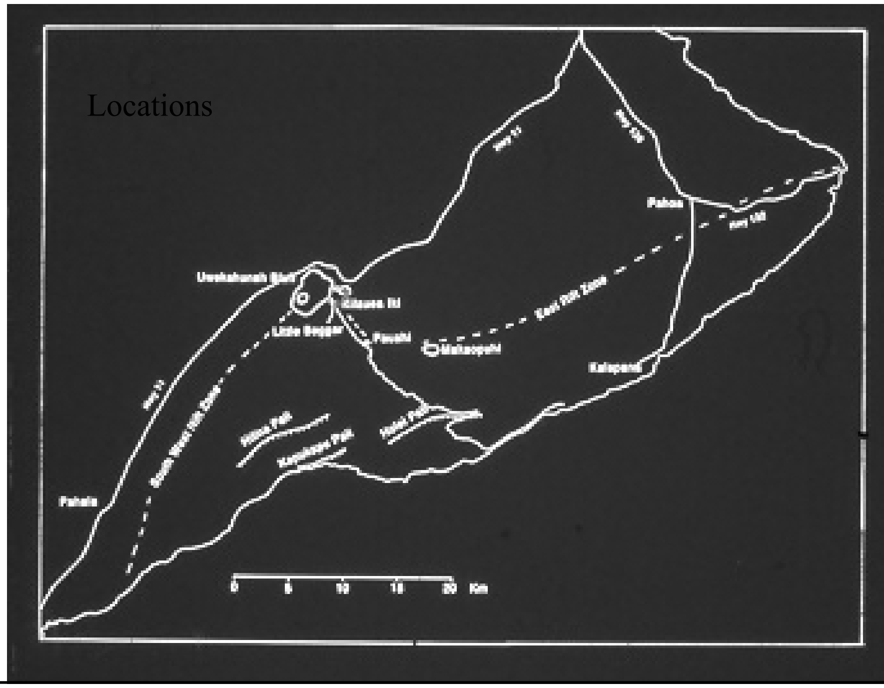
1. Old view – Kilauea was just a subsidiary vent on the flank of Mauna Loa
2. Seismic perspective – earthquakes converge at depths – so both volcanoes are competing for the same magma
3. Geochemical Perspective – geochemical and isotopic differences imply that the two volcanoes have separate plumbing systems and plume source

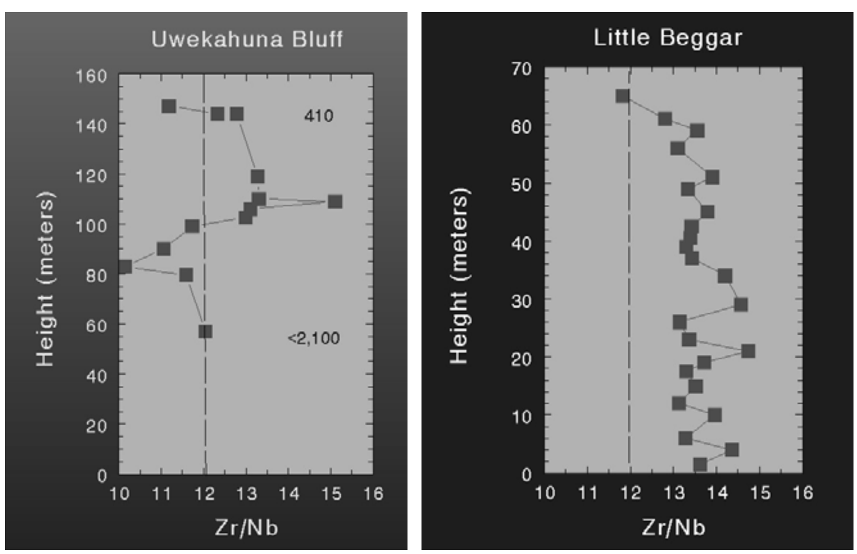

Prehistoric Kilauea
TiO2/Al2O3
CaO/Al2O3
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.65
0.70
0.75
0.80
0.85
0.90
0.95
Zr/Nb<12
Zr/Nb>12
Evolved
Kilauea
Mauna Loa

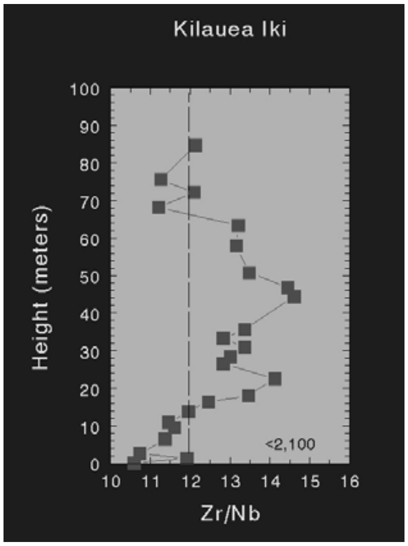

Prehistoric Kilauea
TiO2/Al2O3
Zr/Nb
0.32
0.28
0.24
0.20
0.16
0.12
8
9
10
11
12
13
14
15
16
Zr/Nb<12
Zr/Nb>12
Kilauea
Mauna Loa

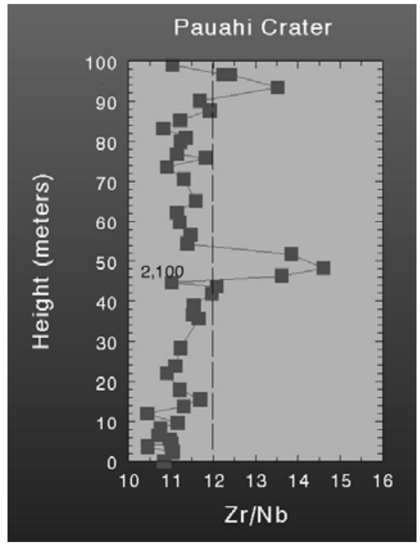

Prehistoric Kilauea
Mauna Loa
Zr/Nb<12
Zr/Nb>12
Zr/Nb
Kilauea
MgO Wt. Percent
16
15
14
13
12
11
10
9
8
5
10
15
20
25

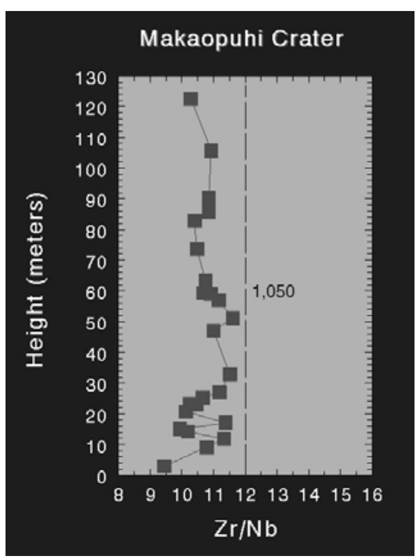

Prehistoric Kilauea Lavas
Kilauea
Mauna Loa
Kilauea
206Pb/204Pb
Mauna Loa
Sr/Nb
18.6
18.5
18.4
18.2
18.1
18.0
20
24
28
32
36
40

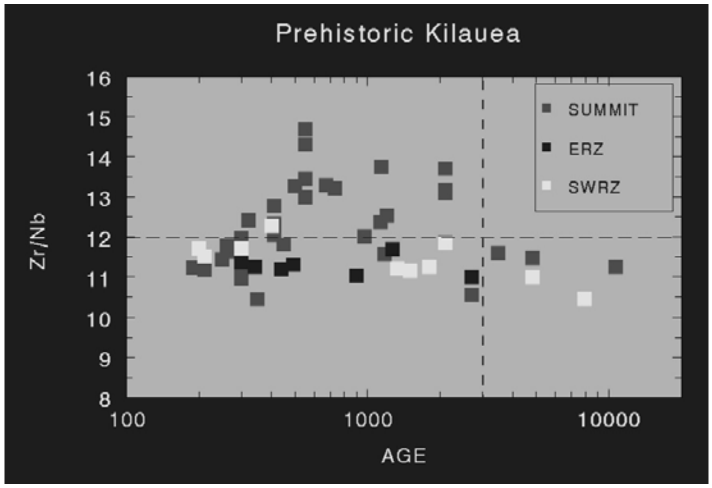

Locations
Uwekahuna Bluff
Little Beggar
Pauahi
Makaopuhi
East Rift Zone
Pahoa
Kalapana
Pahala
0 5 10 15 20 Km


Uwekahuna Bluff
410
<2,100
Height (meters)
Zr/Nb
Little Beggar
Height (meters)
Zr/Nb


Kilauea Iki
Height (meters)
100
90
80
70
60
50
40
30
20
10
0
10 11 12 13 14 15 16
Zr/Nb
<2,100


Pauahi Crater
Height (meters)
100
90
80
70
60
50
40
30
20
10
0
10 11 12 13 14 15 16
Zr/Nb
2,100


Makaopuhi Crater
Height (meters)
130
120
110
100
90
80
70
60
50
40
30
20
10
0
8 9 10 11 12 13 14 15 16
Zr/Nb
1,050



1. Mauna Loa “like” lavas restricted to summit region
2. Younger than 2,000 yrs
3. Older than 400 yrs

What is all the fuss about?

- **Either, a Mauna Loa-like source has supplied Kilauea for a very short period of time.**
- **Or, magma has moved lateraly from Mauna Loa, invading Kilauea's magmatic plumbing system.**

SUMMARY

- The "Event" was very short-lived.
- Mauna Loa-like lavas appear to be restricted to the summit of Kilauea.
- Major element compositions are also consistent with Mauna Loa lavas (including narrow range in MgO).
- Trace elements are not inconsistant with Mauna Loa lavas of the same age.

How did it Happen?