Seismic Structure and Dynamics of the Hawaiian Mantle Plume

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I. Development of the Mantle Plume Concept

II. Seismic Structure Imaged by PLUME

III. Dynamics of Hawaiian Plume

IV. Shear Wave Splitting & Mantle Deformation

IV. Outstanding Questions
I. Development of the Mantle Plume Concept

Hotspots: chains of age-progressive volcanoes on topographic swells, near & far from plate boundaries

Seafloor Topography Corrected for Age and Sediments
I. Development of the Mantle Plume Concept


Morgan [1971] stationary mantle convection plume from the lower mantle.

Classical 3D models of mantle plume beneath the lithosphere.

Variations of the plume concept based on global mantle tomography, laboratory experiments, and dynamical models.

Ribe & Christensen (1999)

Core-mantle boundary

Moore Tackley (1999)

PACIFIC

shallow plumes

deep plumes

superplumes

Courtillot et al. (2003)
II. Hawaiian Plume Lithosphere Undersea Experiment (PLUME)

Gabi Laske (SIO), Cecily Wolfe (UH), Sean Solomon (CIW/LDEO), John Collins (WHOI), Robert Detrick (WHOI/NSF/NOAA), John Orcutt (SIO), David Bercovici (Yale), Erik Hauri (CIW)

Objectives

• Test for a deep mantle plume (image lower-to-upper mantle)
• Determine origin of the hotspot swell (image shallow upper mantle & lithosphere)
II. Hawaiian Plume Lithosphere Undersea Experiment (PLUME)

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The Experiment

- 72 OBS’s (64 recovered), 10 portable land stations
- Phase 1: Narrow aperture array 1/05-1/06
- Phase II. Wider aperture array 04/06-6/07
Mean station delays of $P$ and $S$ waves

1. Slow arrivals on the swell
2. Fast arrivals near margins of the swell
3. Asymmetry:
   - fast arrivals over deep bathymetry on southeast
   - Slow arrivals over shallow bathymetry on west
- Thick (~400 km) elongate body of slow velocity beneath swell in upper mantle
- Fast velocities on outskirts of swell in upper mantle
- Asymmetric structure
- Tilted slow velocities protruding down into lower mantle

S-Wave Tomography, Wolfe et al., Science, 2009
P-Wave Tomography, Wolfe et al., Science, 2009

- Thick (~400 km) elongate body of slow velocity beneath swell in upper mantle
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- Tilted slow velocities protruding down into lower mantle
Rayleigh Wave Tomography, *Laske et al. [GJI, 2011]*

- Fast velocities on outskirts of swell
- Slow velocities beneath the swell
- Thin lithosphere beneath islands
- Complex and asymmetric structure
- Heated lithosphere detected in prior studies
Resolution of body wave tomography:

2146 wave paths for S-wave imaging

Provides dense coverage beneath Hawaii down to ~1500 km depth
The deep anomaly in the S-wave model is created by azimuthally varying patterns in the SKS data.
S-Wave Resolution Tests

Input

Output

900 km depth

Vertical cross section
2-layer S-Wave Checkerboard Test

300 km depth:

900 km depth:
Structure of the Hawaiian Mantle Plume

Rayleigh Wave Tomo.

S-Wave Tomo.

P-Wave Tomo.

Plume ponding beneath lithosphere supports swell

Sinking sub-lithosphere material

Hot tilted plume from lower mantle

Steinberger et al. [2004]
II. CONCLUSIONS of PLUME Seismic Experiment:

S, P, and Rayleigh wave tomography beneath Hawaii from the PLUME yield unprecedented high resolution images of mantle structure beneath Hawaiian hotspot

Direct evidence for:

• Tilted hot plume from lower mantle
• Topographic swell supported by layer of ponded plume material and thinning of lithosphere TBL
• Plume layer surrounded by high-velocity “curtains”
• Asymmetric and complex structure in ponding plume layer
III. Dynamics of the Hawaiian Plume

Not predicted by previous models:
(1) Asymmetric & complex structure
(2) Thick (400 km) plume pancake
Small-scale convection and bilateral asymmetry in the shallow structure of the Hawaiian mantle plume

Maxim Ballmer, Garrett Ito, Jeroen van Hunen, & Paul Tackley [2011]

PREDICTIONS:

- Fast seismic wave speeds on outskirts of swell
- Asymmetry & short-wavelength structure
- Widespread volcanism (shield, rejuvenated, arch)

THIN (<100 km) not thick (~400km) ponding layer
A Double-Layered Thermochemical Hawaiian Plume

Maxim Ballmer, Garrett Ito, Cecily Wolfe (SOEST, UH Manoa)
Sean Solomon (Lamont-Doherty Earth Observatory)

Aoki & Takahashi [2004]

~70% dry peridotite
20% hydrous peridotite
15% eclogite

isosurfaces of melting rate
isosurfaces of temperature

Pancake
Deep eclogite pool

Vertical cross-section \| plate motion

Pressure [GPa]
Density [g/cm³]

300 km
410 km

~1250 - 1600°C
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Melting rate contours

PREDICTIONS:

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✓ Asymmetry & short-wavelength structure
✓ Widespread volcanism (shield, rejuvenated, arch)
✓ Thick (~400km) ponding layer

~70% dry peridotite
20% hydrous peridotite
15% eclogite

Melting rate contours

pancake

depth [km]

vertical cross-section || plate motion
Inverted Seismic Structure Based on Models Versus PLUME Data
Mantle Melting Is Temporally Variable & Bilaterally Asymmetric
Mantle Melting Is Temporally Variable & Bilaterally Asymmetric

- Abouchami et al. (2005)
- Rayleigh Wave Tomo.
- Plate motion
- Pyroxenite contribution
III. Dynamics of the Hawaiian Plume CONCLUSIONS:

- Asymmetric and complex seismic structure can be explained by vigorous convection in the upper mantle especially with thermochemical effects.
- Density maximum of eclogite at depths of 300-410 can give rise to a double-layering of plume in upper mantle.
- Spatially variable and time-dependent melting addresses observations of Hawaiian magmatism.
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IV. Seismic Anisotropy and Mantle Deformation

Garrett Ito, Cecily Wolfe, Robert Dunn (SOEST, UH Manoa)
Yuanyuan Fu, Aibing Li (Univ. Houston)

Shear wave splitting at the Hawaiian hot spot from the PLUME land and ocean bottom seismometer deployments

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Mantle Anisotropy & Shear Wave Splitting With Plate Motion

Shear Wave Splitting

Anisotropy:

20 km below Lithosphere

90 km below Lithosphere

Upwind SIDE: MORE differential shear shrinks area of circular pattern

Downwind Side: LESS differential shear preserves circular pattern
IV. Seismic Anisotropy & Mantle Deformation Beneath Hawaii

Predicted SWS without lithosphere

Predicted SWS with fossil LPO in lithosphere

Collins et al. [2012]
IV. Seismic Anisotropy and Mantle Deformation Beneath Hawaii:
67% of model split directions are within 20° of observed split directions

- Black tics: observed splitting
- Blue tics: model splits
- Red tics: model splits within 20° of observe
IV. Seismic Anisotropy and Mantle Deformation

CONCLUSIONS:

- Observed shear-wave splitting heavily controlled by fossil lithosphere structure
- Variability can be attributed to anisotropy associated with shallow plume pancake
- Olivine-a axes often do NOT parallel flow. Dynamical models are important using seismic observations to characterize mantle flow/deformation
V. Outstanding Questions

Is Hawaii the only double-layered, thermochemical plume?

Hot mantle upwelling across the 660 beneath Yellowstone

Schmandt et al. [2007]

Imaging the mantle beneath Iceland using integrated seismological techniques

Allen et al. [2002]
V. Outstanding Questions

What is the structure of the Hawaiian plume in the deep mantle? What is its ultimate depth of origin?

Monteli et al. [2006]

Cao et al. [2011]
V. Outstanding Questions

From where does the eclogite originate? Where is this mafic material stored and how often does it enter the upper mantle or see the surface?

*Garnero et al. [2007]*

*Thermochemical convection in lower mantle*

*McNamara & Zhong [2005]*

*Ritsema & van Heijst [2011]*
V. Outstanding Questions

How important are mafic materials to the genesis of shield stage volcanism? Secondary volcanism? What would Hawaiian volcanism be without a mafic source?

Sobolev [2005], Parental melt compositions from olivine melt inclusions

Greene et al. [2011]
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Does outside structure from the Pacific Large Low Shear Wave Velocity Province (LLSVP) (seen in global models) in the lowermost mantle bias our regional body wave models?

2650-2890 km depth

Global model by *Grand* [2009]
Common structure in $P$ and $S$ wave models, despite differing wave paths, suggests that the results are likely not biased by lowermost mantle structure outside of our regional model.

$SKS$ wave paths in lowermost mantle

$P$ wave paths in lowermost mantle
Axisymmetric or radially spreading plume beneath stationary plate

- Depth = 100 km olivine-a axes parallel flow
- Depth = 170 km olivine-a axes perpendicular to flow
Shallow part of plume “pancake” dominated by radial shear flow & radial fast Vp directions

Lower part of plume “pancake” is stretching circumferentially & fast Vp direction is perpendicular to flow

Depth = 100 km olivine-a axes parallel flow

Depth = 170 km olivine-a axes perpendicular to flow
Shear wave splitting (SWS) predicted by waveform propagator method

SWS Across Whole Anisotropic Layer

SWS Generated in Lower Asthenosphere

Split Time (s)