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Implications for the origin of Hawaiian volcanism from a converted wave analysis of the mantle transition zone

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ABSTRACT

The debate over the origin of intraplate volcanism has been ongoing since the discovery of age-progression at oceanic “hotspots.” The causes of such anomalous volcanic activity have been attributed to either deep-seated thermal plumes in the convecting mantle or shallower causes such as lithospheric structure and deformation or localized mantle flow. Data from the Hawaiian Plume–Lithosphere Undersea Melt Experiment (PLUME) have made it possible to provide detailed images of upper mantle heterogeneity beneath the Hawaiian Islands with much greater resolution than previous experiments. Using receiver function analysis, we determine the depth to and topography along the mantle transition zone discontinuities. Our results indicate that the 410-km discontinuity deepens from northwest to southeast beneath the Hawaiian Islands, corresponding to an average thermal anomaly of ~325 K located beneath and southeast of the Big Island of Hawaii. In general, temperatures remain elevated by at least ~150 K directly beneath the Big Island, as far as 200 km away from the hottest measurement inferred from the discontinuity structure. Heterogeneity at these length scales raises questions about rheology, convective circulation, and melt transport in the mantle. Our results also robustly indicate the presence of a low-velocity converter in the deep upper mantle, which carries additional implications for melt transport, volatile budget, and chemical composition of the hotspot source.

1. Introduction

The origins of intraplate volcanism have been hotly debated in recent years (see Niu (2005), Davies (2005), Foulger (2005), and Anderson (2011) for an overview). The Hawaiian Islands and Hawaiian–Emperor Seamount chain are often used as the type example for intraplate volcanism, as their linear geometry and extensive history suggests a stable, fixed mantle source for at least 40 million yr (e.g., Wilson, 1963a, 1963b), and perhaps longer, if the bend in the Hawaiian–Emperor chain reflects an abrupt change in plate motion (e.g., Morgan, 1971; Sharp and Clague, 2006), though this is not universally agreed upon (e.g., Norton, 1995; Tarduno et al., 2003). The entire length of the seamount chain may reflect a relatively constant mantle flux dating back to 80 Ma, though the mantle source may have shifted its location or orientation around the time of the bend in the seamount chain (e.g., Tarduno et al., 2003). While many studies have maintained that intraplate volcanism is a result of plumes stemming from the core–mantle boundary (e.g., Morgan, 1971, 1972; Koppers, 2011), others suggest that they originate in the transition zone or mid-mantle (e.g., Davaille, 1999; Cserepes et al., 2000; Foulger et al., 2000) or are a result of upper mantle melting (e.g., Anderson, 2000). Images from seismic tomography suggest that a variety of depths of origins for global hotspot volcanism may exist (Montelli et al., 2004, 2006; Zhao, 2007). Other studies suggest that the anomalous volcanism stems from purely chemical anomalies, with no thermal contribution (e.g., Takahashi et al., 1998).

Geochemical differences between ocean island basalts (OIBs) and mid-ocean ridge basalts (MORBs) have been the primary driver in the debate over the source material of ocean island volcanism (see White (2010) for a review). MORB compositions are relatively consistent along plate boundaries, implying that the upper mantle is relatively homogeneous and that a depleted source rock is a good representation of bulk upper mantle composition (e.g., Workman and Hart, 2005). Relative to MORBs, OIBs contain significantly more volatile components, distinct major element compositional variations (e.g., Dasgupta et al., 2010), and are enriched in trace elements such as Sr, Pb, and Nd and other light rare-earth elements (e.g., Kerr et al., 1995; Hofmann, 1997). Other constraints, including He^3/He^4 ratios, imply that the MORB and OIB source reservoirs have remained isolated over billions of years of convective circulation in the mantle (e.g., Allegre et al., 1983). These distinctions have led researchers to suggest a deep source reservoir for OIBs that is not sampled by the mid-ocean ridge system (e.g., Van Keken et al., 2001).

The determination of the depth-of-origin for hotspot source material therefore remains one of the first-order issues for understanding mantle structure. The complexity of mantle dynamics and interactions with the viscous lithosphere require a simplified natural laboratory in which to test the above models via analysis of

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detailed seismic structure. The oceanic mantle is ideal, due to uniform plate motion, well-studied mid-ocean ridge processes, and presumed homogeneous mantle and lithospheric structure relative to continental regimes. Ocean island chains also prove ideal testing grounds when clear age progressions are present. Seismic imaging of the mantle beneath ocean islands is difficult, however, for several reasons. First, instrumentation has been historically poor. Accessible localities (islands) are few and far between, and the cost of permanent undersea observatories can be prohibitive (e.g., Petitt et al., 2002). Second, islands are by definition anomalies relative to the abyssal plain, yielding inferences that may not be widely applicable. Third, imaging features in the mantle at scales of less than 1000 km typically requires both a dense receiver array and a set of earthquake sources with geometries illuminating the subsurface target. Unless sources span a range of epicentral distances, vertical smearing can impact imaging. On top of these issues, the microseism noise peak in the ocean/ocean island environment severely constrains signal-to-noise ratio of recorded data (e.g., Berger et al., 2004).

For these reasons, the mantle plume debate has persisted with respect to both thermal structure and depth of origin despite global and regional seismic studies of the oceanic mantle (e.g., Shen et al., 1998; Allen et al., 1999, 2002; Montelli et al., 2004, 2006; Li et al., 2003; Chambers et al., 2005a, 2005b; Deuss, 2007; Gu et al., 2009; Schmerr et al., 2010). In order to test these theories, detailed seismic images from tomographic and mantle discontinuity studies must be obtained on a regional to local scale. Tomographic studies invert for seismic velocity, and wave speed anomalies are interpreted as broad changes in the temperature or chemistry of a region. While some tomographic studies show plume-like images in the mantle (Montelli et al., 2004, 2006; Lei and Zhao, 2006; Zhao, 2007; Wolfe et al., 2009, 2011), seismic analysis of the fine-scale aspects of plume structure is better targeted with other methods.

Variations in the depth, thickness, and impedance of mantle discontinuities can be used to interpret thermal and compositional heterogeneity (Bina and Helffrich, 1994). These discontinuities stem from sharp changes in the physical properties of mantle materials, such as mineral phase changes or interfaces between solid and partially molten materials. The mantle transition zone refers to the set of seismically detected velocity and/or density contrasts that have been associated with mineral phase changes at pressures between approximately 14 and 24 GPa at ambient mantle temperatures (e.g., Anderson, 1967, 1970; Ringwood, 1969; Akaogi et al., 1989; Katsura and Ito, 1989; Ito and Takahashi, 1989). The discontinuities bounding the transition zone are the shallower olivine–wadsleyite transition and the deeper ringwoodite–perovskite transition. For simplicity, we will follow the traditional naming convention of “410-km discontinuity” and “660-km discontinuity”, respectively, though the absolute depths are known to vary due to changes in composition, temperature, and volatile content (see Helffrich (2000) for a review).

Because these mineral phase changes occur at different pressures for different thermal and chemical compositions, seismically detected topography along these discontinuities has been used as a mantle thermometer and/or indicator of other heterogeneity. For example, the 410-km discontinuity has a global average depth of 418 km (e.g., Lawrence and Shearer, 2008), but approximately ± 40 km of topography is observed globally (Chambers et al., 2005a). As temperature increases, the pressure necessary to change phases from olivine to wadsleyite also increases (i.e., the phase boundary has a positive Clapeyron slope), causing the discontinuity to shift deeper (Katsura et al., 2004). Changes in composition impart opposite effects; the addition of water and/or iron to olivine causes the discontinuity to move to shallower depths, and broadens the two-phase loop (e.g., Smyth and Frost, 2002; Deon et al., 2011).

At the base of the transition zone, the 660-km discontinuity is also affected by the temperature of the surrounding mantle, but inversely and weaker than at 410 km depth (Higo et al., 2001). Therefore, when ambient mantle is hotter than the global average, the opposite Clapeyron slopes of the 410- and 660-km discontinuities will cause the transition zone to become thinner. Because the calculations of the depths to these discontinuities from seismic observations can be influenced by the velocity structure of the upper mantle, studies often report only the transition zone thickness, yielding a relative temperature anomaly. Globally, transition zone thickness varies from ~217–265 km (Flanagan and Shearer, 1998; Gu et al., 1998; Lawrence and Shearer, 2008), with an average of ~242 km (Lawrence and Shearer, 2008). With respect to mantle plumes, if a deep-seated thermal plume is feeding the intraplate volcanism, then there should be a localized depression of the 410-km discontinuity and a thinned transition zone correlated with active volcanism at the surface. Unfortunately, this discontinuity structure alone is not sufficient to shed light on the thermal structure deeper into the lower mantle, and so we must rely primarily on tomography (with its limitations) to assess plume structure in the lowermost mantle. Further, while seismic imaging methods can provide key information about the thermal and compositional structure of the mantle, patterns of convective circulation may only be inferred. Therefore, while the presence of a positive thermal anomaly in the transition zone is strong indicator of mantle upwelling and a constraint that must be reconciled, in isolation it is insufficient to definitively rule out some of the alternate hypotheses.

The Hawaiian Islands are one of the primary areas of focus for testing the plume hypothesis presented by Morgan (1971). This volcanically active chain of age-progressive islands sits atop a broad bathymetric swell in the central Pacific Ocean. The geographic trend of the islands is consistent with continued northwestern motion of the Pacific Plate over the past 80 million yr (e.g., Wilson, 1963a, 1963b; Tarduno et al., 2003), combined with a relatively stationary and stable source below leading to the observed volcanic activity. The volcanism and seismicity at the Hawaiian Islands have been monitored for over a century (e.g., Tilling, 2012), which has led to a wealth of published studies describing the crust and mantle directly beneath the islands. Additional studies using seismic phases that sample the mantle beneath Hawaii along paths from distant sources and receivers have also been conducted. However, the seismic methods used to study transition zone discontinuity structure are limited either to studying very broad, regional structure (for example, SS precursors, Schmerr and Garnero, 2006; Cao et al., 2011), or local studies with little ability to comment on lateral variability due to limited station locations (for example, receiver functions, Li et al., 2000; Shen et al., 2003; Wölbern et al., 2006; and ScS reverberations, Courtier et al., 2007). Despite these limitations, all of these studies indicate a thinned transition zone near the Hawaiian Islands, consistent with a thermal upwelling extending from the surface to at least 410–660 km, though the exact location of the maximum anomaly varies between studies. Li et al. (2000) noted a 40–50 km thinning of the transition zone south of Hawaii, consistent with a thermal anomaly of ~300 K. A broader, higher resolution study later refined the location of the anomaly, estimating a thermal plume core of ~120 km radius centered southwest of the Big Island of Hawaii (Wölbern et al., 2006). Shen et al. (2003) additionally identified a discontinuity at ~1000 km depth, a feature that is not seen globally and may be a signature unique to plume structure. However, this feature was not detected in the whole-mantle ScS reverberation analysis beneath the islands by Courtier et al. (2007).

Recently available data from the array of land-based and ocean-bottom-seismometers of the Hawaiian Plume–Lithosphere Undersea Melt Experiment (PLUME; Laske et al., 2009) have made it possible to image the heterogeneity of the transition zone beneath the Hawaiian Islands with much greater resolution than previous experiments. The PLUME data have proven to be of sufficient quality to provide several new observations and constraints regarding the crust and mantle structure. For example, Leahy et al. (2010) found that substantial regions of