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Seismic wave speed structure of the Ontong Java Plateau

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ABSTRACT

The Ontong Java Plateau (OJP) represents the result of a significant event in the Earth's geologic history. Limited geophysical and geochemical data, as well as the plateau's relative isolation in the Pacific ocean, have made interpretation of the modern day geologic structure and its 120 Ma formation history difficult. Here we present the highest resolution image to date of the wave speed structure of the OJP region. We use a data set that combines Rayleigh waves extracted from both ambient noise and earthquake waveforms and an iterative finite-frequency tomography methodology. The combination of datasets allow us to best exploit the limited station distribution in the Pacific and image wave speed structures between 35 km and 300 km into the Earth.

We image a region of fast shear wave speeds, greater than 4.75 km/s, that extends to greater than 100 km beneath the plateau. The wave speeds are similar to as observed in cratonic environments and are consistent with a compositional anomaly that resulted from the residuum of eclogite entrainment during the plateau's formation.

The combination of our imaged wave speed structure and previous geochemical work suggest that a surfacing plume head entrained eclogite from the deep mantle and accounts for the anomalous buoyancy characteristics of the plateau and observed fast wave speeds.

1. Introduction

The Ontong Java Plateau (OJP) represents the largest preserved Large Igneous Province (LIP) by volume on the Earth (Coffin and Eldholm, 1994; Gladczenko et al., 1997; Ito and van Keken, 2007). At the surface, the OJPs area of 2 Mkm^2 also makes it the largest oceanic plateau (Gladczenko et al., 1997). Taylor (2006) showed that the OJP, Manihiki Plateau (MP) and Hikurangi Plateau (HP) were once part of the same feature and were subsequently separated by seafloor spreading during the Cretaceous. Including the MP and HP, more than 4 Mkm^2 of ocean floor were covered by the massive outpouring of material associated with the three plateau's formation (Ito and van Keken, 2007). Connections with the Louisville Hotspot Chain have also been made, suggesting that the chain represents a plume tail (Neal et al., 1997; Chandler et al., 2012) to the OJPs surfaced plume head. This major event in Earth's history was a result of a process that is radically different from the current mode of Earth's mantle dynamics and not currently active on the Earth's surface, and resulted in rapid and catastrophic global environmental change (Larson, 1991; Larson and Erba, 1999). Estimates of the volume of magma erupted range from 44 to 57 Mkm^3, over a geologically short time period (Coffin and Eldholm, 1994; Gladczenko et al., 1997; Tejada et al., 2002). Despite its apparent significance to Earth's geologic history, knowledge of the OJP is still under developed.

Current understanding of the OJP comes from a broad range of research. Sampling of the OJPs surface has been done using geochemistry and petrology on recovered rock samples from DSDP site 289 (Hammond et al., 1975) and ODP cruise leg 130 (Berger et al., 1992; Mahoney et al., 1993) as well as sampling on nearby islands in the Solomon chain (Neal et al., 1997; Michael, 1999; Tejada et al., 1996, 2002, 2004; Ishikawa et al., 2004, 2007, 2011). Crust and upper mantle structure has been investigated using gravity and magnetic surveys (Nakanishi et al., 1992; Gladczenko et al., 1997; Ito and Taira, 2000) as well as active-source seismic profiling (Furumoto et al., 1976; Hussong et al., 1979). Deeper seismic structures have been imaged using Rayleigh-wave seismic tomography (Richardson et al., 2000), ScS reverberations for seismic attenuation (Gomer and Okal, 2003) and SKS splitting for anisotropy (Klosko et al., 2001).

The results of these studies paint a complex geologic history spanning 120 million years and despite previous work, a consensus regarding the genesis of the OJP is lacking and several hypotheses have developed. Three main hypotheses on the OJPs origin invoke either 1) the surfacing of a buoyant plume head, 2) vigorous pas-

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sive mantle upwelling at or near a spreading ridge, as responsible for the plateau's emplacement or 3) an impacting bolide resulting in extensive melting (Ingle and Coffin, 2004). Discussions here are limited to hypotheses 1 and 2.

1.1. Plume source

The prevailing idea for the origin of LIPs has been decompression melting of a surfacing mantle plume head (Griffiths et al., 1989; Campbell, 1998). A Rayleigh–Taylor instability originating from the core-mantle boundary or the mantle transition zone located between 410 and 660 km depth can be positively buoyant due to either a thermal or compositional anomaly compared to the ambient mantle (Griffiths et al., 1989; Richards et al., 1989; Olson, 1990; Larson and Kincaid, 1996; Campbell, 1998, 2005). The OJP, and other LIPs, would be a product of high degrees of melting in a plume that rise quickly and adiabatically through the mantle (Larson, 1991; Larson and Kincaid, 1996), resulting in widespread melting, and possible drying and depletion of the mantle beneath a forming plateau (Hall and Kincaid, 2004). Larson (1991) suggested this excess of heat, originating from the core-mantle boundary, could alter normal mantle convection, changing the frequency of magnetic reversals and leading to the observed mid-Cretaceous magnetic quite zone following the formation of the OJP.

Perhaps the most compelling evidence for a plume source to the OJP is the volume and rate of erupted material. Erupted volume estimates range from 44 to 57 Mkm^3 over 6–14 Myrs (Coffin and Eldholm, 1994; Gladczenko et al., 1997; Tejada et al., 2002). Tejada et al. (1996, 2002) determine the main plateau forming event occurred around 120 Ma, with a smaller, but significant, volume of material emplaced around 90 Ma. Geochemically, samples represent high degrees of partial melting of a relatively homogeneous and well-buffered OIB-like source (Tejada et al., 1996; Michael, 1999). Minor enrichment in siderophile elements, such as molybdenum (Mo), members of the platinum group, and gold (Au), may suggest a core-mantle boundary source, consistent with a plume hypothesis (Jain et al., 1996; Neal et al., 1997; Ely and Neal, 2003).

Despite the evidence of a plume source for the OJP, complications arise when examining the emplacement depth and isostatic topography of the plateau. The vesicularity of the OJP lavas and presence of microfossils suggest that plateau emplacement was entirely submarine at depths greater than 800 m below sea level (Mahoney et al., 2001). Korenaga (2005) suggested that based on a realistic geotherm (1500 °C) for a mantle hot enough to induce melting, the plateau should have been emplaced at or above sea level based solely on the isostatic topography; the addition of a buoyant plume head would dynamically raise the plateau further. Using numerical models, Farnetani and Richards (1994), suggested uplift of approximately 5 km above abyssal sea floor when lithospheric extension is allowed in their model, similar to the pre-emplacement tectonic setting near the OJP. Hall and Kincaid (2004) suggested the formation of a viscous "plug" due to significant melt extraction and dehydration. A viscous plug would be more resistant to mantle flow and able to persist for >120 Ma. In addition to a lack of uplift, post-emplacement subsidence has been retarded relative to normal seafloor and seafloor adjacent to the plateau (Neal et al., 1997), suggesting a remnant positive buoyancy within the mantle beneath the OJP.

1.2. Passive rift driven upwelling

As an alternative to the plume-driven hypothesis, (Korenaga, 2005) proposed that entrainment of dense eclogite fragments, by vigorous plate-driven mantle flow due to fast plate spreading rates, could explain both the topography and geochemistry of the OJP.

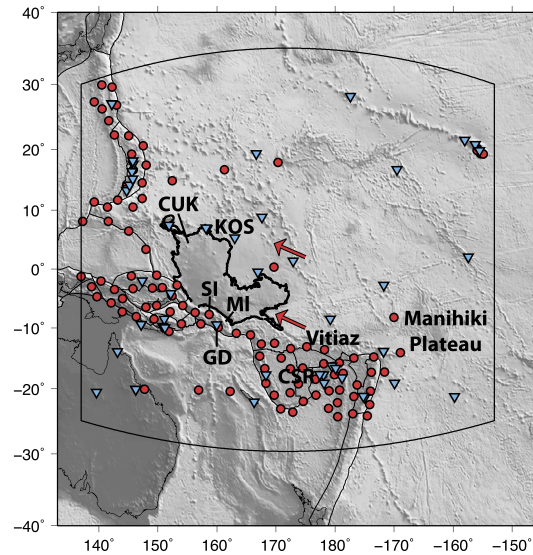

Fig. 1. 54 Seismic stations (inverted triangles) and 105 earthquake events (circles) used for this study in the Pacific Ocean. Our computational domain is outlined in black. The 4000 m bathymetric contour of the Ontong Java Plateau (OJP) is outlined in black. Modern plate boundaries are shown with a thin black line. The red arrows show modern Pacific plate motion. Major features have been labeled in black: Central Spreading Ridge (CSR), the Vitiaz Lineament, and Manihiki Plateau. The location of the Solomon Islands of Santa Isabel Island (SI), Guadalcanal (GD), and Malaita Island (MI) as well as the Micronesian islands of Kosrae (KOS) and Chuuk (CUK) are also highlighted. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Korenaga (2005) suggested the dense eclogite comes from fragments of subducted crust that stalled at the top of the transition zone. Initial formation of the combined plateaus occurred in the vicinity of the Tongareva triple junction (Pacific–Phoenix–Farallon); the Osbourn Trough separates the MP and HP, while spreading in the Ellice Basin separated the OJP and MP (Larson, 1997; Billen and Stock, 2000; Viso et al., 2005; Taylor, 2006). Nearby magnetic lineations (M0–M7) imply a half spreading rate of 7.7 cm/yr between 120–129 Ma (Larson, 1997). Korenaga (2005) suggested that this rapid spreading rate alone should be large enough to entrain material denser than nominal mantle, and would only be enhanced by the presence of a nearby triple junction. To produce approximately 24 km thick crust, the heterogeneous mantle entrained by plate motion would need to be made up of 25% eclogite fragments which experience 100% melting in a mantle with a potential temperature of 1300 °C (Korenaga, 2005).

What follows is a description of our tomography methodology, using a unique data set combining Rayleigh waves extracted from both ambient noise and earthquake waveforms. This allows us to obtain resolution at depths in the crust and upper mantle necessary for interpretation of the OJPs wave speed structure and arrive at a hypothesis regarding its formation.

2. Methodology

To determine the 3-dimensional wave speed structure beneath the OJP we employed a two phase, iterative, tomographic technique using full-waveform ambient noise and earthquake data. Due to the sparse coverage of seismic stations and earthquakes in the Pacific ocean and the relative isolation of the OJP (Fig. 1), a two step process was used to image the seismic wave speed structure beneath the plateau. In a first step, we used empirical Green's functions (Shen et al., 2012) derived from ambient noise data at periods up to 200 seconds. This ambient noise-only model provided an improved base model for subsequent iterations using joint ambient noise and earthquake data. The use of Green's func-