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Teleseismic imaging of the mantle beneath southernmost China: New insights into the Hainan plume

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ABSTRACT

Intraplate volcanism during the Late Cenozoic in the Leiqiong area of southernmost China, with basaltic lava flows covering a total of more than 7000 km^2, has been attributed to an underlying Hainan plume. To clarify detailed features of the Hainan plume, such as the morphology of its magmatic conduits, the depth of its magmatic pool in the upper mantle and the pattern of mantle upwelling, we determined tomographic images of the mantle down to a depth of 1100 km beneath southern China using 18,503 high-quality arrival-time data of 392 distant earthquakes recorded by a dense seismic array. Our results show a mushroom-like continuous low-velocity anomaly characterized by a columnar tail with a diameter of 200–300 km extending down to the lower mantle beneath north of the Hainan hotspot and a head spreading laterally in and around the mantle transition zone, indicating a magmatic pool in the upper mantle. Further upward, the plume head is decomposed into smaller patches, and when reaching the base of the lithosphere, a pancake-like anomaly has formed to feed the Hainan hotspot. This result challenges the classical model of a fixed thermal plume that rises vertically to the surface. Hence we propose a new layering-style model for the magmatic upwelling of the Hainan plume. Our results indicate spatial complexities and variations of mantle plumes probably due to heterogeneous compositions and thermochemical structures of the deep mantle.

1. Introduction

The Late Cenozoic intraplate basaltic magmatism, as a prominent feature in Southeast Asia, occurred extensively and voluminously in the Leiqiong area, the Indochina peninsula and the South China Sea basin after the cessation of seafloor spreading of the South China Sea. These basaltic provinces, dominated by tholeiites and alkali basalts (Wang et al., 2012), share the same isotopic and geochemical characteristics (Wang et al., 2013; Yan et al., 2014) and display light rare-earth-element enriched patterns and typical oceanic island basalt (OIB)-type incompatible element distributions (Tu et al., 1991; Zou and Fan, 2010).

Field investigations and drilling have shown that at least nine volcanic eruption episodes had taken place in the Leiqiong area during the Miocene and the Holocene, with a peak age of late Pliocene to middle Pleistocene (Flower et al., 1992). The basaltic plateau in the Hainan Island has elevations up to >100 m, with a maximum thickness of about 1000 m, and the basaltic lava flows cover a total of more than 7000 km^2 in the Leiqiong area (Fig. 1). The time-averaged supply of magma was estimated to be 0.1–0.25 km^3 yr^{-1} in the Leiqiong area (Flower et al., 1992), which is significantly greater than that of the typical OIB shields (e.g., Swanson, 1972) and close to the estimates for the major flood basalt episodes (Cox, 1980).

One popular view is that intraplate volcanism is driven by a hot deep mantle plume (Morgan, 1971). Regional and global tomographic studies have revealed a continuous low-velocity (low-V) anomaly reflecting magmatic upwelling from the lower mantle beneath Leiqiong and its adjacent area, indicating the existence of the Hainan plume (e.g., Lebedev and Nolet, 2003; Zhao, 2004, 2007; Montelli et al., 2004, 2006; Huang and Zhao, 2006). Local seismic tomography has clearly imaged the Hainan plume in the upper mantle (Lei et al., 2009; Huang, 2014). Additional evidence for the Hainan plume includes extensive synchronous OIB-type basalts (e.g., Flower et al., 1992; Zou and Fan, 2010), a thin mantle transition zone (Wang and Huang, 2012), a high mantle potential temperature (e.g., Hoang and Flower, 1998; Wang et al., 2012), and geochemical signatures of the basalts reflecting a lower-mantle plume origin (e.g., Zou and Fan, 2010; Wang et al., 2013).

Recent studies on mantle plumes, however, have uncovered that the simple, vertical upwelling of the classical plume model is contradictory with geophysical observations (e.g., Wolfe et al., 2009; Villagomez et al., 2014), and the morphology of magmatic conduits and the pattern of plume upwelling are highly dependent on the mantle temperature,

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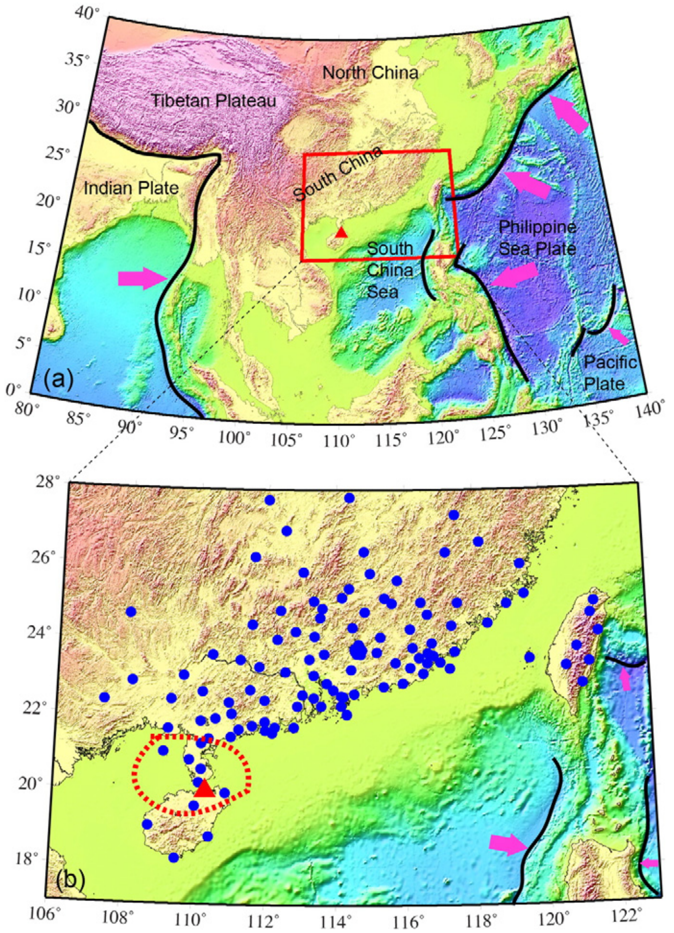

Fig. 1. (a) Regional tectonics and location of the Hainan intraplate volcano. (b) Map of the study area. The blue dots show the seismic stations used. The red triangle denotes the Hainan volcano. The red dashed circle shows the distribution of basalts in the Leiqiong area. The black lines denote oceanic trenches. The purple arrows denote directions of plate subductions.

composition, and thermochemical condition (e.g., Deschamps et al., 2011; Ballmer et al., 2013). Although many previous studies have shown the existence of the Hainan plume, its detailed features are still unclear, and there are many questions about it. For example, is there a plume-like magmatic conduit with a head and a tail? Is its magmatic upwelling vertical or tilted? What is the morphology of its magmatic plumbing system? Does the plume branch into multiple smaller conduits in the shallow mantle? These issues are of global importance for understanding the intraplate volcanism and dynamics of mantle plumes (Witze, 2013; French and Romanowicz, 2015).

In this work we determine a high-resolution mantle tomography model down to a depth of 1100 km using a large number of high-quality teleseismic data recorded by a wide-aperture seismic network in southern China (Fig. 1). Our results shed new light on the origin of the Hainan plume and its magmatic plumbing system in the upper mantle.

2. Data and method

We selected earthquakes with epicentral distances between 30° and 90° from our study area, and with magnitudes greater than M 6.0. As a result, 392 teleseismic events (Fig. 2) are selected, which were recorded by 124 permanent seismic stations in the study region during January 2010 to August 2014. These events have a fairly good azimuthal distribution with respect to our network. Our data set includes 18,503 direct P-wave arrival times from the 392 teleseismic events. The teleseismic data were carefully selected based on the following criteria: (1) To minimize errors introduced by hypocentral mislocations and origin times, and to reduce the path effect outside the modeling space, relative travel-time residuals instead of raw travel-time residuals are adopted (Zhao et al., 1994); (2) each event was recorded by more than 20 stations; (3) in this study, most relative travel-time residuals are within ±2 s. To exclude less accurate data, we chose the data with relative travel-time residuals less than 2 s; (4) large earthquakes mainly occur in the plate boundaries or active tectonic belts. For the tomographic inversion, we need a good azimuthal distribution of teleseismic events. Therefore, when some large earthquakes cluster in a very small area, we only chose the best-located event in that area which was recorded by the maximum number of seismic stations.

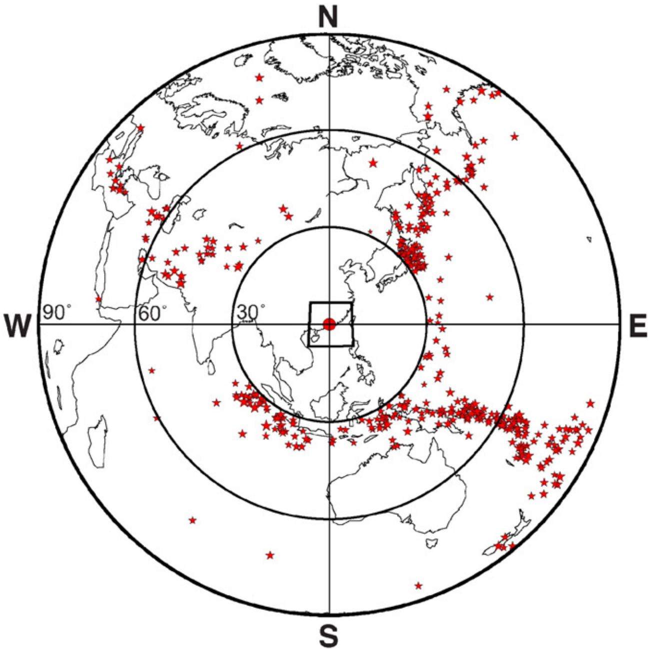

Fig. 2. Distribution of 392 teleseismic events (red stars) used in this study. An equidistant-azimuthal projection is adopted. The map center is the center of the seismic network. The concentric circles correspond to epicentral distances of 30°, 60° and 90°.

We used the teleseismic tomography method (Zhao et al., 1994) to study the three-dimensional (3D) P-wave velocity structure under the study region. The 1-D starting model for the 3-D tomographic inversion is derived from the iasp91 Earth model (Kennett and Engdahl, 1991). Teleseismic rays arrive at stations sub-vertically and rarely crisscross in the crust, thus the crustal structure cannot be imaged well using only the teleseismic data. Therefore, to remove the effect of the crustal heterogeneity so as to better image the mantle structure, we used the 3D crustal velocity model of CRUST1.0 (Laske et al., 2013) to correct the teleseismic relative residuals following the approach of Zhao et al. (2006).

The mean relative residuals at every station, referred to simply as residuals, averaged for all events produce a spatial pattern of early or delayed arrivals (Fig. 3). The distribution pattern of the mean relative residuals is similar before (Fig. 3a) and after (Fig. 3b) the crustal correction, though there are some variations in the magnitude of the mean relative residuals. Fig. 3c–f shows the distribution of average relative residuals at every station for the events in the NE, SE, SW and NW quadrants, respectively. Because teleseismic rays arrive at stations sub-vertically, the general trend of positive or negative mean relative residuals primarily reflects low-velocity (low-V) or high-velocity (high-V) anomalies in the crust and mantle beneath the study region (Zhao and Hasegawa, 1994). An obvious feature is that positive residuals are