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Identification of an ancient mantle reservoir and young recycled materials in the source region of a young mantle plume: Implications for potential linkages between plume and plate tectonics

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ABSTRACT

Whether or not mantle plumes and plate subduction are genetically linked is a fundamental geoscience question that impinges on our understanding of how the Earth works. Late Cenozoic basalts in Southeast Asia are globally unique in relation to this question because they occur above a seismically detected thermal plume adjacent to deep subducted slabs. In this study, we present new Pb, Sr, Nd, and Os isotope data for the Hainan flood basalts. Together with a compilation of published results, our work shows that less contaminated basaltic samples from the synchronous basaltic eruptions in Hainan–Leizhou peninsula, the Indochina peninsula and the South China Sea seamounts share the same isotopic and geochemical characteristics. They have FOZO-like Sr, Nd, and Pb isotopic compositions (the dominant lower mantle component). These basalts have primitive Pb isotopic compositions that lie on, or very close to, 4.5- to 4.4-Ga geochrons on $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram, suggesting a mantle source developed early in Earth's history (4.5–4.4 Ga). Furthermore, our detailed geochemical and Sr, Nd, Pb and Os isotopic analyses suggest the presence of 0.5–0.2 Ga recycled components in the late Cenozoic Hainan plume basalts. This implies a mantle circulation rate of >1 cm/yr, which is similar to that of previous estimates for the Hawaiian mantle plume. The identification of the ancient mantle reservoir and young recycled materials in the source region of these synchronous basalts is consistent with the seismically detected lower mantle-rooted Hainan plume that is adjacent to deep subducted slab-like seismic structures just above the core–mantle boundary. We speculate that the continued deep subduction and the presence of a dense segregated basaltic layer may have triggered the plume to rise from the thermal–chemical pile. This work therefore suggests a dynamic linkage between deep subduction and mantle plume generation.

1. Introduction: Plume versus plate tectonics

Subduction of oceanic slabs to as deep as the core–mantle boundary (CMB) as a part of plate tectonic processes, and the rise of hot mantle plumes from the lower mantle, are two of the first-order phenomena that operated through much of Earth's history (e.g., Hofmann and White, 1982; Li and Zhong, 2009; Zindler and Hart, 1986). However, it is still unclear how the two systems interact with each other and whether they are parts of a single geodynamic system. Answers to these questions impinge on our understanding of how the Earth works (e.g., Li and Zhong, 2009). At least some plumes are believed to have originated from the CMB, resulting in a bottom-up flux of energy and mass to the Earth's surface (e.g., Campbell and Griffiths, 1990; Griffiths and Campbell, 1990; Courtillot et al., 2003). On the other hand, high resolution seismic tomographic images (e.g., Fukao et al., 2001, 2009; van der Hilst et al., 1997) show that deep subducted slabs can penetrate the mantle transition zone, likely to fall into the lower mantle and ultimately accumulate above the CMB. It is believed that the Earth's materials are circulated between its surface and the lower mantle through these two processes.

Hofmann and White (1982) were the first to link the formation of mantle plumes to deep subduction in a conceptual model, suggesting that plumes are the results of rising long-term isolated oceanic crust at the CMB and thus a general consequence of plate tectonics. Niu and O'Hara (2003) proposed instead that plumes were produced by subducted oceanic lithospheric mantle (the harzburgite layer) at the CMB that was separated from the basaltic layer. However, because the oceanic lithospheric mantle

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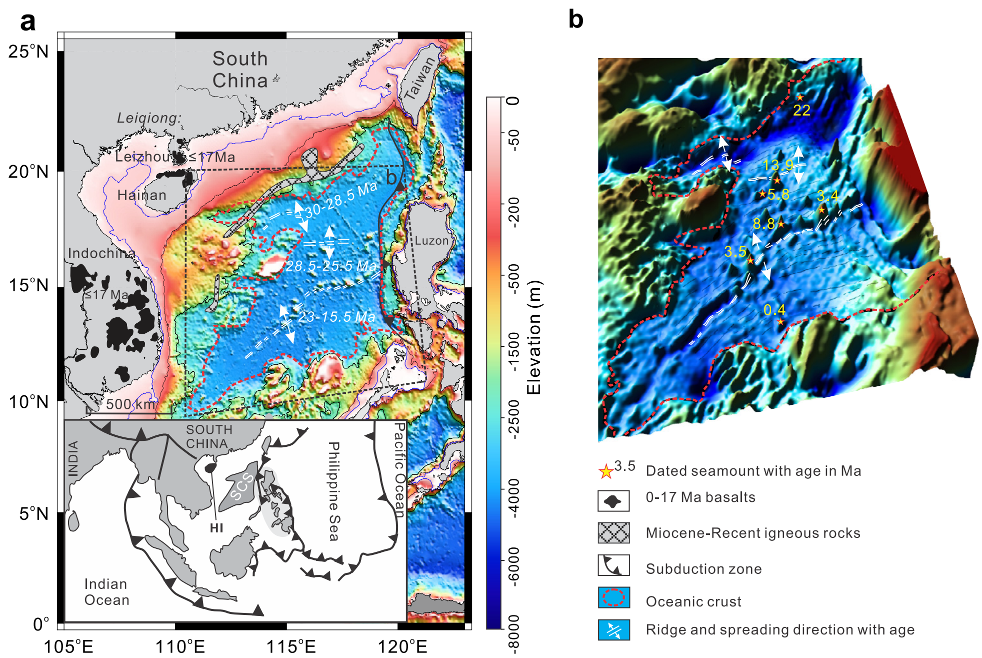

Fig. 1. Geological and bathymetric map of the South China Sea and adjacent regions showing late Cenozoic basaltic volcanism, ridge spreading directions and seamounts in the South China Sea (SCS). Italic numbers in white in (a) show the spreading ages in Ma (Braitenberg et al., 2006). Inset in (a) shows the major subduction zones in the region where HI stands for Hainan Island. (b) Three-dimensional geomorphologic features of seamounts in the South China Sea modified after Braitenberg et al. (2006). Yellow stars are sites where seamount basalts have been dated (Yan et al., 2006). The bathymetric map in (a) is from website: http://cmtt.tori.org.tw/data/Appmap/maplist.htm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

is extremely depleted in incompatible elements, this latter model cannot explain the typical characteristics of plume-induced rocks that are enriched in incompatible elements (e.g., Hofmann, 1997; White, 2010).

Whether or not deep-subducted oceanic crust can lead to the formation of mantle plumes also depends on the balance between their thermal buoyancy and compositional buoyancy (e.g., Ogawa, 2010). Thermal buoyancy due to energy released by heat-producing elements (U, Th, and K_2O) and heat conducted from the Earth's core may ultimately overcome the negative compositional density (Ogawa, 2010; Tackley, 2011). Heat-producing element concentrations of subducted oceanic crust (Th = 0.48 ppm, U = 0.20 ppm, and K_2O = 0.33 wt.%; Stracke et al., 2003) are an order of magnitude higher than those of any peridotitic mantle reservoir including the depleted upper mantle (Workman and Hart, 2005), the chondritic bulk silicate Earth (McDonough and Sun, 1995), and the nonchondritic bulk silicate Earth (Carlson and Boyet, 2008; O'Neill and Palme, 2008). Recent numerical modeling results showed that both harzburgite and basaltic layers of subducted slabs stored at the CMB could form plume-like thermal upwelling (plumes?) or could be entrained by classic plumes (e.g., Ogawa, 2010; Tackley, 2011).

To date, geochemical, petrological, and experimental studies have recognized recycled oceanic lithospheric mantle (e.g., Lassiter and Hauri, 1998), basaltic crust (e.g., Hauri, 1996; Jackson et al., 2012; Kogiso and Hirschmann, 2006; Mallik and Dasgupta, 2012; Sobolev et al., 2000, 2005, 2007, 2011b; Takahahshi et al., 1998), gabbro (e.g., Stroncik and Devey, 2011; Yaxley and Sobolev, 2007), and sediments (e.g., Rapp et al., 2008) in mantle plumes. It is generally accepted that subducted oceanic crust and its subsequent reaction products are the dominant forms of heterogeneity in a mantle plume (e.g., Hauri, 1996; Hofmann, 1988, 1997; Kogiso and Hirschmann, 2006; Mallik and Dasgupta, 2012; Sobolev et al., 2000, 2005, 2007, 2011b; Takahahshi et al., 1998).

Global supercontinent reconstructions and the large igneous province (LIP) record show that both the timing and location of plume events appear to have been dominantly controlled by the first order geometry of global subduction zones (e.g., Li and Zhong, 2009). It has been speculated that the sinking of subducted slabs to the lower mantle could not only push the dense chemical layer upward, but also enhance or trigger thermal instability in the lower mantle and the formation of thermal–chemical domes (and thus plumes or superplume; e.g., Li and Zhong, 2009; Steinberger and Torsvik, 2012; Zhong et al., 2007). Thermo-chemical convection modeling shows that the formation of the current large and isolated Pacific and African mantle superswells (or superplumes, a term we prefer to use in this paper) may be a natural consequence of such plate tectonic processes (e.g., Zhang et al., 2010; Steinberger and Torsvik, 2012). However, there are yet no clear case studies that have demonstrated the actual working of such a model with direct linkages between subduction and mantle plume formation.

The late Cenozoic basalt province in Southeast Asia (Fig. 1) is the first example that may imply direct links between a young mantle plume and deep subduction. A hypothesized young and lower mantle-rooted plume near Hainan Island is supported by the existence of extensive synchronous OIB-type basalts (e.g., Flower et al., 1992; Hoang and Flower, 1998; Tu et al., 1991; Wang et al., 2012; Zou and Fan, 2010), a lower mantle-rooted plume-like low-velocity seismic structure (e.g., Huang and Zhao, 2006; Montelli et al., 2006; Zhao, 2007), a thin mantle transition zone in the region (Wang and Huang, 2012), high mantle potential temperature (Hoang and Flower, 1998; Wang et al., 2012; Wang and Huang, 2012), and geochemical signatures for the basalts suggesting a lower mantle plume origin (Zou and Fan, 2010).

On the other hand, unlike classic plumes since the Mesozoic that occur dominantly above the two mantle superplumes (e.g., Anderson, 1982; Burke and Torsvik, 2004), the Hainan plume is located within the Eurasian mantle downwelling zone and almost encircled by major subduction zones (Fig. 1). Furthermore, geophysical investigations not only identified a plume-like seismic structure (e.g., Huang and Zhao, 2006; Montelli et al., 2006; Zhao, 2007), but also detected deep-subducted slabs down to the