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Geochemical nature of sub-ridge mantle and opening dynamics of the South China Sea

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ABSTRACT

The Indian-type mantle (i.e., above the north hemisphere reference line on the plot of $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$) has been considered as a "Southern Hemisphere" geochemical signature, whose origin remains enigmatic. The South China Sea is an extensional basin formed after rifting of the Euro-Asia continent in the Northern Hemisphere, however, the geochemical nature of the igneous crust remains unexplored. For the first time, IODP Expedition 349 has recovered seafloor basalts covered by the thick sediments in the Southwest sub-basin (Sites U1433 and U1434) and the East sub-basin (Site U1431). The Southwest sub-basin consists of enriched (E)-MORB type basalts, and the East sub-basin consists of both normal (N)-MORB-type and E-MORB-type basalts based on trace element compositions. The basalts of the two sub-basins are Indian-type MORBs based on Sr–Nd–Pb–Hf isotope compositions, and the Southwest sub-basin basalts show isotopic compositions (i.e., $^{206}Pb/^{204}Pb$ of 17.59–17.89) distinctly different from the East sub-basin (i.e., $^{206}Pb/^{204}Pb$ of 18.38–18.57), suggesting a sub-basin scale mantle compositional heterogeneity and different histories of mantle compositional evolution. Two different enriched mantle end-members (EM1 and EM2) are responsible for the genesis of the Indian-type mantle in the South China Sea. We have modeled the influences of Hainan mantle plume and lower continental crust based on Sr–Nd–Pb–Hf isotope compositions. The results indicate that the influence of Hainan plume can explain the elevated $^{206}Pb/^{204}Pb$ of the East sub-basin basalts, and the recycling of lower continental crust can explain the low $^{206}Pb/^{204}Pb$ of the Southwest sub-basin basalts. Based on the strong geochemical imprints of Hainan plume in the ridge magmatism, we propose that the Hainan plume might have promoted the opening of the South China Sea, during which the Hainan plume contributed enriched component to the sub-ridge mantle and caused thermal erosion and return of lower continental crust to the convective mantle. These results imply an *in situ* origin of the Indian-type mantle that can help understand the genesis of the "Southern Hemisphere" geochemical anomaly in the Northern Hemispheric extensional basin.

1. Introduction

The upper mantle of the Southern Hemisphere (i.e., the Indian and the South Atlantic Oceans) generally has Sr–Nd–Pb isotopic compositions distinctive from the Northern Hemisphere (i.e., the Pacific and the North Atlantic Oceans), which is termed as Indian-type upper mantle or upper mantle with Dupal anomaly (i.e., above the north hemisphere reference line (NHRL) on the plot of $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$) (Dupré and Allègre, 1983; Hart, 1984, 1988; Agranier et al., 2005). The genesis of Indian-type mantle is fundamental for understanding the origin of large-scale mantle geochemical heterogeneity and how the Earth's upper mantle evolved differently in the Southern and Northern Hemispheres. However, the origin of the Indian-type mantle has long been highly speculative and debated. The Indian-type mantle has

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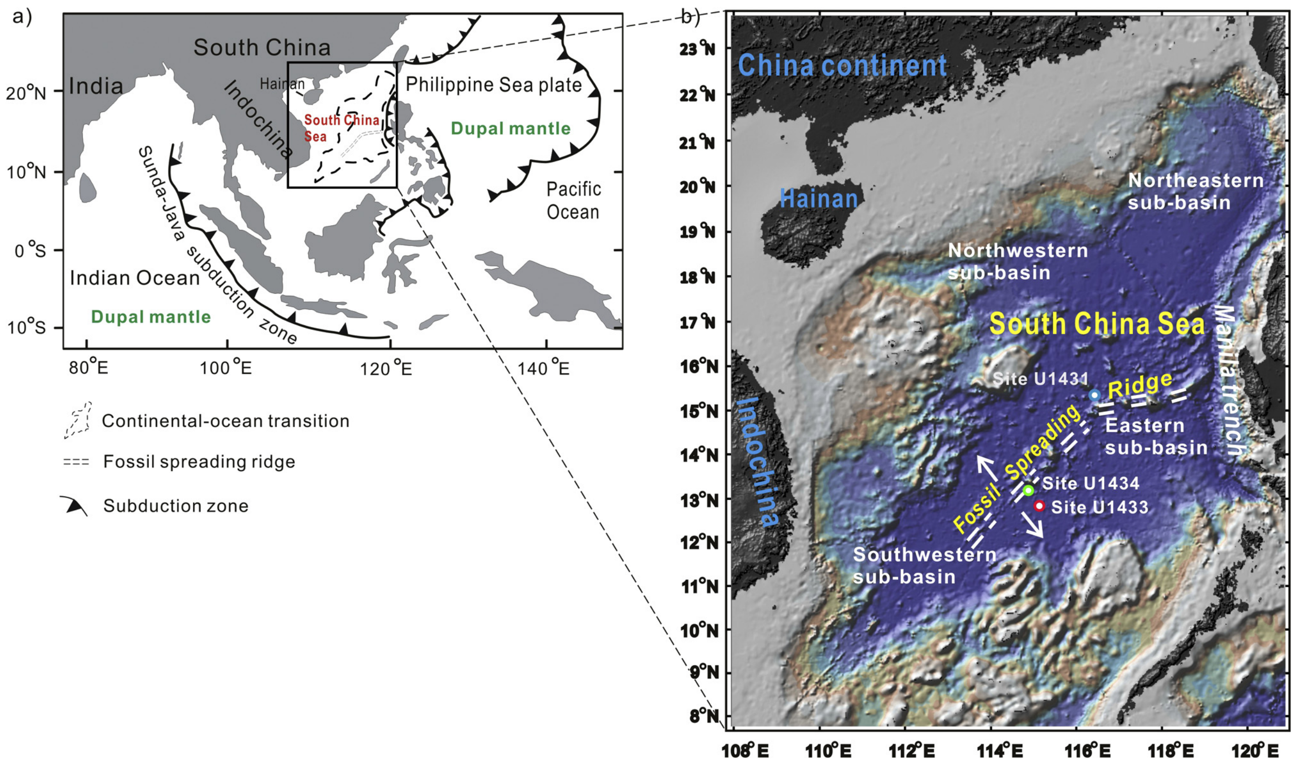

Fig. 1. Geologic setting of the South China Sea and sampling. (a) Tectonic setting of the western Pacific basins; (b) Map of the South China Sea and IODP Sites U1431, U1433 and U1434.

been attributed to, i.e., recycling of detached continental material in the shallow mantle (Escrig et al., 2004), recycling of oceanic crust plus sediment through plate subduction (Rehkiimper and Hofmann, 1997) and contamination of deep-rooted mantle plumes (Castillo, 1988; Storey et al., 1989; Wen, 2006). With increasing geochemical data availability, the igneous oceanic crust of some of the Northern Hemispheric western Pacific basins also has been shown to have Indian-type mantle sources (Hickey-Vargas, 1998; Flower et al., 2001). The origin of the Indian-type upper mantle in the Northern Hemispheric basins is crucial for understanding how the "Southern Hemispheric" geochemical anomaly was formed.

The South China Sea is located at the junction of the Euro-Asia continent, the Indian Ocean and the western Pacific Ocean (Fig. 1), which is a Northern Hemispheric extensional basin formed by rifting of the Euro-Asia continent between 33–15.5 Ma (Taylor and Hayes, 1983; Briais et al., 1993; Li et al., 2014). The nature of upper mantle of the South China Sea is poorly constrained due to the lack of samples of igneous oceanic crust. The seafloor basalts formed during the spreading of the South China Sea provide opportunity to investigate the nature of the upper mantle after rifting of the Euro-Asia continent. Also, the South China Sea basin basalts are important for understanding whether the continent break-up has caused recycling of continental materials in the convective mantle. Moreover, the extensive intraplate volcanism with mantle sources showing Dupal anomaly occurred surrounding the South China Sea since the early Cenozoic (Hoang et al., 1996; Chung et al., 1997; Zou and Fan, 2010; Hoang et al., 2013; Li et al., 2013; Wang et al., 2013). One possible origin of the volcanism is attributed to the Hainan mantle plume (Yan and Shi, 2007; Zou and Fan, 2010; Li et al., 2013; Wang et al., 2013). The extensive intraplate volcanism occurred before 33 Ma surrounding the South China Sea suggests that the Hainan plume could have initiated before the opening of the South China Sea (Yan et al., 2006). Thus, the Hainan mantle plume has potentially contaminated the mantle source of the South China Sea through plume-ridge interactions (Schilling et al., 1985; Xu et al., 2012).

For the first time, the International Ocean Discovery Program (IODP) Expedition 349 has recovered seafloor basalts formed by ridge spreading in the Southwest sub-basin (Sites U1433 and U1434) and the East sub-basin (Site U1431) (Fig. 1). In this study, we have analyzed major and trace elements and Sr–Nd–Pb–Hf isotopes of the basalt samples at IODP Sites U1431, U1433 and U1434. The geochemistry of these basalt cores is crucial for testing: (1) the nature of upper mantle source of the South China Sea and if the Indian-type mantle exists in the South China Sea; (2) the existence of Hainan plume and its influence on the opening dynamics of the South China Sea; and (3) whether *in situ* geologic processes can produce the Indian-type mantle in the Northern Hemispheric western Pacific basins.

2. Geologic setting and sampling

The South China Sea is one of the largest continental marginal basins in the western Pacific, and was formed by rifting of the southeast Euro-Asia continent during 33–15.5 Ma (Taylor and Hayes, 1983; Briais et al., 1993; Li et al., 2014). The deep-water basin of the South China Sea can be divided into four sub-basins, including the East sub-basin, the Southwest sub-basin, the Northwest sub-basin and the northeast sub-basin (Fig. 1). On the basis of seafloor magnetic records, the East sub-basin (the largest sub-basin) was formed by north-south spreading between 33–15.5 Ma and the Southwest sub-basin was formed by northwest–southeast spreading between 24–16 Ma (Li et al., 2014). The East sub-basin has a smaller average water depth than the Southwest basin (Ru and Pigott, 1986; Sibuet et al., 2016). A number of seamounts were formed in the South China Sea, including a seamount chain formed along the ridge shortly after spreading cessation (Fig. 1). Extensive intraplate volcanism also occurred on the continent margins surrounding the South China Sea (Hoang et al., 1996; Chung et al., 1997; Zou and Fan, 2010; Hoang et al., 2013; Li et al., 2013; Wang et al., 2013), of which the volcanism of Hainan Island has