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U–Th isotopes in Hainan basalts: Implications for sub-asthenospheric origin of EM2 mantle endmember and the dynamics of melting beneath Hainan Island

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ABSTRACT

Extensive (about 5000 km^3) basaltic magmas erupted on the Hainan Island, south China, mostly during the past 1 million years. U–Th disequilibrium data as well as Nd, Sr, Pb isotopes and major and trace element concentrations were measured on the youngest lavas from Maanling volcano and Leihuling volcano of the Hainan Island. All the Holocene Hainan basalts display light rare earth element (LREE) enriched patterns and ocean island basalt (OIB)-type incompatible element distributions. Their ε_{Nd} values range from +4.1 to +4.8, $^{87}Sr/^{86}Sr$ ratios vary from 0.7039 to 0.7042, and $^{206}Pb/^{204}Pb$ ratios range from 18.63 to 18.71. The Hainan lavas are characterized by their depleted Sr–Nd isotopic compositions and Dupal-like EM2 (enriched mantle 2) Pb isotope signatures with time-integrated high Th/U and $^{235}U/Pb$.

The olivine tholeiites from Maanling display 18–20% ^{230}Th excesses and the alkali olivine basalts from Leihuling show 22–32% ^{230}Th excesses. The pronounced ^{230}Th excesses in the Holocene basalts indicate that the Holocene Hainan lavas were produced by melting of a mantle source in the garnet stability field (>75 km). Since the lithosphere thickness beneath the Hainan Island is thin (55 km), the garnet peridotite mantle source for the Hainan basalts is not located in the lithospheric mantle. The Nd isotopic compositions do not indicate a highly depleted asthenospheric mantle source. We thus suggest that the EM2 mantle source for the young Hainan basalts is in the mantle transition zone or more likely lower mantle, which is consistent with a plume origin. The significant ^{230}Th excesses also suggest slow (<1 cm/year) upwelling, possibly indicative of a weakly buoyant mantle plume. The older EM2 Cenozoic basalts from Hainan, South China Sea Basin and adjacent areas may also originate from partial melting of lower mantle materials in the rising Hainan plume.

1. Introduction

The volcanic eruptions in the northern Hainan Island (20°N, 110°E), south China, produced about 5000 km^3 basaltic magmas (Fig. 1). Although the eruptions may have initiated more than 1 million years ago, most of the basalts were produced over a time interval of 200,000 to 500,000 years (Flower et al., 1992). The average magma supply of 0.1 to 0.25 km^3/year approaches that of a major flood basalt episode (Flower et al., 1992). The Hainan eruptions are part of a regional magmatic episode surrounding the South China Sea Basin and nearby regions, such as Vietnam (Hoang and Flower, 1998), Thailand (Zhou and Mukasa, 1997) and SE China (Zou et al., 2000). These volcanic rocks surrounding the South China Sea Basin, and those from seamounts within the South China Sea Basin, are younger than the South China Sea sea-floor extension, i.e., postdating the opening of the South China Sea Basin (at 30 to 16 million years ago).

The Hainan lavas, located at the northern edge of the South China Sea Basin, may present a microcosm of the volcanic activity surrounding the South China Sea Basin (Flower et al., 1992). It has been recognized (Tu et al., 1991; Flower et al., 1992) that (1) chemically the Hainan basalts resemble the oceanic island basalts (OIB) with enriched OIB-type incompatible element distributions, and (2) isotopically the Hainan basalts are characterized by the intriguing Dupal-like Pb isotopic signatures and depleted Sr–Nd isotopic compositions. There are still debates about the origins of the Hainan volcanoes, with implications for the origins of the 'Southern Hemisphere' Dupal anomaly in the Northern Hemisphere Hainan basalts (Tu et al., 1991; Tu et al., 1992; Liu, 1999; Zhao, 2007). On a global scale, it is not clear whether such Dupal mantle reservoirs are mainly derived from shallow subcontinental lithospheric mantle (Hawkesworth et al., 1990; Tu et al., 1991) or from deep mantle (e.g., lower mantle) (Hart, 1984; Castillo, 1988; Hart et al., 1992).

To provide new insights into the origins of the Hainan basalts, additional geological tools (in addition to Nd, Sr and Pb isotopes and seismic images) are needed. Young basalts erupted ~9000 years (9 ka) ago at Maanling volcano and Leihuling volcano (Fan et al., 2004) in

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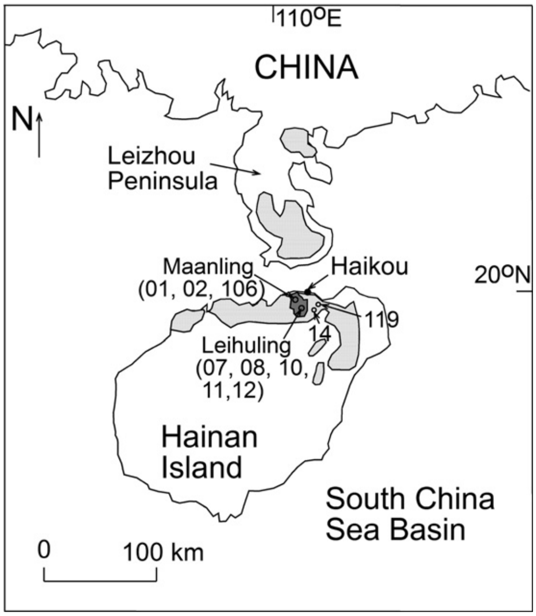

Fig. 1. Distribution of late Cenozoic basalts in the northern Hainan Island and Leizhou Peninsula, and sample locations. Shaded areas are late Cenozoic basalts. The dark shaded area represents locations of Holocene lavas.

Hainan Island. These young basalts provide ideal opportunities to apply short-lived U–Th disequilibrium to investigate the origins of the Hainan basalts. U–Th disequilibrium has been demonstrated as an effective tool for investigating the origins of young basalts (Asmerom and Edwards, 1995; Reid, 1995; Asmerom, 1999). Although EM2-like Cenozoic basalts are widespread in the South China Sea Basin and nearby regions, such as Vietnam (Hoang and Flower, 1998) and Thailand (Zhou and Mukasa, 1997) and SE China (Zou et al., 2000), few basalts are young enough for the short-lived U–Th disequilibrium studies.

Here we carry out a systematic U–Th disequilibrium, Nd, Sr and Pb isotope as well as major and trace element study of young lavas from Hainan Island. Our aims are (1) investigate the origins of the Hainan Holocene lavas and the possible link with plume volcanism and (2) constrain the melting conditions below Hainan Island. Obviously this U–Th disequilibrium study builds on pioneering Nd–Sr–Pb isotope studies of the Hainan basalts (Tu et al., 1991; Flower et al., 1992) and recent seismic tomographic imaging (Lebedev and Nolet, 2003; Huang and Zhao, 2006; Lei and Zhao, 2009).

2. Analytical methods

Thorium isotopic compositions of most samples were measured using a VG 54 mass spectrometer equipped with a WARP energy filter (VG54-WARP) and an ion counting system, except for 3 samples (HN106, HN119 and HN11) that were measured by a Cameca IMS 1270 ion microprobe at UCLA. The mass resolution for the ion probe IMS 1270 work is at 5000. The revised chemical method (Zou et al., 2008) to separate and purify thorium involves two columns (1) a 400 µl TRU Spec column to separate Th from other major and trace elements, and (2) a 100 µl anion resin column to purify Th. Major and trace elements were measured by ICP-MS at the GeoAnalytical Center at the Washington State University and the Institute of Geology and Geophysics, Chinese Academy of Sciences. Sample powders were prepared with an agate mill. Nd, Sr and Pb isotopic compositions as well as U and Th concentrations were measured using VG 54 WARP at UCLA. Analytical details on Nd, Sr and Pb isotopes and U and Th concentrations at UCLA using TIMS have been documented in Zou et al. (2003). Nd and Sr isotopic compositions were normalized to $^{146}Nd/^{144}Nd = 0.7219$ and $^{86}Sr/^{88}Sr = 0.1194$, respectively. The measured Nd and Sr isotope standard values are $^{143}Nd/^{144}Nd = 0.511843 \pm 13$ ($n = 24$) for La Jolla and $^{87}Sr/^{86}Sr = 0.710239 \pm 16$ ($n = 13$) for NBS 987. Replicate analyses of Pb isotope standard NBS 981 give $^{206}Pb/^{204}Pb = 16.896 \pm 0.013$, $^{207}Pb/^{204}Pb = 15.435 \pm 0.014$, and $^{208}Pb/^{204}Pb = 36.525 \pm 0.041$. Relative to the following values for NBS981: $^{206}Pb/^{204}Pb = 16.9356$, $^{207}Pb/^{204}Pb = 15.4891$, and $^{208}Pb/^{204}Pb = 36.7006$ (Todt et al., 1996), Pb isotopic data in samples were corrected for mass fractionation of 0.118% per atomic mass unit (AMU) for $^{206}Pb/^{204}Pb$, 0.117% per AMU for $^{207}Pb/^{204}Pb$, and 0.119% per AMU for $^{208}Pb/^{204}Pb$.

3. Results

We selected 10 samples for major, trace element and isotope analyses, including 3 Holocene samples from Maanling, 5 Holocene samples from Leihuling and 2 Pleistocene samples from Sanjiaoyuan (HN14) and Bopian (HN119) (Fig. 1). Major and trace element concentrations (in wt.%) are presented in Table 1. According to CIPW norms (Table 1), the Maanling samples are olivine tholeiites, and the Leihuling samples are mostly alkali olivine basalts with minor olivine tholeiites. As for the two older Pleistocene rocks, the Sanjiaoyuan sample (HN14) is olivine tholeiite and the Bopian sample (HN119) is quartz tholeiite.

The MgO content varies from 6.5% to 7.5% for Maanling tholeiites, and 9.6% to 12.8% for Leihuling alkali basalts, 9.1% for Sanjiaoyuan and 6.8% for Bopian. Their mg numbers (molar $Mg/(Mg + Fe^{2+})$) are 0.59 to 0.61 for Maanling, 0.65–0.66 for Leihuling, 0.67 for Sanjiaoyuan and 0.61 for Bopian. The Holocene basalts from Leihuling and Maanling have high TiO_2 contents, ranging from 2.3 to 2.8%. The Pleistocene lavas have lower TiO_2 (2.2–1.6%).

All basaltic rocks from Hainan Island are enriched in light rare earth elements (LREEs) over heavy rare earth elements (HREEs) (Fig. 2). None of the samples displays any negative Eu anomalies. In the spider diagram (Fig. 2), except for HN119, all samples show appreciable enrichment in high field strength elements (HFSEs), such as Nb and Ta.

The Sr, Nd and Pb isotope data show highly restricted range within each locality (Table 2). The ε_{Nd} values are $+4.5$ to $+4.8$ for Maanling, and $+4.1$ to $+4.4$ for Leihuling. The $^{87}Sr/^{86}Sr$ values range from 0.70385 to 0.70392 for Maanling, and 0.70418 to 0.70427 for Leihuling. The $^{206}Pb/^{204}Pb$ ratios are 18.10 to 18.63 for Maanling, and 18.66 to 18.70 for Leihuling.

The Nd isotope compositions indicate that source rocks for the Maanling and Leihuling lavas are moderately depleted and are homogeneous. The Hainan basalts are less depleted as compared to the Central Indian Ridge MORBS or some basalts from central East China (Fig. 3). In the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagrams (Fig. 4), all samples plot above the Northern Hemisphere Reference Line (NHRL) (Hart, 1984) and thus display Dupal Pb anomalies (Tu et al., 1991; Flower et al., 1992). The Nd–Sr–Pb isotope data suggest that they are EM2 like basalts (Figs. 3 and 4).

The U–Th isotope results are presented on a ($^{230}Th/^{232}Th$) vs. ($^{238}U/^{232}Th$) equiline diagram in Fig. 5. All Holocene samples (Maanling and Leihuling) display significant ^{230}Th excesses (Fig. 5). The ($^{230}Th/^{238}U$) values are 1.18 to 1.20 for Maanling, and 1.23 to 1.32 for Leihuling. One Pleistocene basaltic sample (HN14) has ($^{230}Th/^{238}U$) value of 1.10 and another Pleistocene quartz tholeiite displays U–Th equilibrium.

4. Discussion

The Hainan samples appear to be relatively primitive basalts without significant crustal contamination or fractional crystallization. All the samples have high mg numbers (0.59 to 0.67) (Table 1). Their high mg numbers suggest that the samples closely reflect source compositions and mantle processes, and are not significantly affected