Contents lists available at ScienceDirect

Lithos



journal homepage: www.elsevier.com/locate/lithos

The origin of Cenozoic basalts from central Inner Mongolia, East China: The consequence of recent mantle metasomatism genetically associated with seismically observed paleo-Pacific slab in the mantle transition zone



Pengyuan Guo^{a,b,*}, Yaoling Niu^{c,d,*}, Pu Sun^c, Lei Ye^b, Jinju Liu^b, Yu Zhang^b, Yue-xing Feng^e, Jian-xin Zhao^e

^a Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences, Sanya 572000, China

^b School of Earth Sciences, Lanzhou University, Lanzhou 730000, China

^c Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China

^d Department of Earth Sciences, Durham University, Durham DH1 3LE, UK

^e Radiogenic Isotope Facility, School of Earth Sciences, The University of Queensland, Brisbane, QLD 4072, Australia

ARTICLE INFO

Article history: Received 27 March 2015 Accepted 4 November 2015 Available online 18 November 2015

Keywords: Intra-plate basalts Metasomatism Hydrous low-F melt Recycled ocean crust Subducted paleo-Pacific plate

ABSTRACT

We present new major element, trace element and Sr-Nd-Hf isotope data on Cenozoic basalts from central Inner Mongolia (CIM) in eastern China to study the origin of the incompatible-element enriched component in these basalts by testing whether or not the paleo-Pacific plate lying in the mantle transition zone beneath eastern China is the immediate cause. The Cenozoic CIM basalts have a large variation in major element, trace element and isotope compositions. Fractional crystallization of olivine and clinopyroxene can readily explain much of the major element compositional variation, while trace element and isotope ratio variation largely reflect source heterogeneities and source histories. The variably low 87 Sr/ 86 Sr, high ϵ_{Nd} , high ϵ_{Hf} and elevated ratios of high field strength element over large ion lithophile element (HFSE/LILE, e.g., Nb/U, Nb/La) indicate that the CIM basalts are of asthenospheric origin, which is characterized by mixing between DMM and EM1. However, the CIM basalts are enriched in incompatible elements and enriched in the progressively more incompatible elements (e.g., variably high $[La/Sm]_N = 1.66-3.38$), suggesting that the magma source(s) must have been enriched prior to the major episode of the magmatism. Participation of subducted ocean crust in the mantle source region of these basalts is recognized, but cannot be the major source material because the subducted ocean crust is expectedly too depleted in incompatible elements (e.g., $[La/Sm]_N \ll 1$) to produce magmas highly enriched in incompatible elements with $[La/Sm]_N \gg 1$. With the new data, we consider that low mass fraction (low-F) melt metasomatism in the seismic low velocity zone (LVZ) beneath eastern China as the most likely process to generate incompatible-element enriched source(s) for mantle melts parental to the Cenozoic CIM basalts. The low-F metasomatic agent most likely resulted from dehydration melting of the transition-zone paleo-Pacific slab, which has been taking place in the Cenozoic. This recent/current metasomatic process also explains the strong decoupling of the abundances and ratios of incompatible elements (e.g., Rb/Sr, Sm/Nd, Lu/Hf, La/Sm, Sm/Yb) from Sr-Nd-Hf isotopes because of the inadequate time for radiogenic ingrowth. In this case, we emphasize that the Cenozoic volcanism in eastern China (including the CIM basalts) is a special consequence of plate tectonics. Because of the known presence of subducted oceanic lithosphere beneath eastern China and because of the close resemblance of the intra-plate CIM alkaline basalts with the present-day ocean island basalts (OIBs) in terms of incompatible element systematics, we emphasize the potential role of subducted ocean crust in mantle source regions of oceanic basalts, including E-MORBs (enriched type mid-ocean ridge basalts) and OIBs, but low-F melt metasomatism in the source regions is required as the principal enrichment mechanism because otherwise it is unlikely to produce incompatible-element enriched signature in E-MORB and OIB.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Since the first proposal of "mantle plumes from ancient oceanic crust" (Hofmann and White, 1982), it has been widely accepted that recycled oceanic crust (ROC) as the source of ocean island basalts (OIBs) and some enriched-type mid-ocean ridge basalts (E-MORBs) (e.g., Hauri et al., 1996; Lassiter and Hauri, 1998; Niu and Batiza, 1997; Rehkämper and Hofmann, 1997; Sobolev et al., 2007; White, 2010) despite obvious



^{*} Corresponding authors at: Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences, Lizhigou Road, Sanya, Hainan 572000, China. Tel.: +86 13919368426.

E-mail addresses: guopy12@lzu.edu.cn (P. Guo), yaoling.niu@foxmail.com (Y. Niu).

difficulties (Niu and O'Hara, 2003; Niu et al., 2002, 2012) and lacking recycled component in OIB (Anderson et al., 2015). This ROC model for OIB has been popularized in recent years by equating possible pyroxenite veins or veinlets in mantle peridotite as subducted ocean crust (e.g., Hirschmann et al., 2003; Kogiso et al., 2003; Sobolev et al., 2000, 2005, 2007; Yang and Zhou, 2013). However, it is noteworthy that the above proposal is based on the speculation that the ocean crust can subduct to the core-mantle boundary and then return to the upper mantle source regions of OIB and E-MORB (Hofmann and White, 1982). It is actually unknown whether ROC can indeed be present in the upper mantle OIB and E-MORB source regions. In this case, the widespread Cenozoic intra-plate basalts in eastern China (Fig. 1a) together with the presence of paleo-Pacific plate in the mantle transition zone beneath the region (Fig. 1b; Kárason and van Der Hilst, 2000; Huang and Zhao, 2006) offer an unprecedented test ground for evaluating the potential significance of the ROC in contributing to incompatible-element enriched signatures of intra-plate basalts on land and beneath ocean basins.

Multiple lines of evidence suggest that subduction of the paleo-Pacific plate strongly influenced geological processes in eastern China since the Mesozoic (Guo et al., 2014a; Niu, 2005, 2014; Wang et al., 2015; Wu et al., 2005; Zhou and Li, 2000; Zhu et al., 2012). For example, the lithosphere thinning accompanied by the widespread volcanism during the Mesozoic is interpreted to be genetically related to such a subducted slab (Guo et al., 2014a; Niu, 2005, 2014; Xu, 2014; Xu et al., 2012; Zhu et al., 2012). However, the contribution of and the roles played by the subducted paleo-Pacific plate in the extensive Cenozoic intra-plate volcanism in eastern China remain poorly evaluated. Xu and co-workers advocate the subducted paleo-Pacific ocean crust as the ultimate source of these basalts (Xu, 2014; Xu et al., 2012). Our work also emphasized the importance of subducted seafloor components in the petrogenesis of the Cenozoic basalts in the region (Guo et al., 2014a; Zhang et al., 2007). However, the problems with the ROC model remain because the subducted ocean crust is known to be depleted in incompatible elements (Niu and O'Hara, 2003; Niu et al., 2002, 2012), and to melt or partially melt such depleted ocean crust alone is far inadequate and practically not possible to produce incompatible element highly enriched OIB in general and the Cenozoic basalts in eastern China in particular, let alone to produce high-magnesian melts (e.g., Green and Ringwood, 1968; Niu and O'Hara, 2003). Therefore, it is imperative to objectively evaluate if melting of the subducted paleo-Pacific ocean crust can yield incompatible element highly enriched Cenozoic basalts widespread in eastern China. If not, alternative sources and processes are required.

This paper is intended to address these very issues by presenting and discussing new bulk-rock major element, trace element and Sr–Nd–Hf isotope data on the Cenozoic basalts from central Inner Mongolia (CIM) of eastern China. Our data indicate the contribution of the subducted ocean crust to the petrogenesis of the CIM basalts, but it is in-adequate to produce the incompatible-element enriched basalts. The data strongly suggest that the recent/current low mass fraction (low-F) melt metasomatism is the effective mechanism required to refertilize the mantle sources for incompatible element highly enriched CIM basalts in particular and for the Cenozoic alkali basalts in eastern China in general. Due to the close resemblance of intra-plate CIM alkaline basalts with the present-day OIB and E-MORB in terms of incompatible element systematics, we stress that our results on the petrogenesis of the CIM basalts can offer insights into an improved understanding of the petrogenesis of OIB and E-MORB.

2. Geological background and sample description

2.1. Temporal and spatial distribution of Cenozoic basalts in central Inner Mongolia

The Cenozoic intra-plate volcanism in eastern China is widespread, from Hainan island in the south to Wudalianchi in the northeast (Fig. 1a), and is thought to be associated with extensional basins and their bounding faults. As an important part of the Cenozoic volcanism in eastern China, the central Inner Mongolia (CIM) volcanic province covers a large area of >20,000 km², including the Chifeng volcanic field, Jining volcanic field and Abaga volcanic field (Fig. 1c). Note that we also include the Cenozoic basalts in the Zhangbei area, Hebei province, into the Jining volcanic field because of their proximity in time and space. We, thus, consider these basalts sampled from Damaping (named as DMP-) in the Zhangbei area (Fig. 1c) as a whole series together with other Jining basalts in the following section. Different from the Cenozoic basalts along the coastal regions, the CIM Cenozoic basalts erupted far in the interior of the continental China, as far as west of the Great Gradient Line (GGL), which marks the sharp contrast in elevation, topography, crust thickness, lithosphere thickness, heat flow, Bouguer gravity anomaly and upper mantle seismic velocity structures etc. between the high plateaus to the west and hilly plains to the east (Niu, 2005, 2014). The CIM Cenozoic basalts comprise multiple flows (horizontal/subhorizontal layers) that build lava plateaus with the total sequence of tens to hundreds of meters thick. There are also mantle xenoliths (spinel lherzolite and pyroxenite) in alkaline basalts from the Jining volcanic field (Chen et al., 2004; Xu, 2002; H.F. Zhang et al., 2012; Zhao et al., 2013) and the Abaga volcanic field (Deng and Macdougall, 1992; M. Zhang et al., 2012; Zou et al., 2014). The CIM Cenozoic basaltic volcanism spanned a long time period, from the late Eocene to the Pleistocene (~36.4 to ~0.11 Ma) according to K-Ar (Han et al., 1999; Ho et al., 2008, 2011; Luo and Chen, 1990; Shi et al., 2002; Zhang and Han, 2006; Zheng et al., 2002) and Ar-Ar age data (Wang et al., 2015; Zhao et al., 2013). Such a variably large spatial and temporal distribution of the Cenozoic CIM basalts offers a prime opportunity to evaluate the potential contribution of the subducted paleo-Pacific plate in the mantle transition zone to the Cenozoic volcanism in eastern China.

2.2. Samples and petrography

We present data of fifty basaltic samples in this study, including 16 samples from Chifeng volcanic field, 15 samples from Jining volcanic field and 19 samples from Abaga volcanic field (Fig. 1c). The detailed sample sites are given in Appendix 1. The CIM Cenozoic lavas are porphyric with phenocrysts (~5-15%) dominated by olivine with minor plagioclase and clinopyroxene. The olivine phenocrysts are subhedral to anhedral with embayed absorption shapes. They vary in size from ~0.5 mm to as large as ~5.0 mm with most being ~1.0 mm. The DMB samples from the Chifeng volcanic field have plagioclase phenocrysts. These plagioclase phenocrysts are fine- to coarse-grained (up to 2.0 mm), and euhedral to subhedral. A few large plagioclase phenocrysts display zoning. Some clinopyroxene phenocrysts appear as glomeroporphyritic aggregates, and some show disequilibrium sieve textures or corroded shapes with complex zoning and kink bands. The groundmass is mostly composed of microlites of plagioclase, olivine, clinopyxene and Fe-Ti oxides. Our samples are mostly fresh except for some samples showing olivine iddingsitization.

3. Analytical methods

We chose freshest samples for geochemical analysis. Weathered surfaces, pen marks and saw marks were ground off and thoroughly cleaned. The samples were then crushed into chips of ~0.5 cm to select fresh matrix material so as to obtain basaltic melt compositions (phenocrysts avoided). The matrix material was then ultrasonically-cleaned with Milli-Q water and dried before powdered using an agate mill under a clean environment.

Whole rock major and trace elements were analyzed using Leeman Prodigy inductively coupled plasma-optical emission spectrometer (ICP



Fig. 1. (a) Sketch map of major tectonic divisions of eastern China and the distribution of the Cenozoic basalts. The isopleth of the crustal thickness is from Li et al. (2006). (b) Western Pacific-eastern China mantle seismic tomography across three sections at the latitude of 30°N, 39°N and 43°N, showing the paleo-Pacific slab lying horizontally in the mantle transition zone between the ~410 km and ~660 km seismic discontinuities (after Huang and Zhao, 2006); and (c) the distribution and sample locations of the CIM Cenozoic basalts. All the sample locations are indicated as abbreviations (for example, Damaping is abbreviated as DMP), and see Appendix 1 for all the abbreviations of corresponding locations.

OES) and Agilent-7500a inductively coupled plasma mass spectrometer (ICP MS), respectively, at China University of Geosciences, Beijing (CUGB). Thirty five milligram powder of each sample was dissolved with acid mix (1:1) of distilled HF and HNO₃ in a high-pressure jacket equipped Teflon beaker till complete digestion/dissolution. Precisions (1 σ) for most major element oxides are better than 1.0% with the exception of TiO₂ (<1.5%) and P₂O₅ (1.0–1.5%). Loss on ignition (LOI) was determined by placing 500 mg of samples in the muffle furnace at 1000 °C for 2 h before being cooled in a desiccator and reweighed. For trace elements, analytical precision is better than 5% for most elements, but is 5–15% for Gd and Ta. During trace element analysis, rock standards GSR-1, GSR-3 and AGV-2 were used to monitor the analytical accuracy and precision (see Appendix 1). Analytical details and reference rock standards are also given in Guo et al. (2014a).

Thirty-four samples were chosen for bulk-rock Sr-Nd-Hf isotope analysis (Appendix 2). Elemental separation/purification of twentyeight samples was done in the Institute of Geology and Geophysics (Beijing), Chinese Academy of Sciences (IGG-CAS; see Yang et al., 2010). Strontium isotope analysis was done using Thermal Ionization Mass Spectrometer (TIMS) in Tianjin Institute of Geology and Mineral Resources. The measured ⁸⁷Sr/⁸⁶Sr ratios were corrected for mass-fractionation using ${}^{86}\text{Sr}/{}^{88}\text{Sr} = 0.1194$. During our sample analysis, the measured values for NBS-987 Sr standard is 87 Sr/ 86 Sr = 0.710250 ± 5 (n = 4, 2SD). Neodymium isotope analysis was conducted using a Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC ICP-MS) at China University of Geosciences, Wuhan (CUGW). The measured ¹⁴³Nd/¹⁴⁴Nd ratios were corrected for mass fractionation to $^{146}\mathrm{Nd}/^{144}\mathrm{Nd}$ = 0.7219 and the analysis of standard JNdi-1 Nd gave $^{143}\text{Nd}/^{144}\text{Nd} = 0.512101 \pm 4$ (n = 7, 2SD). Hafnium isotopic analysis was done using MC ICP-MS in the IGG-CAS. The ¹⁷⁶Hf/¹⁷⁷Hf ratios were normalized to 179 Hf/ 177 Hf = 0.7325, and an Alfa Hf standard was measured 11 times and gave an average 176 Hf/ 177 Hf value of 0.282169 \pm 6 (n = 11, 2SD). The analytical details are given in Guo et al. (2014a).

The bulk-rock Sr-Nd-Hf isotopic compositions of six samples in this study (see Appendix 2) were analyzed in the Radiogenic Isotope Facility at The University of Queensland (RIF-UQ), Australia. The measurement of ⁸⁷Sr/⁸⁶Sr, ¹⁴³Nd/¹⁴⁴Nd and ¹⁷⁶Hf/¹⁷⁷Hf ratios was conducted in static mode on a Nu Plasma HR MC-ICP-MS using a modified CETAC ASX-110FR auto-sampler and a DSN-100 dissolvation nebulizing system. The measured ⁸⁷Sr/⁸⁶Sr, ¹⁴³Nd/¹⁴⁴Nd and ¹⁷⁶Hf/¹⁷⁷Hf ratios were also corrected for mass fractionation using the exponential law by normalizing to ${}^{86}\text{Sr}/{}^{88}\text{Sr} = 0.1194$, ${}^{146}\text{Nd}/{}^{144}\text{Nd} = 0.7219$ and ${}^{179}\text{Hf}/{}^{177}\text{Hf} = 0.7325$, respectively. Instrument drift was monitored and calibrated with standards. During our sample analysis, the measured average value for NBS-987 Sr standard is 87 Sr/ 86 Sr = 0.710248 ± 9 (n = 26, 2SD). An inhouse Nd standard, Ames Nd Metal, was used as an Nd isotope drift monitor. During our analysis, 39 measurements of Nd Metal yielded a mean $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.511967 \pm 8 (n = 39, 2SD), corresponding to an average international standard JNdi-1 143 Nd/ 144 Nd of 0.512113 \pm 9 (n = 20, 2SD). The in-house Hf standard monitor was measured between every 5 samples and 37 repeated measurements gave an average ¹⁷⁶Hf/¹⁷⁷Hf value of 0.282133 \pm 3 (n = 37, 2SD), which were used to calibrate the instrument drift to 0.282145 \pm 10, corresponding to a mean value of 0.282160 ± 10 (n = 16, 2SD) for JMS-475 standard.

The values of USGS reference materials BCR-2 and BHVO-2 run together with our samples, both in IGG-CAS and RIF-UQ, are given in Appendix 3. They are all consistent with the reference values (GeoREM, http://georem.mpch-mainz.gwdg.de/).

4. Analytical results

4.1. Major and trace element compositions

Major and trace element data on the CIM Cenozoic basalts are given in Appendix 1. The CIM Cenozoic basalts range from tholeiitic to alkaline (Fig. 2a) with large major and minor element compositional variation (Fig. 2b–h). They are variably evolved ($Mg^{\#} = 0.49-0.67$) from anticipated primary magmas (i.e., $Mg^{\#} \ge 0.72$) in equilibrium with mantle olivine. In the MgO variation diagram, all our three basalt series define significant negative correlations of SiO₂, Al₂O₃ with MgO (Fig. 2b, c) and positive correlations of Fe₂O^T₃, CaO/Al₂O₃, Cr and Ni with MgO (Fig. 2d, f, h, i). These correlations are to a first order consistent with the petrography that olivine and clinopyroxene are the dominant liquidus minerals.

Fig. 3 shows chondrite-normalized rare earth element (REE) patterns and primitive-mantle normalized multi-elements spidergram of the CIM Cenozoic basalts. For comparison, the average presentday ocean island basalts (OIBs), enriched type mid-ocean ridge basalts (E-MORB) (Sun and McDonough, 1989), the marine carbonate (MC), global subducted sediments (GLOSS) (Plank and Langmuir, 1998) and the bulk ocean crust (OC; Niu and O'Hara, 2003) are also plotted. Clearly, the CIM Cenozoic basalts display a considerable variation from highly light-rare-earth-element (LREE) enriched to mildly LREE-enriched compositions (Fig. 4a) with [La/ $Sm_N = 1.66-3.38$ (with an average of 2.76 for N = 50), suggesting the more enriched source regions than the primitive mantle. Despite the large variation of incompatible element abundances (Fig. 3b), the CIM Cenozoic basalts exhibit generally consistent patterns of being more enriched in the progressively more incompatible elements except for excess of Nb-Ta and Ba-Sr (Fig. 3b, d, f). The striking Nb-Ta enrichment in the CIM Cenozoic basalts is also illustrated in Fig. 4 following Niu and Batiza (1997), in which our new data of the CIM Cenozoic basalts show much more elevated $[Ta/U]_N$ and $[Nb/Th]_N$ values than primitive mantle (PM) and even oceanic basalts (i.e., OIBs and MORBs).

4.2. Whole rock Sr-Nd-Hf isotopes

Whole rock Sr-Nd-Hf isotope data on the CIM Cenozoic basalts are given in Appendix 2. Due to the short radiogenic time (<36.4 Ma) and thereby negligibly small radiogenic ingrowth, we did not correct the isotope ratios in CIM basalts to their eruption ages. The Abaga basalts show depleted and uniform Nd-Hf isotopic compositions with ε_{Nd} and ε_{Hf} values being 4.80–6.44, 8.67–10.87, respectively. But their ⁸⁷Sr/⁸⁶Sr ratios are relatively varied, from 0.703812 to 0.705292. In the Sr-Nd plot (Fig. 5a), three samples (GGW-01, GGW-07, GGW-18) display high ⁸⁷Sr/⁸⁶Sr (as high as 0.7053) at a given high ε_{Nd} value (>4.5) and plot outside the region defined by OIB (Stracke et al., 2003, 2005). Chifeng samples generally show depleted Sr-Nd-Hf isotopic characters with lower ε_{Nd} (1.38–4.75) and ε_{Hf} (4.63–8.45) relative to the Abaga samples (Fig. 5b), and their ⁸⁷Sr/⁸⁶Sr varying from 0.703837 to 0.704813, plotted in the OIB region (Stracke et al., 2003, 2005). The nine analyzed Jining volcanic rocks show a wide range in their ⁸⁷Sr/⁸⁶Sr (0.704079-0.705366), ¹⁴³Nd/¹⁴⁴Nd (0.512463-0.512996) and ¹⁷⁶Hf/¹⁷⁷Hf (0.282767–0.282978), displaying the obvious mixing trend between DMM and EM1 in 87 Sr/ 86 Sr- ε_{Nd} and ε_{Nd} - ε_{Hf} spaces (Fig. 5).

Importantly, there are no correlations between $[La/Sm]_N$ ([Sm/Yb]_N) and Sr–Nd–Hf isotopes (Fig. 6a–c). This is also the case for Rb/Sr, Sm/Nd and Lu/Hf with Sr–Nd–Hf isotopes (Fig. 6d–f). That is, the radiogenic isotopes (for example, ⁸⁷Sr, ¹⁴³Nd, ¹⁷⁶Hf) are unsupported by parent/daughter ratios (for example, Rb/Sr, Sm/Nd, Lu/Hf) of the basalt sources. Fig. 7 shows the correlation coefficients of Sr–Nd–Hf isotopic ratios with incompatible element abundances of the CIM basalts using our new data together with the previously published data (Deng and Macdougall, 1992; Guo et al., 2014a; Han et al., 1999; Ho et al., 2008, 2011; W.H. Zhang et al., 2012; Zhou, 2012). In contrast to the more significant



Fig. 2. (a) The K₂O + Na₂O vs. SiO₂ diagram (Le Bas et al., 1986) for the CIM Cenozoic basalts plotted on an anhydrous basis. The dash line indicates the boundary between alkaline and tholeiitic basalts (McDonald and Katsura, 1964). (b)–(h) MgO-variation diagrams showing major element oxides, Sc, Cr, Ni and CaO/Al₂O₃ for the CIM Cenozoic basalts. Arrows with decreasing MgO approximate first-order trends dominated by fractional crystallization.



Fig. 3. (a, c, e) Chondrite normalized rare earth element patterns and (b, d, f) primitive mantle normalized incompatible element patterns of the CIM Cenozoic basalts. Chondrite and primitive mantle values are from Sun and McDonough (1989). For comparison, average present-day ocean island basalts (OIBs), enriched type mid-ocean ridge basalts (E-MORBs) (Sun and McDonough, 1989), marine carbonate (MC), global subducted sediments (GLOSS) (Plank and Langmuir, 1998) and bulk ocean crust (OC; Niu and O'Hara, 2003) are also plotted.

correlations of Sr–Nd–Hf isotopes with the progressively more incompatible elements (towards left) illustrated by the East Pacific Rise (EPR) seamount lavas (Niu et al., 2002; Zhang et al., private communication), the CIM basalts do not show such correlations, which reinforces the significant decoupling of incompatible elements with Sr–Nd–Hf isotopes.



Fig. 4. Ta^{*}($[Ta/U]_N$) vs. Nb^{*}($[Nb/Th]_N$) diagram (after Niu and Batiza, 1997) suggests that subducted ocean crust may indeed contribute to the magma sources of the CIM basalts (as do for the East Pacific Rise seamount lavas). LCC and UCC are, respectively, average composition of the lower and upper crust of the NCC (Gao et al., 1998); PM denotes primitive mantle (Sun and McDonough, 1989).

5. Discussion

5.1. Effect of fractionation and crustal contamination on magma compositions

As shown in Figs. 2–5, the CIM Cenozoic basalts display large compositional variations. Apart from the magma source heterogeneity and the extent of melting, crystal fractionation and crustal contamination can be important factors contributing to the compositional variations. It is, therefore, necessary to evaluate the potential effect of the fractional crystallization and crustal contamination before discussing source characteristics of the CIM Cenozoic basalts.

The CIM samples show evolved character with Mg[#] ranging from 0.49 to 0.67. Their SiO₂, Al₂O₃ negatively correlate with MgO (Fig. 2b, c), while $Fe_2O_3^T$, CaO/Al₂O₃, Cr and Ni positively correlate with MgO (Fig. 2d, e, g, h). All these major element systematics are consistent with olivine and clinopyroxene being the dominant liquidus minerals during cooling and fractional crystallization as observed petrographically. Sc does not

correlate with MgO (Fig. 2f), implying clinopyroxene fractionation may be insignificant although crystallization of olivine and plagioclase can balance the Sc depletion effect by clinopyroxene. One sample from Abaga volcanic field (GGW-14) differs from the others by its significantly higher MgO, Ni and Cr contents (Fig. 2), which is explained as the presence of micro-olivine and clinopyroxene phenocrysts in the analyzed bulk-rock sample. Furthermore, Al₂O₃ increases with decreasing MgO (Fig. 2c), which together with the lack of marked Eu anomaly (Fig. 3a, c, e) suggests that plagioclase was not a major liquidus phase. Therefore, we suggest that the major element compositional variation in the CIM basalts is largely controlled by varying extent of fractional crystallization of olivine and clinopyroxene.

The East China continental crust is generally characterized by elevated abundances of SiO₂ (61.57 wt.% on average) and large ion lithophile elements (LILEs; e.g., Rb, Ba, Th, U), depletion of high field strength elements (HFSEs; e.g., Nb, Ta) (Gao et al., 1998), with high ⁸⁷Sr/⁸⁶Sr, low 143 Nd/ 144 Nd and low 176 Hf/ 177 Hf (Jiang et al., 2013). Therefore, the involvement of continental crust materials will inevitably lower the ¹⁴³Nd/¹⁴⁴Nd and ¹⁷⁶Hf/¹⁷⁷Hf values while raising SiO₂, ratios of large ion lithophile element over high field strength element (LILE/HFSE; e.g., Th/Nb; Th/Ta) and ⁸⁷Sr/⁸⁶Sr in the erupted continental basalts (Guo et al., 2014a). For Abaga basalts, ¹⁴³Nd/¹⁴⁴Nd, ¹⁷⁶Hf/¹⁷⁷Hf and especially LILE/HFSE values are essentially constant with increasing SiO₂ (Fig. 8), indicating negligible crustal contamination if any. The varied ⁸⁷Sr/⁸⁶Sr for Abaga samples is interpreted as reflecting mantle source or source histories (see below discussion). For Jining series, all the samples show insignificant crustal contamination with no positive correlation between ⁸⁷Sr/⁸⁶Sr, HFSE/LILE with SiO₂ (Fig. 8a, d, e, f). Despite two samples (QLT-01 and LC-02) display lower ¹⁴³Nd/¹⁴⁴Nd, $^{176}\mathrm{Hf}/^{177}\mathrm{Hf}$ with higher SiO_2 (being consistent with crustal contamination), the striking Nb-Ta positive anomalies (Fig. 3) and the high $[Ta/U]_N$ and $[Nb/Th]_N$ values (Fig. 4) for these two samples are the strong evidence that they experienced negligible crustal materials assimilation. Furthermore, the presence of mantle xenoliths in Abaga volcanic field (M. Zhang et al., 2012; Zou et al., 2014) and Jining volcanic field (Xu, 2002; H.F. Zhang et al., 2012; Zhao et al., 2013) is also consistent with the interpretation of rapid ascent of magmas and thereby having limited crustal residence time for significant assimilation/contamination. As for the Chifeng samples, ⁸⁷Sr/⁸⁶Sr, ¹⁴³Nd/¹⁴⁴Nd, ¹⁷⁶Hf/¹⁷⁷Hf and HFSE/LILE also show no obvious correlations with SiO₂ if precluding the sample YJOD-10, being consistent with most of the samples studied had negligible crustal materials assimilation during magma ascent. The obvious Nb-Ta positive anomalies (Fig. 3) and the high $[Ta/U]_N$ and $[Nb/Th]_N$ values



Fig. 5. Sr, Nd and Hf isotope compositions of the CIM Cenozoic basalts. For comparison, OIB and MORB data (from the database compilation of Stracke et al., 2003, 2005) are plotted in the diagram. Also shown are the published Sr–Nd isotope data of garnet–pyroxene entrained in Cenozoic basalts from Damaping (DMP) (Xu, 2002). Reference Terrestrial Array ($\epsilon_{Hf} = 1.36\epsilon_{Nd} + 2.95$) is after Vervoort and Blichert-Toft (1999).



Fig. 6. Sr-Nd-Hf isotopic ratios against [La/Sm]_N to illustrate that radiogenic isotopes are unsupported by parent/daughter ratios (similarly for Rb/Sr, Sm/Nd and Lu/Hf) (i.e., decoupled), suggesting recent source enrichment (too recent to produce radiogenic ingrowth).

(Fig. 4) for Chifeng basalts reinforce the conclusion that these samples had little crustal material involved. Only sample YJQD-10 displays crustal contamination characters with slightly higher Th/Nb, Th/Ta and lower ¹⁴³Nd/¹⁴⁴Nd, ¹⁷⁶Hf/¹⁷⁷Hf with elevated SiO₂ (Fig. 8), and thus we will avoid using this sample (YJQD-10) in the following discussion.

5.2. The asthenospheric mantle source character of the CIM basalts

The CIM Cenozoic basalts have high $[Dy/Yb]_N = 1.69-2.81$ (with an average of 2.15 for N = 50). For partial melts from spinel peridotite mantle source, the $[Dy/Yb]_N$ value would be close to unity, because bulk (peridotite/melt) distribution coefficients of Dy and Yb are similar (Baker et al., 1997). Given the lithosphere thickness in the CIM area is

~80–90 km (Zhu, 2007) and the inferred garnet-spinel face boundary near the solidus condition is ~85 km deep (Robinson and Wood, 1998), the high [Dy/Yb]_N values in the CIM Cenozoic basalts are most consistent with the "lid effect" (see Niu et al., 2011) with the melting limited in the sub-lithospheric mantle garnet stability field where garnet present as a residual phase ($D_{gar/melt}^{Yb} >> D_{gar/melt}^{Dy}$); no melting is expected in the spinel peridotite stability field which is within the lithosphere in the region.

The three series of CIM basalts generally exhibit a relatively large Sr-Nd-Hf isotopic variation (Fig. 5), indicating mantle source heterogeneities. Apart from three GGW samples with high 87 Sr/ 86 Sr and high 143 Nd/ 144 Nd (see discussion below), the negative correlation observed between 87 Sr/ 86 Sr and 143 Nd/ 144 Nd (Fig. 5a), and positive



Fig. 7. Correlation coefficients (R-values; left axis) of Sr–Nd–Hf isotopic ratios with incompatible element abundances of CIM basalts are plotted in the order of decreasing relative incompatibility. The data used in this diagram are our new data together with the literature data (Deng and Macdougall, 1992; Guo et al., 2014a; Han et al., 1999; Ho et al., 2008, 2011; W.H. Zhang et al., 2012; Zhou, 2012). We also plot the East Pacific Rise (EPR) seamount data (Niu et al., 2002; Zhang et al., private communication) for comparison. The decoupled correlations of Sr–Nd–Hf isotopic ratios with incompatible element abundances in CIM basalts demonstrate the young nature of the metasomatic source enrichments compared to the coupled and relatively more ancient enrichments of metasomatic origin in the sources of the EPR.

correlation between ¹⁴³Nd/¹⁴⁴Nd and ¹⁷⁶Hf/¹⁷⁷Hf (Fig. 5b), especially for the Jining series, strongly indicate two mantle reservoirs in the origin of the CIM basalts: a MORB-like source with a fairly low ⁸⁷Sr/⁸⁶Sr, high¹⁴³Nd/¹⁴⁴Nd and ¹⁷⁶Hf/¹⁷⁷Hf, and another component, the EM1 with moderate ⁸⁷Sr/⁸⁶Sr, low¹⁴³Nd/¹⁴⁴Nd and ¹⁷⁶Hf/¹⁷⁷Hf defined by Zindler and Hart (1986). This is also consistent with the previous explanation that the Cenozoic basalts in NCC originated from partial melting of the asthenosphere characterized by DMM + EM1 (e.g., Basu et al., 1991; Choi et al., 2006). The high Nb/U (50.4–194.2; average at 85.2, N = 50) and Nb/La (1.22–2.31; average at 1.92, N = 50) ratios provide further evidence that the CIM Cenozoic basalts are of asthenospheric origin. This is because the Nb/U ratios for CIM basalts are significantly higher than those of MORBs and OIBs (Nb/U = 47 ± 10; Hofmann et al., 1986), also because melts of lithospheric mantle origin would have Nb/La < 1 (Smith et al., 1999).

Note that three samples (GGW-01, GGW-07, GGW-18) from Abaga volcanic field have high 87 Sr/ 86 Sr at a given high ε_{Nd} (>4.5) and plot away from the OIB field (Fig. 5; Stracke et al., 2003, 2005). As discussed above, crustal contamination can be precluded as the potential process during magma ascent. Also, surface weathering can also be ruled out because the samples are fresh and because Sr correlates well with "alteration immobile" elements (e.g., Th, Nb, La, Zr) (not shown). We thus propose that such isotopic signature must be inherited from magmatic processes, including heterogeneities in the mantle sources. Xu (2002) reported garnet-pyroxenite characterized by high ⁸⁷Sr/⁸⁶Sr, high¹⁴³Nd/¹⁴⁴Nd and elevated incompatible element entrained in Damaping Cenozoic basalts, and interpreted these garnet-pyroxenite as representing segregates from melts derived from partial melting of hydrothermally altered oceanic crust. With trace element and isotopic characteristics of the three GGW samples, we suggest the possibility that some of the CIM basalts may have assimilated the earlier formed garnet-pyroxenite with inherited signatures of altered ocean crust (Fig. 5a).

5.3. Possible signature of recycled ocean crust in the CIM basalts

Niu and Batiza (1997) consider the high $[Ta/U]_N$ and $[Nb/Th]_N$ in oceanic basalts as reflecting the contribution of subducted ocean crust, because subduction related arc magmatism is inferred to be the only known process that can effectively fractionate Nb from Th, and Ta

from U. This is because in the flux-melting model for subduction-zone magmatism, the island arc magmas are produced by slab-dehydration induced mantle wedge melting, and the "slab-dehydration" supplies water and water soluble elements (Th and U as well as Ba, Rb, Cs, K, Sr etc.) to the arc magmatism whereas HFSEs (i.e., Nb, Ta) are left in the residual ocean crust (also see Rudnick et al., 2000). The involvement of such residual ocean crust with $[Ta/U]_N > 1$ and $[Nb/Th]_N > 1$ in the mantle sources can explain the excess Nb and Ta in oceanic basalts (both E-MORBs and OIBs; Niu and Batiza, 1997) (Fig. 4). While this interpretation is logical, it remains unknown if subducted ocean crust can indeed enter the mantle source regions of oceanic basalts. Given the known presence of the paleo-Pacific slab with "residual ocean crust" in the mantle transition zone beneath eastern China (Huang and Zhao, 2006; Kárason and van Der Hilst, 2000), the excess Nb and Ta in the CIM basalts (see Fig. 4) may be at least circumstantial evidence for the involvement of subducted ocean crust in the petrogenesis of the CIM basalts in particular and the Cenozoic basalts in eastern China in general as inferred from stable isotopes of fluid inclusions in mantle xenoliths in these basalts (Zhang et al., 2007). Recent studies of Mesozoic-Cenozoic basalts in eastern China support this notion (Li et al., 2015; Xu, 2014; Xu et al., 2012).

Nevertheless, the ocean crust is too depleted in incompatible elements to be the enriched component required for OIB on a global scale (Niu and O'Hara, 2003; Niu et al., 2012) and also for the CIM basalts (Fig. 3). The ocean crust, after passing through the subductionzone dehydration, would be even more depleted in LILEs, making the subducted ocean crust unsuitable for incompatible element enriched component in OIB and in CIM basalts. Hence, even if it can be proved that subducted ocean crust can indeed contribute to OIB and CIM basalts as inferred from the excess Nb and Ta (Fig. 4), it cannot be the major source materials for incompatible-element enriched Cenozoic basalts in eastern China as further demonstrated below. Also, it is not possible to partially melt the basaltic/picritic ocean crust to produce basaltic melts with high MgO, but will produce melts of more silicic composition (e.g., Green and Ringwood, 1968; Niu and O'Hara, 2003).

Fig. 9 compares the average CIM Cenozoic basalts with subduction zone dehydration-modified residual ocean crust (normalized to average present-day ocean crust; after Niu and O'Hara, 2003). The average CIM Cenozoic basalts are generally more enriched in the progressively



Fig. 8. (a-c) ⁸⁷Sr/⁸⁶Sr, ¹⁴³Nd/¹⁴⁴Nd, ¹⁷⁶Hf/¹⁷⁷Hf variation with SiO₂, and (d-e) LILE/HFSE (La/Nb, Th/Nb and Th/Ta) vs. SiO₂ diagrams for CIM basalts to illustrate negligible crustal contamination before eruption.

more incompatible elements than the average present-day ocean crust, whereas residual ocean crust, after passing through subduction zone with 100% (Residual ocean crust 1) and 50% (Residual ocean crust 2) dehydration reactions, shows depleted geochemical signatures with outstanding positive Nb-Ta anomalies when compared with the average ocean crust. The effects of subduction zone dehydration modification were approximated using fluid-rock distribution coefficients obtained in dehydration experiments on an MORB-like amphibolite (Kogiso et al., 1997; Appendix 4). For comparison, we also plot average western Pacific island arc tholeiites (IAB; Niu and O'Hara, 2003), which is depleted in REEs and significantly more so in water-insoluble incompatible elements (e.g., Nb, Ta, Ti), but enriched in water-soluble incompatible elements (e.g., Rb, Ba, K), being complementary to the residual ocean crust (Fig. 9). Together with the above argument, we, thus, suggest

that the subducted paleo-Pacific ocean crust might contribute to the magma source of the CIM basalts, but to melt or partially melt the subducted paleo-Pacific ocean crust alone with such residual geochemical signatures cannot produce the OIB-like CIM Cenozoic basalts due to their extreme depletion in incompatible elements, especially water-soluble incompatible elements, of the residual ocean crust.

5.4. Prior mantle source metasomatism is required for the CIM basalts

Niu and the co-workers recognized that OIB source materials are more enriched in incompatible elements than the primitive mantle (i.e., $[La/Sm]_{OIB}$ source > $[La/Sm]_{PM}$) and are enriched in the progressively more incompatible elements, which requires that the OIB source regions have undergone a prior low mass fraction (low-F) melt



Fig. 9. Multi-element spidergram of the average CIM Cenozoic basalts and subduction dehydration-modified residual ocean crust normalized to present-day mean composition of ocean crust (Niu and O'Hara, 2003). For comparison, average island arc tholeiites (IAB, Niu and O'Hara, 2003), average present-day ocean island basalts (OIBs) and enriched type mid-ocean ridge basalts (E-MORBs) (Sun and McDonough, 1989) are also plotted. In the diagram, residual ocean crusts 1 and 2 denote variable subduction-modified bulk ocean crust with 100% dehydration modification and 50% dehydration modification, respectively. In the calculations, the element in the residual basaltic ocean crust is calculated using the law: $X_{RC} = X_{BOC} + F_X$, where X_{RC} is the concentration of an element in the subduction zone dehydration modified basaltic ocean crust, X_{BOC} refers to the concentration of an element in bulk ocean crust, and F_X is the modification coefficient of an element during the dehydration reaction. The bulk ocean crust composition is from Niu and O'Hara (2003), and the modification coefficients during the subduction the subduction from Kogiso et al. (1997).

refertilization or mantle metasomatism (e.g., Niu and O'Hara, 2003; Niu et al., 2002, 2012). Obviously, the CIM basalts resemble the present-day average OIB in term of incompatible element systematics and many of the CIM samples are in fact more enriched than OIB with [La/Sm]_N as high as 3.38 (Fig. 3a). Therefore, the incompatible element enriched characteristics of the CIM basalts require their source(s) to have undergone low-F melt metasomatism prior to the magmatism.

Studies have illustrated that as oceanic lithosphere thickens due to cooling with time through basal accretion. In response, incompatible element- and volatile-enriched low degree partial melts (Low-F melts) atop the asthenosphere are readily frozen and incorporated as "metasomatic" dikes or veins in the thickening lithosphere at the lithosphere–asthenosphere boundary (LAB; e.g., Niu, 2008; Niu et al., 2012; Pilet et al., 2008). Consequently, reinjection of such metasomatized oceanic mantle lithosphere into the asthenosphere, after passing through the subduction zone, would contribute enriched component to the upper mantle source regions of intra-plate basalts (Niu, 2008; Niu et al., 2012; Zhang et al., 2007). Also, given the presence of subducted paleo-Pacific plate in the mantle transition zone beneath eastern China (Huang and Zhao, 2006; Kárason and van Der Hilst, 2000), we propose that the fertile components (enriched in incompatible elements and volatiles) of the stagnant paleo-Pacific plate can contribute more directly and efficiently to the magma source of the CIM basalts. We can envisage that under the ambient heating, the cold slab, especially the basaltic ocean crust and the "metasomatic" dikes or veins at the base of subducted oceanic slab, would readily undergo dehydration melting (Niu, 2005, 2014; Wang et al., 2015), producing incipient low-F melts that rises, percolates and sequestrates more volatiles and incompatible elements in the asthenospheric upper mantle and become progressively more enriched low-F melts with elevated abundances of incompatible elements and volatiles (e.g., H₂O, CO₂) as well as moreto-less incompatible element ratios (e.g., La/Sm, Sm/Yb, Rb/Sr, Nd/Sm and Hf/Lu). Contribution of such highly enriched low-F hydrous melts in the asthenospheric source regions will inevitably result in the incompatible element-enriched characteristics of the CIM basalts. It is important to note that such "metasomatism" is too recent (and current) to produce isotopic ingrowth, leading to the decoupling between incompatible elements and radiogenic isotopes (Figs. 6, 7).

In fact, mantle metasomatism is likely widespread at the base of the growing lithosphere beneath ocean basins and continents as inferred from massif peridotites and mantle xenoliths in erupted alkali basalts worldwide (e.g., Frey and Green, 1974; Frey et al., 1985; McKenzie and O'Nions, 1995; Niu et al., 2012; O'Reilly and Griffin, 1988; Takazawa et al., 2000).

5.5. Is recycled terrigenous sediment important as the enriched component for the CIM basalts?

Note that terrigenous sediments could also be a potential candidate to be the enriched component contributed to the source of CIM basalts. However, these CIM basalts display striking elevated Nb-Ta (Figs. 3b) and 4), which is inconsistent with the involvement of terrigenous sediments in the petrogenesis of CIM basalts because terrigenous sediments of upper continental crust compositions have characteristic depletion of Nb (vs. Th) and Ta (U) (Fig. 4; Rudnick and Gao, 2003). Also, as discussed above, the subducted residual ocean crust must have excess Nb (vs. Th) and Ta (vs. U) and partial melting of such a crust would inevitably produce the incipient low-F melts with elevated Nb and Ta abundances. Hence, contribution of subducted terrigenous sediments, if any, is insignificant to the petrogenesis of the CIM basalts. In this context, we should note that marine carbonate can carry excess Ba and Sr (Plank and Langmuir, 1998) into the mantle transition zone along with other sediments and the basaltic ocean crust, which can explain the excess Ba and Sr in some intra-plate basalts and highly alkali-rich

melts of mantle metasomatic origin (Guo et al., 2014b; Zeng et al., 2010).

5.6. The petrogenetic model of the highly enriched CIM Cenozoic basalts

The data and discussion above allow us to envisage the petrogenesis of the incompatible-element enriched CIM Cenozoic basalts. Fig. 10a illustrates that the CIM Cenozoic basalts were produced in the context that subducted paleo-Pacific slab has been horizontally lying in the mantle transition zone beneath eastern China (also see Fig. 1b).

Fig. 10b shows that the low-F melts were produced through low degree partial melting of the stagnant paleo-Pacific slab (including the oceanic mantle lithosphere, the basaltic ocean crust and the subducted marine sediments with carbonate), while the water was released as the water-enriched phases transformed into the water-less-enriched phases (Fukao et al., 2009; Schmandt et al., 2014), forming hydrous low-F melts enriched in volatiles (e.g. H₂O, CO₂) and incompatible elements with elevated Nb–Ta and Ba–Sr. Such hydrous low-F melts would migrate upward because of buoyancy, during which they percolate and sequestrate more volatiles and incompatible elements in the asthenospheric upper mantle and became progressively more enriched low-F melts. Fig. 10c illustrates that the hydrous low-F melts played double roles when reached the sub-lithospheric mantle: (1) metasomatized the upper asthenospheric mantle with high contents of volatiles (e.g. H₂O, CO₂) and incompatible elements (see above and also Niu, 2008; Niu et al., 2012; Pilet et al., 2008); (2) lower the solidus of the LVZ and facilitate its melting (Green et al., 2010), which is also interpreted as the process of LVZ formation beneath continents (Niu, 2014). This inference is well supported by the recent research that the "primary" magmas for the Cenozoic intra-plate basalts from Shuangliao have high H₂O content (0.90-3.06 wt.%; Chen et al., 2015). Our model is also consistent with the proposal that the fluid from the subducted paleo-Pacific plate triggered the partial melting of the metasomatized mantle and resulted in the magmatism in East China (Kuritani et al., 2011; Sakuyama et al., 2013) and Korea (Sakuyama et al., 2014). Melting of such recently formed LVZ with incompatible element enriched character can readily produce enriched melts with decoupled characteristics between Sr-Nd-Hf isotopes and incompatible elements in the CIM basalts. Furthermore, the assimilation of the earlier-formed metasomatic minerals and vein lithologies can further enrich the magmas and result in highly enriched Cenozoic basalts in the CIM area and in the entire eastern China in general.

In general, the widespread highly enriched Cenozoic basalts in eastern China (including the CIM area) are ultimately related genetically to the subduction of the paleo-Pacific plate and thus we propose that these intra-plate basalts are a special consequence of plate tectonics.



Fig. 10. Graphical description of the petrogenesis of the CIM Cenozoic basalts. Fig. 10a illustrates that the CIM Cenozoic basalts were produced in the context of the subducted Pacific slab lying in the mantle transition zone beneath eastern China. Fig. 10b shows that the stagnant slab (see Niu, 2014) can release water with time as being heated by the ambience, forming hydrous incipient (very low degree) melts enriched in volatiles (e.g. H₂O, CO₂), and all the incompatible elements. Fig. 10c illustrates that the hydrous low-F melt metasomatizes the LVZ with high contents of volatiles and incompatible elements and also facilitates the partial melting due to lowering the solidus of the LVZ, forming the pristine CIM magmas. Assimilation of the earlier-formed metasomatic veins or minerals further enhanced enrichments and resulted in the incompatible element and alkaline highly enriched CIM Cenozoic basalts.

5.7. Implications for the petrogenesis of OIB and E-MORB

We have shown above that the CIM Cenozoic basalts have the contribution of the ocean crust as suggested by the excess Nb and Ta (i.e., $[Nb/Th]_N > 1$ and $[Ta/U]_N > 1$) in the CIM basalts (Fig. 4) and the presence of subducted oceanic lithosphere beneath eastern China (Huang and Zhao, 2006; Kárason and van Der Hilst, 2000). As shown in Figs. 3 and 4, the CIM basalts resemble present-day average OIB and E-MORB (Sun and McDonough, 1989) in terms of incompatible element systematics, especially the positive Nb-Ta anomalies (Figs. 3b, 4), suggesting their similar petrogenesis. We herein infer that the recycled ocean crust could indeed contribute to the source regions of OIB and E-MORB if and only if subducted ocean crust had not entered the lower mantle (Niu and O'Hara, 2003; Niu et al., 2012). However, we must emphasize that melting of the ocean crust cannot produce incompatible element-enriched signature of E-MORB and OIB (see Fig. 9). Low-F melt metasomatism in the source regions is required for incompatible element enriched component in the sources of intra-plate settings like OIB in ocean basins and the CIM Cenozoic basalts in eastern China, as otherwise it is impossible to produce incompatible-element enriched basaltic melts. Therefore, indiscriminate emphasis of ROC in the petrogenesis of OIB or OIB-like intra-plate basalts has resulted in and will continue to lead to chains of conceptual errors that prevent us from genuine understanding of mantle dynamics and terrestrial magmatism.

6. Summary

- (1) The CIM Cenozoic basalts show large major element, trace element and Sr-Nd-Hf isotope compositional variations. The major element variation can be explained by varying extent of fractional crystallization dominated by clinopyroxene and olivine, likely from compositionally varied parental magmas. The trace element and the isotopic variations reflect source compositional heterogeneities.
- (2) The excess Nb and Ta in the CIM basalts may indicate involvement of subducted ocean crust in the source region. However, the subducted ocean crust is not the incompatible elementenriched component in the CIM basalts.
- (3) The incompatible element enriched character of the CIM basalts reflect enriched sources, whose origin is most consistent with recent low-F melt metasomatism. The low-F melt is probably originated from dehydration melting of the paleo-Pacific slab lying in the mantle transition zone beneath eastern China. The low-F hydrous melt rose and percolated in the upper mantle asthenosphere, sequestrating more incompatible elements and volatiles and refertilizing the source regions of the CIM basalts in particular and eastern China Cenozoic basalts in general and also lowering the solidus of the source regions. Thus we consider the Cenozoic magmatism taking place in the CIM area, as well as in the entire eastern China, as a special consequence of plate tectonics.
- (4) As the low-F melt metasomatism is recent and is likely still taking place, the short time scale has not allowed radiogenic isotope ingrowth, resulting in the decoupling of incompatible elements and Sr-Nd-Hf radiogenic isotopes. This simple observation affords a powerful line of evidence for the action and snapshot of low-F melt metasomatism of intra-plate basaltic mantle sources.
- (5) We infer that OIB and E-MORB source regions could also have contributions of subducted ocean crust on the basis of excess Nb and Ta in both the CIM basalts and oceanic basalts. If this inference is correct, then significant amount of subducted ocean crust may remain in the upper mantle.
- (6) We must emphasize, however, that the inferred subducted ocean crust in the mantle source regions of intra-plate basalts cannot

be the incompatible element enriched component. The latter is of low-F melt metasomatic origin. Emphatically, mantle metasomatism is required for the incompatible element enriched component in the mantle source regions of intra-plate basalts beneath both ocean basins and continents.

Acknowledgments

We thank Junping Gao, Piaoer Fu, Wenli Sun, Huixia Cui, Yuxin Ma for their field company and sample preparation for the geochemistry analysis. We acknowledge Prof. Li Su for major and trace elements analyses; Yueheng Yang, Chaofeng Li, Xianghui Li, Entao Liu and Wei Zhou for assistance with Sr–Nd–Hf isotope separation; Huaikun Li, Hongying Zhou for measurement of Sr isotopes; Prf. Lian Zhou for detection of Nd isotope. This work was supported by the National Natural Science Foundation of China (NSFC grants 91014003 and 41130314), by Key Research Program of the Chinese Academy of Sciences (Grant No.: KGZD-EW-T07) and by the Knowledge Innovation Program of the Sanya Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences (Grant No.: Y570031QY1).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx. doi.org/10.1016/j.lithos.2015.11.010.

References

- Anderson, M.B., Elliott, T., Freymuth, H., Sims, K.W.W., Niu, Y.L., Kelly, K.A., 2015. The terrestrial uranium isotope cycle. Nature 517, 356–359.
- Baker, J.A., Menzies, M.A., Thirlwall, M.F., Macpherson, C.G., 1997. Petrogenesis of Quaternary intraplate volcanism, Sana'a, Yemen: implications for plumelithosphere interaction and polybaric melt hybridization. Journal of Petrology 38, 1359–1390.
- Basu, A.R., Wang, J.W., Huang, W.K., Xie, G.H., Tatsumoto, M., 1991. Major element, REE and Pb, Nd and Sr isotopic geochemistry of Cenozoic volcanic rocks of eastern China: implications for origin from suboceanic-type mantle reservoirs. Earth and Planetary Science Letters 105, 149–169.
- Chen, Y., Wu, T.R., Xu, X., Zhang, S.T., 2004. Discovery of mantle xenoliths bearing Miocene potassium-rich olivine basalt and its significance in Siziwang Qi area, Inner Mongolia. Geological Journal of China Universities 10, 586–591 (in Chinese with English abstract).
- Chen, H., Xia, Q.K., Ingrin, J., Jia, Z.B., Feng, M., 2015. Changing recycled oceanic components in the mantle source of the Shuangliao Cenozoic basalts, NE China: new constraints from water content. Tectonophysics 650, 113–123.
- Choi, S.H., Mukasa, S.B., Kwon, S.T., Andronikov, A.V., 2006. Sr, Nd, Pb and Hf isotopic compositions of late Cenozoic alkali basalts in South Korea: evidence for mixing between the two dominant asthenospheric mantle domains beneath East Asia. Chemical Geology 232, 134–151.
- Deng, F.L., Macdougall, J.D., 1992. Proterozoic depletion of the lithosphere recorded in mantle xenoliths from Inner Mongolia. Nature 360, 333–336.
- Frey, F.A., Green, D.H., 1974. Mineralogy, geochemistry and origin of Iherzolite inclusions in Victorian basanites. Geochimica et Cosmochimica Acta 38, 1023–1059.
- Frey, F.A., Suen, C.J., Stockman, H., 1985. The Ronda high temperature peridotite: geochemistry and petrogenesis. Geochimica et Cosmochimica Acta 49, 2469–2491.
- Fukao, Y., Obayashi, M., Nakakuki, T., 2009. Stagnant slab: a review. Annual Review of Earth and Planetary Sciences 37, 19–46.
- Gao, S., Luo, T.C., Zhang, B.R., Zhang, H.F., Han, Y.W., Zhao, Z.D., Hu, Y.K., 1998. Chemical composition of the continental crust as revealed by studies in East China. Geochimica et Cosmochimica Acta 62, 1959–1975.
- Green, T.H., Ringwood, A.E., 1968. Genesis of the calc-alkaline igneous rock suite. Contributions to Mineralogy and Petrology 18, 105–162.
- Green, D.H., Hibberson, W.O., Kovács, I., Rosenthal, A., 2010. Water and its influence on the lithosphere–asthenosphere boundary. Nature 467, 448–451.
- Guo, P.Y., Niu, Y.L., Ye, L., Liu, J.J., Sun, P., Cui, H.X., Su, L., Zhao, J.X., Feng, Y.X., 2014a. Lithosphere thinning beneath west North China Craton: evidence from geochemical and Sr–Nd–Hf isotope compositions of lining basalts. Lithos 202 (203), 37–54.
- Guo, P.Y., Niu, Y.L., Yu, X.H., 2014b. A synthesis and new perspective on the petrogenesis of kamafugites from West Qinling, China, in a global context. Journal of Asian Earth Sciences 79, 86–96.
- Han, B.F., Wang, S.G., Kagami, H., 1999. Trace element and Nd–Sr isotope constraints on origin of the Chifeng flood basalts, North China. Chemical Geology 155, 187–199.
- Hauri, E.H., Lassiter, J.C., DePaolo, D.J., 1996. Osmium isotope systematics of drilled lavas from Mauna Loa, Hawaii. Journal of Geophysical Research 101, 11793–11806.

Hirschmann, M.M., Kogiso, T., Baker, M.B., Stolper, E.M., 2003. Alkalic magmas generated by partial melting of garnet pyroxenite. Geology 31, 481–484.

- Ho, K.S., Liu, Y., Chen, J.C., Yang, H.J., 2008. Elemental and Sr-Nd-Pb isotopic compositions of late Cenozoic Abaga basalts, Inner Mongolia: implications for petrogenesis and mantle process. Geochemical Journal 42, 339–357.
- Ho, K.S., Liu, Y., Chen, J.C., You, C.F., Yang, H.J., 2011. Geochemical characteristics of Cenozoic Jining basalts of the western North China Craton: evidence for the role of the lower crust, lithosphere, and asthenosphere in petrogenesis. Terrestrial, Atmospheric and Oceanic Sciences 22, 15–40.
- Hofmann, A.W., White, W.M., 1982. Mantle plumes from ancient oceanic crust. Earth and Planetary Science Letters 57, 421–436.
- Hofmann, A.W., Jochum, K.P., Seufert, M., White, W.M., 1986. Nb and Pb in oceanic basalts: new constraints on mantle evolution. Earth and Planetary Science Letters 79, 33–45.
- Huang, J., Zhao, D., 2006. High-resolution mantle tomography of China and surrounding regions. Journal of Geophysical Research 111 (B9).
- Jiang, N., Guo, J.H., Chang, G.H., 2013. Nature and evolution of the lower crust in the eastern North China craton: a review. Earth-Science Reviews 122, 1–9.
- Kárason, H., van Der Hilst, R.D., 2000. Constraints on mantle convection from seismic tomography. In: Richards, M.A., Gordon, R., van Der Hilst, R.D. (Eds.), History and Dynamics of Plate Motion. Am. Geophys. Union Geophys. Monogr. Ser. 121, pp. 277–288.
- Kogiso, T., Tatsumi, Y., Nakano, S., 1997. Trace element transport during dehydration processes in the subducted oceanic crust. Earth and Planetary Science Letters 148, 193–205.
- Kogiso, T., Hirschmann, M.M., Frost, D.J., 2003. High-pressure partial melting of garnet pyroxenite: possible mafic lithologies in the source of ocean island basalts. Earth and Planetary Science Letters 216, 603–617.
- Kuritani, T., Ohtani, E., Kimura, J.I., 2011. Intensive hydration of the mantle transition zone beneath China caused by ancient slab stagnation. Nature Geoscience 4, 713–716.
- Lassiter, J.C., Hauri, E.H., 1998. Osmium-isotope variations in Hawaiian lavas: evidence for recycled oceanic lithosphere in the Hawaiian plume. Earth and Planetary Science Letters 164, 483–496.
- Le Bas, M.J., Le Maitre, R.W., Strekeisen, A., Zanettin, B., 1986. Chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology 27, 745–750.
- Li, S.L., Mooney, W.D., Fan, J., 2006. Crustal structure of mainland China from deep seismic sounding data. Tectonophysics 420, 239–252.
- Li, Y.Q., Ma, C.Q., Robinson, P.T., Zhou, Q., Liu, M.L., 2015. Recycling of oceanic crust from a stagnant slab in the mantle transition zone: evidence from Cenozoic continental basalts in Zhejiang Province, SE China. Lithos 230, 146–165.
- Luo, X.Q., Chen, Q.T., 1990. Preliminary study on geochronology for Cenozoic basalts from Inner Mongolia. Acta Petrologica et Mineralogica 9, 36–46 (in Chinese with English abstract).
- McDonald, G.A., Katsura, T., 1964. Chemical composition of Hawaiian Lavas. Journal of Petrology 5, 82–133.
- McKenzie, D., O'Nions, R.K., 1995. The source regions of oceanic island basalts. Journal of Petrology 36, 133–159.
- Niu, Y.L., 2005. Generation and evolution of basaltic magmas: some basic concepts and a hypothesis for the origin of the Mesozoic and Cenozoic volcanism in eastern China. Geological Journal of China Universities 11, 9–46.
- Niu, Y.L., 2008. The origin of alkaline lavas. Science 320, 883-884.
- Niu, Y.L., 2014. Geological understanding of plate tectonics: basic concepts, illustrations, examples and new perspectives. Global Tectonics & Metallogeny 10, 23–46.
- Niu, Y.L., Batiza, R., 1997. Trace element evidence from seamounts for recycled oceanic crust in the eastern equatorial Pacific mantle. Earth and Planetary Science Letters 148, 471–484.
- Niu, Y.L., O'Hara, M.J., 2003. Origin of ocean island basalts: a new perspective from petrology, geochemistry, and mineral physics considerations. Journal of Geophysical Research 108 (B4), 2209. http://dx.doi.org/10.1029/2002JB002048.
- Niu, Y.L., Regelous, M., Wendt, J.I., Batiza, R., O'Hara, M.J., 2002. Geochemistry of near-EPR seamounts: importance of source vs. process and the origin of enriched mantle component. Earth and Planetary Science Letters 199, 327–345.
- Niu, Y.L., Wilson, M., Humphreys, E.R., O'Hara, M.J., 2011. The origin of intra-plate ocean island basalts (OIB): the lid effect and its geodynamic implications. Journal of Petrology 52, 1443–1468.
- Niu, Y.L., Wilson, M., Humphreys, E.R., O'Hara, M.J., 2012. A trace element perspective on the source of ocean island basalts (OIB) and fate of subducted oceanic crust (SOC) and mantle lithosphere (SML). Episodes 35, 310–327.
- O'Reilly, Y.S., Griffin, W.L., 1988. Mantle metasomatism beneath western Victoria, Australia: I, Metasomatic processes in Cr-diopside Iherzolites. Geochimica et Cosmochimica Acta 52, 433–447.
- Plank, T., Langmuir, C.H., 1998. The chemical composition of subducting sediment and its consequences for the crust and mantle. Chemical geology 145 (3), 325–394.
- Pilet, S., Baker, M.B., Stolper, E.M., 2008. Metasomatized lithosphere and the origin of alkaline lavas. Science 320, 916–919.
- Rehkämper, M., Hofmann, A.W., 1997. Recycled oceanic crust and sediment in Indian Ocean MORB. Earth and Planetary Science Letters 147, 93–106.
- Robinson, J.A.C., Wood, B.J., 1998. The depth of the spinel to garnet transition at the peridotite solidus. Earth and Planetary Science Letters 164, 277–284.
- Rudnick, R.L., Gao, S., 2003. Composition of the continental crust. Treatise on geochemistry 3, 1–64.
- Rudnick, R.L., Barth, M., Horn, I., McDonough, W.F., 2000. Rutile-bearing refractory eclogites: missing link between continents and depleted mantle. Science 287, 278–281.

- Sakuyama, T., Tian, W., Kimura, J.I., Fukao, Y., Hirahara, Y., Takahashi, T., ... Tatsumi, Y., 2013. Melting of dehydrated oceanic crust from the stagnant slab and of the hydrated mantle transition zone: constraints from Cenozoic alkaline basalts in eastern China. Chemical Geology 359, 32–48.
- Sakuyama, T., Nagaoka, S., Miyazaki, T., Chang, Q., Takahashi, T., Hirahara, Y., Senda, R., Itaya, T., Kimure, J., Ozawa, K., 2014. Melting of the uppermost metasomatized asthenosphere triggered by fluid fluxing from ancient subducted sediment: constraints from the Quaternary basalt lavas at Chugaryeong volcano, Korea. Journal of Petrology 55, 499–528.
- Schmandt, B., Jacobsen, S.D., Becker, T.W., Liu, Z., Dueker, K.G., 2014. Dehydration melting at the top of the lower mantle. Science 344, 1265–1268.
- Shi, R.P., Zhu, R.X., Pan, Y.X., Shi, G.H., Hoffman, K.A., 2002. Paleointensity study of Early Miocene lavas from Pingzhuang, Inner Mongolia, China. Geophysical Research Letters 29, 22-1–22-4.
- Smith, E.I., Sánchez, A., Walker, J.D., Wang, K., 1999. Geochemistry of mafic magmas in the Hurricane Volcanic Field, Utah: implications for small- and large-scale chemical variability of the lithospheric mantle. Journal of Geology 107, 433–448.
- Sobolev, A.V., Hofmann, A.W., Nikogosian, I.K., 2000. Recycled oceanic crust observed in 'ghost plagioclase' within the source of Mauna Loa lavas. Nature 404, 986–990.Sobolev, A.V., Hofmann, A.W., Sobolev, S.V., Nikogosian, I.K., 2005. An olivine-free mantle
- source of Hawaii shide basalts. Nature 434, 590–597.
- Sobolev, A.V., Hofmann, A.W., Kuzmin, D.V., Yaxley, G.M., Arndt, N.T., Chung, S.L., ... Teklay, M., 2007. The amount of recycled crust in sources of mantle-derived melts. Science 316, 412–417.
- Stracke, A., Bizimis, M., Salters, V.J.M., 2003. Recycling oceanic crust: quantitative constraints. Geochemistry, Geophysics, Geosystems 4. http://dx.doi.org/10.1029/2001GC000223.
- Stracke, A., Hofmann, A.W., Hart, S.R., 2005. FOZO, HIMU, and the rest of the mantle zoo. Geochemistry, Geophysics, Geosystems 6. http://dx.doi.org/10.1029/2004GC000824.
- Sun, S.-S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins. Geol. Soc. Spec. Publ. 42, pp. 313–345.
- Takazawa, E., Frey, F.A., Shimizu, N., Obata, M., 2000. Whole rock compositional variations in an upper mantle peridotite (Horoman, Hokkaido, Japan): are they consistent with a partial melting process? Geochimica et Cosmochimica Acta 64, 695–716.
- Vervoort, J.D., Blichert-Toft, J., 1999. Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time. Geochimica et Cosmochimica Acta 63, 533–556.
- Wang, X.C., Wilde, S.A., Li, Q.L., et al., 2015. Continental flood basalts derived from the hydrous mantle transition zone. Nature Communications 6.
- White, W.M., 2010. Ocean island basalts and mantle plumes: the geochemical perspective. Annual Review of Earth and Planetary Sciences 38, 133–160.
- Wu, F.Y., Lin, J.Q., Wilde, S.A., Zhang, X.O., Yang, J.H., 2005. Nature and significance of the Early Cretaceous giant igneous event in eastern China. Earth and Planetary Science Letters 233, 103–119.
- Xu, Y.G., 2002. Evidence for crustal components in the mantle and constraints on crustal recycling mechanisms: pyroxenite xenoliths from Hannuoba, North China. Chemical Geology 182, 301–322.
- Xu, Y.G., 2014. Recycled oceanic crust in the source of 90–40 Ma basalts in North and Northeast China: evidence, provenance and significance. Geochimica et Cosmochimica Acta 143, 49–67.
- Xu, Y.G., Zhang, H.H., Qiu, H.N., Ge, W.C., Wu, F.Y., 2012. Oceanic crust components in continental basalts from Shuangliao, Northeast China: derived from the mantle transition zone? Chemical Geology 328, 168–184.
- Yang, Z.F., Zhou, J.H., 2013. Can we identify source lithology of basalt? Scientific Reports 3, 1856.
- Yang, Y.H., Zhang, H.F., Chu, Z.Y., Xie, L.W., Wu, F.Y., 2010. Combined chemical separation of Lu, Hf, Rb, Sr, Sm and Nd from a single rock digest and precise and accurate isotope determinations of Lu–Hf, Rb–Sr and Sm–Nd isotope systems using Multi-Collector ICP-MS and TIMS. International Journal of Mass Spectrometry 290, 120–126.
- Zeng, G., Chen, L.H., Xu, X.S., Jiang, S.Y., Hofmann, A.W., 2010. Carbonated mantle sources for Cenozoic intra-plate alkaline basalts in Shandong, North China. Chemical Geology 273, 35–45.
- Zhang, W.H., Han, B.F., 2006. K-Ar chronology and geochemistry of Jining Cenozoic basalts, Inner Mongolia, and geodynamic implications. Acta Petrolei Sinica 22, 1597–1607 (in Chinese with English abstract).
- Zhang, M.J., Hu, P.Q., Niu, Y.L., Su, S.G., 2007. Chemical and stable isotopic constraints on the nature and origin of volatiles in the sub-continental lithospheric mantle beneath eastern China. Lithos 96, 55–66.
- Zhang, H.F., Sun, Y.L., Tang, Y.J., Xiao, Y., Zhang, W.H., Zhao, X.M., Santosh, M., Menzies, M.A., 2012a. Melt-peridotite interaction in the Pre-Cambrian mantle beneath the western North China Craton: petrology, geochemistry and Sr, Nd and Re isotopes. Lithos 149, 100–114.
- Zhang, M., Yang, J.H., Sun, J.F., Wu, F.Y., Zhang, M., 2012b. Juvenile subcontinental lithospheric mantle beneath the eastern part of the Central Asian Orogenic Belt. Chemical Geology 328, 109–122.
- Zhang, W.H., Zhang, H.F., Fan, W.M., Han, B.F., Zhou, M.F., 2012c. The genesis of Cenozoic basalts from the Jining area, northern China: Sr–Nd–Pb–Hf isotope evidence. Journal of Asian Earth Sciences 61, 128–142.
- Zhao, X.M., Zhang, H.F., Su, F., Hu, Z.C., Lo, C.H., Wang, Y., Yang, S.H., Guo, J.H., 2013. Phlogopite ⁴⁰Ar/³⁹Ar geochronology of mantle xenoliths from the North China Craton: constraints on the eruption ages of Cenozoic basalts. Gondwana Research 23, 208–219.
- Zheng, Z., Tanak, H., Tatsumi, Y., Kono, M., 2002. Basalt platforms in Inner Mongolia and Hebei Province, northeastern China: new K–Ar ages, geochemistries, and revision of palaeomagnetic results. Geophysical Journal International 151, 654–662.
- Zhou, Y., 2012. Characteristics and Petrogenesis of the Chifeng Cenozoic Hannuoba Basalt (M.S. thesis) Jilin Univ (in Chinese with English abstract).

Zhou, X.M., Li, W.X., 2000. Origin of Late Mesozoic igneous rocks in Southeastern China: implications for lithosphere subduction and underplating of mafic magmas. Tectonophysics 326, 269–287.

- Tectonophysics 326, 269–287.
 Zhu, J.S., 2007. The structural characteristics of lithosphere in the continent of Eurasia and its marginal seas. Frontiers of Earth Science 14, 1–20.
 Zhu, R.X., Xu, Y.G., Zhu, G., Zhang, H.F., Xia, Q.K., Zheng, T.Y., 2012. Destruction of the North China Craton. Science China Earth Sciences 55, 1565–1587.

Zindler, A., Hart, S., 1986. Chemical geodynamics. Annual Review of Earth and Planetary

 Zindier, A., Hart, S., 1986. Chemical geodynamics. Annual Review of Earth and Planetary Sciences Letters 14, 493–571.
 Zou, D.Y., Liu, Y.S., Hu, Z.C., Gao, S., Zong, K.Q., Xu, R., Deng, L.X., He, D.T., Gao, C.G., 2014. Pyroxenite and peridotite xenoliths from Hexigten, Inner Mongolia: insights into the Paleo-Asian Ocean subduction-related melt/fluid-peridotite interaction. Geochimica et Cosmochimica Acta 140, 435–454.