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Generation of Cenozoic intraplate basalts in the big mantle wedge under eastern Asia

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Abstract The roles of subduction of the Pacific plate and the big mantle wedge (BMW) in the evolution of east Asian continental margin have attracted lots of attention in past years. This paper reviews recent progresses regarding the composition and chemical heterogeneity of the BMW beneath eastern Asia and geochemistry of Cenozoic basalts in the region, with attempts to put forward a general model accounting for the generation of intraplate magma in a BMW system. Some key points of this review are summarized in the following. (1) Cenozoic basalts from eastern China are interpreted as a mixture of high-Si melts and low-Si melts. Wherever they are from, northeast, north or south China, Cenozoic basalts share a common low-Si basalt endmember, which is characterized by high alkali, $Fe_2O_3^T$ and TiO_2 contents, HIMU-like trace element composition and relatively low $^{206}Pb/^{204}Pb$ compared to classic HIMU basalts. Their Nd-Hf isotopic compositions resemble that of Pacific Mantle domain and their source is composed of carbonated eclogites and peridotites. The high-Si basalt endmember is characterized by low alkali, $Fe_2O_3^T$ and TiO_2 contents, Indian Mantle-type Pb-Nd-Hf isotopic compositions, and a predominant garnet pyroxenitic source. High-Si basalts show isotopic provinciality, with those from North China and South China displaying EM1-type and EM2-type components, respectively, while basalts from Northeast China containing both EM1- and EM2-type components. (2) The source of Cenozoic basalts from eastern China contains abundant recycled materials, including oceanic crust and lithospheric mantle components as well as carbonate sediments and water. According to their spatial distribution and deep seismic tomography, it is inferred that the recycled components are mostly from stagnant slabs in the mantle transition zone, whereas EM1 and EM2 components are from the shallow mantle. (3) Comparison of solidi of garnet pyroxenite, carbonated eclogite and peridotite with regional geotherm constrains the initial melting depth of high-Si and low-Si basalts at <100 km and ~300 km, respectively. It is suggested that the BMW under eastern Asia is vertically heterogeneous, with the upper part containing EM1 and EM2 components and isotopically resembling the Indian mantle domain, whereas the lower part containing components derived from the Pacific mantle domain. Contents of H_2O and CO_2 decrease gradually from bottom to top of the BMW. (4) Melting of the BMW to generate Cenozoic intraplate basalts is triggered by decarbonization and dehydration of the slabs stagnated in the mantle transition zone.

Keywords Big mantle wedge, Subduction of west Pacific plate, Cenozoic intraplate basalt, Eastern China, East Asia

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1. Introduction

Global seismic tomography reveals stagnation of the Pacific plate within the mantle transition zone (MTZ) by its westward subduction along Japan-Izu-Bonin-Mariana trough (Figure 1a; Fukao et al., 1992; Huang and Zhao, 2006; Li and Van der Hilst, 2010). Zhao et al. (2004), Ohtani and Zhao

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(2009) referred the upper mantle above the stagnant slab to as the Big Mantle Wedge (BMW). The BMW system is clearly different from the so-called small mantle wedge geographically next to trenches (Figure 1b, i.e., the trench-arc-backarc basin system). The small mantle wedge system refers to as the wedge above the subducting plate with a dimention of 100 km in depth and 200 km in width. With a distance of over 1000 km from the trench, the relevant area of the BMW is considered as an intraplate setting. As illustrated in Figure 1b, the BMW, the flat-flying slab in the MTZ and the lower mantle constitute a "sandwich-like" mantle structure beneath eastern Asia.

The modern plate tectonic theory successfully describes the operation of small mantle wedge system and interaction between subducting slab and mantle, and well accounts for the origins of seismicity, arc volcanism and formation of porphyry copper deposits in this system. However, no theory is available yet for the operation of the BMW system and associated crust-mantle interactions. In particular, data are very limited regarding the formation, composition and recycling mechanism of the BMW under eastern Asia and its interactions with surrounding mantle. Investigations into these questions will not only help improve our understanding of regional geology in eastern Asia, but also is of great importance in advancing modern plate tectonic theory.

The BMW structure revealed by seismic tomography reflects the present-day images of the deep structure. Using a high-resolution model of P-wave tomography and paleo-age data of ancient seafloor, Liu X et al. (2017) constrained the flat-lying slab in the MTZ is no more than 20 million years, and it is the subducted Pacific plate rather than the proposed Izanagi plate. Nevertheless, these authors acknowledged that the BMW beneath Eastern Asia may have been there for >110 million years. Because the stagnation of subducting slabs within the MTZ is largely due to the retreat of trenches (Griffiths et al., 1995), the initiation of retreat of west Pacific plate subduction can be used to constrain the formation age of the BMW beneath eastern Asia (Ma and Xu, 2017). The tempo-spatial migration pattern of late Mesozoic magmatism in east Asian continental margin (Kiminami and Imaoka, 2013; Ma and Xu, 2017) suggests that the retreat of west Pacific plate subduction started in Early Cretaceous. Therefore, the BMW beneath eastern Asia may have been formed as early as in the Early Cretaceous. Similar conclusion has been reached by Li S G et al. (2017) based on the light-Mg isotopic compositions observed for <110 Ma basalts from eastern China. In this sense, the genesis of Late Cretaceous-Cenozoic intraplate basalts in eastern China can be linked to

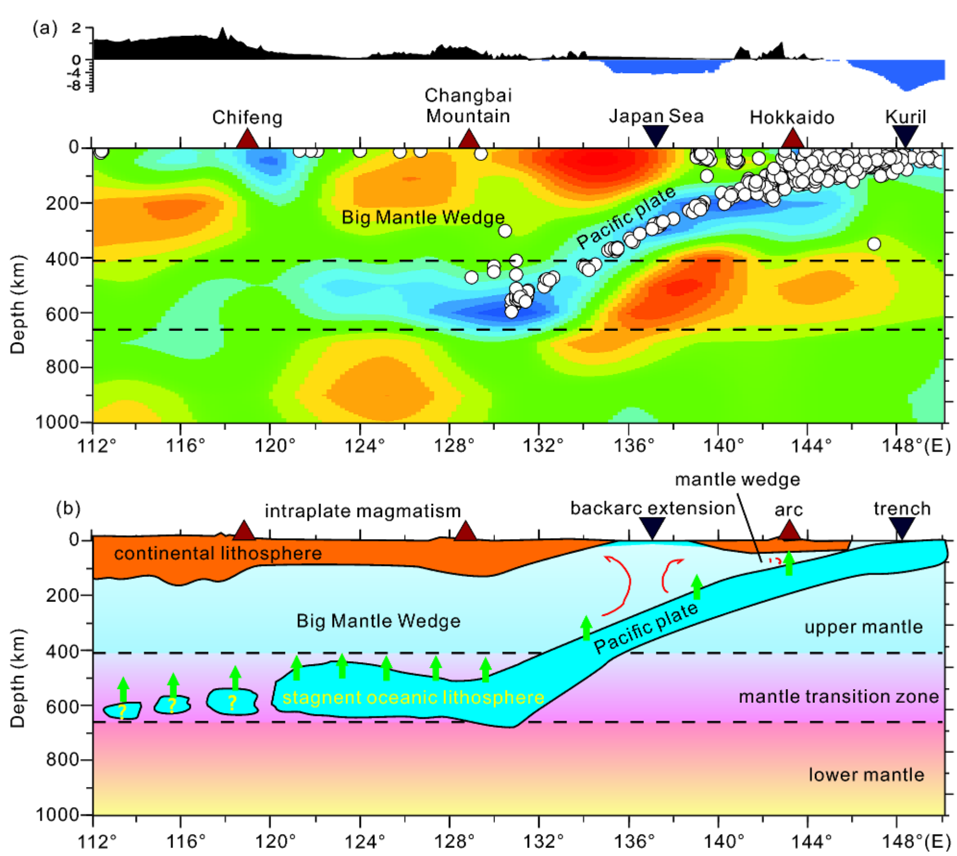

Figure 1 The Big Mantle Wedge (BMW) under eastern Asia. (a) Seismic tomographic images (modified after Huang and Zhao, 2006); (b) cartoon illustrating the difference between BMW and small mantle wedge (modified after Zhao and Tian, 2013).

the composition of and geodynamic processes within the BMW system.

The wide-spread Cenozoic basalts in eastern China are traditionally interpreted as a result of back-arc extension related to the westward subduction of the Pacific plate underneath east Asian continental margin. In terms of petrology and geochemistry, these basalts are classified as typical intraplate magmas. Nevertheless, a number of questions remain to answer. Why do these basalts have compositions similar to oceanic island basalts (OIB) despite their occurrence in a continental setting? Isotopically, why do they exhibit an Indian Mantle signature despite their location in the Pacific tectonic realm? What is the mechanism by which the subduction of the Pacific plate transports surface materials into the BMW system? How are recycled materials involved in mantle metasomatism and in magma generation? Given the stagnant slabs within the MTZ under eastern China, Cenozoic basalts in this region are most likely derived from the BMW rather than from the lower mantle. Consequently, they must retain important information regarding the composition and chemical heterogeneity of the BMW.

Recent studies on Cenozoic basalts from eastern China provide insights into these long-lasting questions. Zhao et al. (2004) first proposed that the Changbai volcano was triggered by hydration of the BMW by water released from stagnant slabs within the MTZ. This hydration model has been subsequently applied to Cenozoic mantle-derived magmas in the entire east Asian continental margins (Niu, 2005; Ohtani and Zhao, 2009). Petrochemical analyses and isotopic tracing further identify several particularities of the mantle rocks from this region. Liu et al. (2015a) and Chen et al. (2015) found that H_2O contents in some Cenozoic basalts from eastern China are as high as in typical island arc magmas. In addition, recycled oceanic crustal components are identified in the source of late Cretaceous-Cenozoic basalts (Zhang et al., 2009; Xu Y G et al., 2012; Xu, 2014; Li et al., 2014; Li H Y et al., 2017). These rocks are also characterized by light Mg isotopic compositions compared to the normal mantle values, which has been attributed to recycled sedimentary carbonates (Yang et al., 2012; Huang et al., 2015; Liu S A et al., 2016; Li S G et al., 2017) transported to the deep mantle by subduction. Moreover, the subduction of the Pacific plate is considered as the principle trigger of the destruction of the North China Craton (Zhu et al., 2012). All these new results highlight the important role of the BMW system in the genesis of intraplate basalts and perhaps in the operation of global tectonic system.

This paper reviews recent progresses made in this field, with emphasis being placed on identification of recycled components in basalt source, and on constraining their origins. Various lines of observations and information will be integrated to formulate a new model accounting for the generation of intraplate magma in a BMW system.

2. Composition of the BMW beneath East Asia and related recycling processes

The stagnation of subducted slabs within the MTZ suggests that the subduction of west Pacific Plate transported huge amount of sediment, oceanic crust and lithosphere into the upper mantle beneath eastern Asia. It has been estimated that annual input of sediments to the mantle via subduction is 2.5 km^3, of which the input by northwest Pacific subduction system occupies about 1/3 (Stern and Scholl, 2010). It can therefore be imagined that the BMW beneath eastern Asia contains huge amount of recycled oceanic crust, sediment, water and carbonate and their derivatives, and these recycled components may have exerted critical effects on dynamic system of the BMW and mantle melting/metasomatism. Below summarizes the progresses made by geochemical tracing in identifying components in the BMW beneath eastern Asia.

2.1 Recycled oceanic crust components in the BMW beneath eastern Asia

Although Pacific subduction has long been invoked as the trigger of post-Mesozoic geologic evolution and magmatism in eastern Asia, material evidence for its involvement in regional geologic evolution is not confirmed until recent years. The main evidences include:

(1) Cenozoic basalts from eastern China display geochemical characteristics very similar to OIB (Figure 2a), including remarkable depletion of highly incompatible elements like Rb, Ba, Th and U relative to Nb and Ta, negative anomalies of Pb and K, OIB-like Nb/U and Ce/Pb ratios (which are indicative of dehydrated oceanic crust) (Zhang et al., 2009; Xu Y G et al., 2012; Xu Z et al., 2012).

(2) Fe/Mn ratios of Cenozoic basalts from eastern China are higher than mid-ocean ridge basalts (MORB) (Figure 2b). Some basalts, such as Eocene basalts from Shuangliao, have Fe_2O_3 reaching 13.4–14.6%, resembling that of the classic HIMU basalts at given MgO contents (Chauvel et al., 1992).

(3) In the plot of Sr-Nd isotopes (Figure 2c), the majority of Cenozoic basalts from eastern China delineates a negative correlation, reflecting a mixing between a depleted mantle component and two enriched components (EM1 and EM2). The enriched components could be derived from asthenosphere, lithospheric mantle and crustal contamination (Zhou and Armstrong, 1982; Peng et al., 1986; Zhi et al., 1990; Xu et al., 2005). Of particular is the positive Sr-Nd isotopic correlation defined by the Shuangliao basalts (Figure 2d), which strongly argues against crustal contamination. The Shuangliao basalts show positive Eu, Sr, Nb and Ta anomalies, and depletion in very incompatible elements (Rb, Ba, Th, U, K), reminiscent of HIMU-type OIBs which

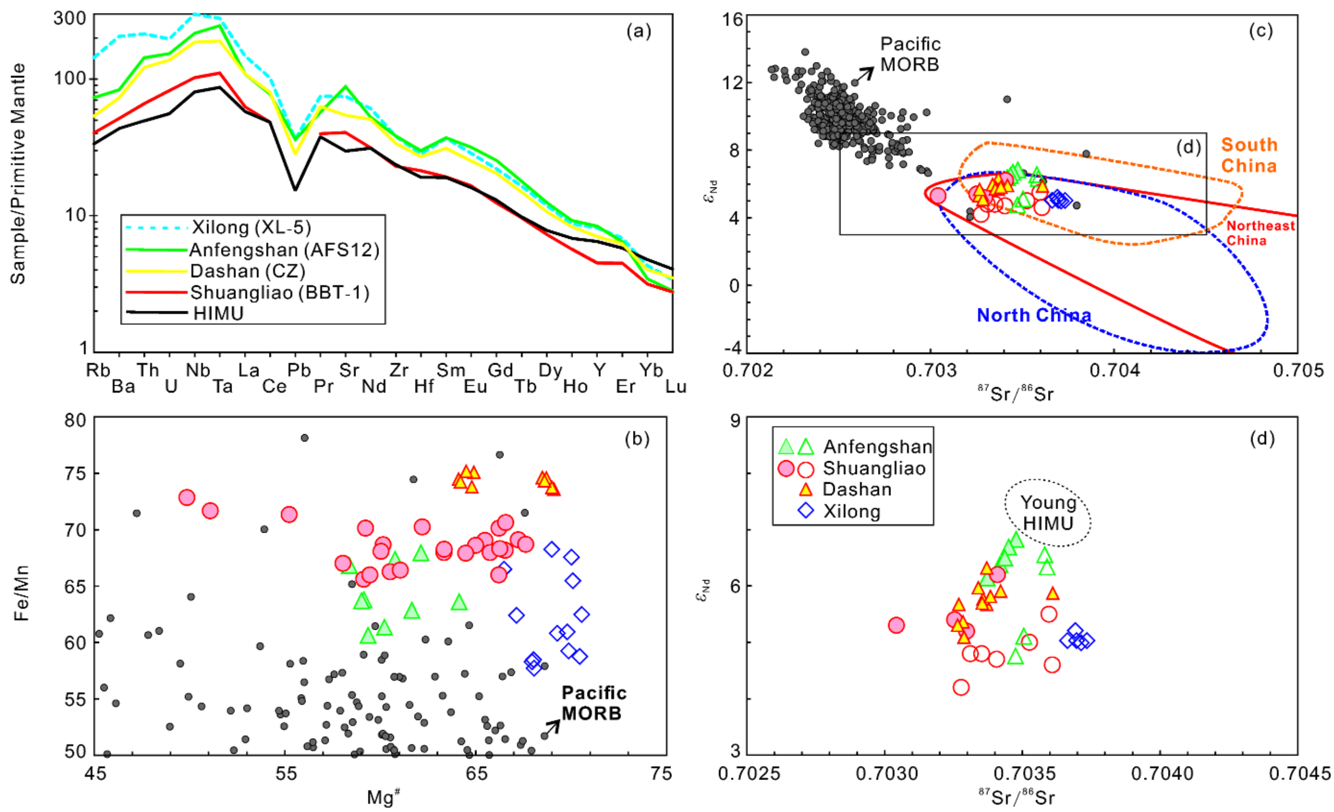

Figure 2 (a) Trace element spiderdiagram of representative basalt samples from eastern China; (b) Fe/Mn versus MgO; (c), (d) whole rock Sr-Ndisotopic correlation. Data of basanite and nephenlite: Shuangliao (Xu Y G et al., 2012); Dashan (Sakuyama et al., 2013; Li et al., 2016a; Zhang J B et al., 2017); Xilong (Liu S C et al., 2016); Anfengshan (Chen et al., 2009). Data for Pacific MORB from PetDB (http://www.earthchem.org/petdb), HIMU basalt is the average of St. Helena basalts (Willbold and Stracke, 2006).

contain recycled altered oceanic crust (Hofmann and White, 1982; Chauvel et al., 1992). It is worthwhile pointing out that the Shuangliao basalts have $^{206}Pb/^{204}Pb$ (18.13 to 18.39) lower than typical HIMU basalts (>20), suggesting a young recycled oceanic component in the source (Thirlwall, 1997; Xu Y G et al., 2012). To account for the relationship between ε_{Nd} and Ba/Nb, a young HIMU component (represented by high ε_{Nd} Shuangliao basalt) and a component derived from mixing of the depleted mantle end-member and EM1 are required (Figure 2d). The latter one is garnet pyroxenite component which will be discussed in subsequent sections.

(4) The oxygen isotopic composition of mantle peridotites is very homogeneous (Mattey et al., 1994). However, the lower and upper oceanic crust show $\delta^{18}O$ values lower and higher than the normal mantle, respectively (Gregory and Taylor, 1981). Hence, oxygen isotopic compositions of phenocrysts in basalt represent a viable means to identify recycled components in basalt source (Eiler, 2001). $\delta^{18}O$ values of phenocrysts of olivine, clinopyroxene and plagioclase in Cenozoic basaltic lavas from Shangdong, Northern Jiangsu and Northeastern Anhui (Xu Z et al., 2012) are less than the mantle values, implying subducted oceanic crust in magma source, which has been subjected to metamorphic dehydration and high-temperature water-rock interaction. $\delta^{18}O$ of clinopyroxene phenocrysts of 106 Ma to 60 Ma in the North China Craton are found to be higher than those of clinopyroxene phenocrysts in MORB (Liu J et al., 2017). Such oxygen isotopic compositions are attributable to recycled, altered upper oceanic crust (Liu J et al., 2017).

(5) Composition of olivine phenocryst in basalt can be used to characterize source mineralogy (Sobolev et al., 2005; Herzberg, 2011). Since partitioning of Ni in olivine is much higher than in pyroxene, olivines crystallized from melts derived from pyroxenites and peridotites may have significantly different Ni contents. Sobolev et al. (2007) found that olivines from picrites of many large igneous provinces have Ni contents higher than those from MORB, and postulated that the source of mantle plume contains variable amount of pyroxenites produced by interaction between recycled oceanic crust-derived melts and peridotites. Compared with olivine phenocrysts in MORB, those of Cenozoic basalts from eastern China have higher Ni contents and Fe/Mn ratios and lower Ca and Mn contents (Figure 3a), implying a dominant pyroxenitic source. The melt inclusions hosted in high-Mg olivines show low CaO contents; in the CS-MS-A diagram, all the high MgO melt inclusions (MgO>6.0 wt.%) project in the field between garnet (Gt) +clinopyroxene (Cpx)-liquid (L) and Gt+Cpx+orthopyrox-

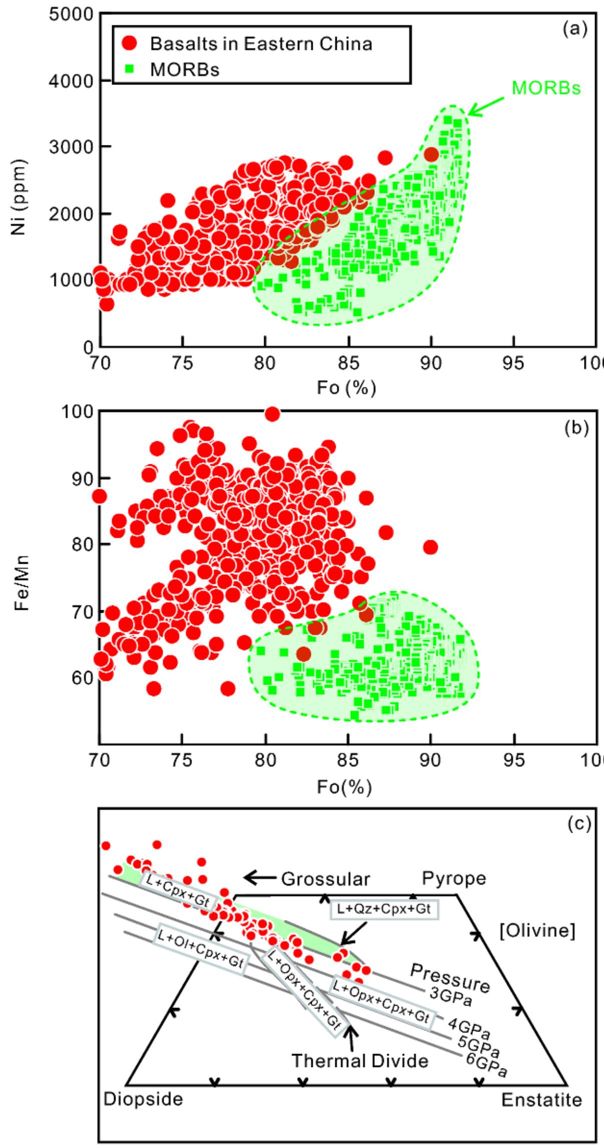

Figure 3 (a), (b) Composition of olivine phenocrysts from Cenozoic basalts in eastern China, (c) composition of melt inclusions hosted in olivine phenocrysts.

ene (Opx)-L near 3.0 GPa, further suggesting that residual minerals are mainly garnet and clinopyroxene (Hong et al., 2013). Nevertheless, a few melt inclusions are plotted along the L+Ol+Cpx+Gt line at 3.0 GPa, indicating minor olivine residues in the source. Although it is hard to define the origin of these pyroxenites, according to their whole rock chemical and isotopic compositions, they most likely represent secondary reactive pyroxenites formed by interaction between recycled oceanic crust-derived melts and peridotites.

2.2 Water in the BMW under eastern Asia

2.2.1 Water in the sub-lithospheric mantle

Water in the upper mantle can be directly determined by nominally anhydrous minerals in mantle peridotites. The water distribution in the sub-lithospheric mantle under eastern China has been constrained by studies on the peridotite xenoliths carried in the Late Cretaceous-Cenozoic basalts (Xia et al., 2010, 2013; Hao et al., 2012, 2016a, 2016b; Li Y Q et al., 2015). Figure 4 shows that the water contents in the sub-lithospheric mantle beneath the eastern China are highly heterogeneous. Water contents of the sub-lithospheric mantle beneath North and Northeast China are extremely low (34±34 and 47±32 ppm, 1 ppm=1 mg L^{-1}, respectively), compared to those beneath the typical cratons and off-craton (119±54 and 78±45 ppm, respectively). In particular, the sub-lithospheric mantle beneath the northern part of the Northeast China is virtually anhydrous (~0 ppm). The sub-lithospheric mantle beneath the South China has relatively high water contents (90±45 ppm).

Xia et al. (2010) proposed that during the thinning of the North China Craton, its sub-lithospheric mantle was baked from below by the upwelling asthenosphere, resulting in the loss of water. Following this hypothesis, they further deduced that the sub-lithospheric mantle beneath North and Northeast China could be the remnants of ancient cratonic lithosphere (Xia et al., 2010; Hao et al., 2016b). However, this conclusion conflicts with the cognition built on the petrography, geochemistry and Re-Os isotope of the mantle xenoliths, which have shown that the ancient lithospheric mantle survives only in the western part (including the Hebi area) of the North China (Xu et al., 2008; Gao et al., 2002; Wu et al., 2003, 2006; Liu et al., 2011; Hong et al., 2012; Chu et al., 2009). Additionally, the lithospheric mantle beneath the oceanic islands heated by the anomalously hot mantle plume contains some water (e.g., 50–90 ppm H_2O in the Hawaiian lithospheric mantle; Peslier and Bizimis, 2015). Although heated by super mantle plumes for a long time, the lithospheric mantle under South Africa Craton and the Massif Central in France have water contents higher than that under North and Northeast China. These observations suggest that the dry lithospheric mantle under North and Northeast China cannot be due to the baking by upwelling asthenosphere. Alternatively, the dryness of the peridotite xenoliths reflects the nature of a newly accreted lithospheric mantle. The transformation from asthenospheric mantle to lithospheric mantle often accompanies with low degree of partial melting. This process would result in extremely low water in the lithospheric mantle, because of the high incompatibility of water ($D^{\text{peridotite/melt}}$=0.005–0.009; Hirschmann et al., 2009). For example, <3% degrees of partial melting of the asthenospheric mantle (H_2O=~120 ppm; Salters and Stracke, 2004) would have only <20 ppm H_2O. The poor water of the lithospheric mantle, on the other hand, indicates that the released water from the stagnant slabs in the mantle transition zone may not influence the shallow lithospheric mantle, probably due to the long distance and high reactivity of water.

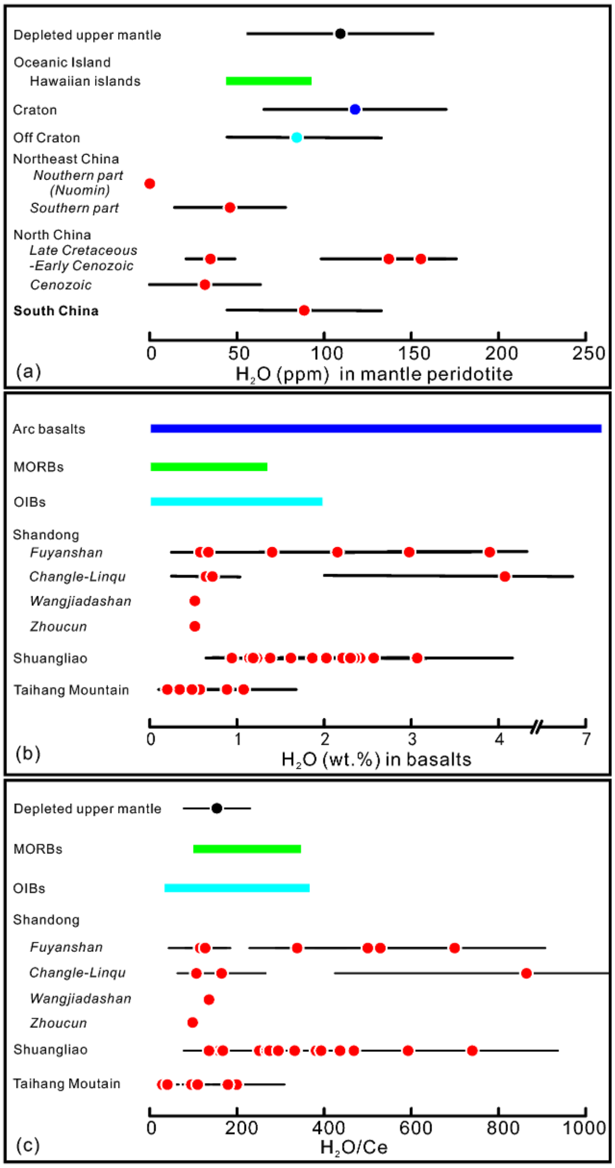

Figure 4 Water contents of peridotite xenoliths (a), Cenozoic basalts (b) and H_2O/Ce ratios (c) in eastern China. Data sources for peridotite xenoliths: Craton and Off Craton (Xia et al., 2010); Hawaiian islands (Peslier and Bizimis, 2015); Depleted upper mantle (Salters and Stracke, 2004); Northeast China (Hao et al., 2016b); Late Cretaceous-Early Cenozoic in North China (Li P et al., 2015); Cenozoic in North China (Xia et al., 2010); South China (Hao et al., 2016b). Data sources for water and H_2O/Ce in basaltic lavas: Mid oceanic ridge basalts (MORBs), PETDB database; Oceanic island basalts (OIBs), Georock database; Shandong (Liu et al., 2015a; Xu, 2014; Hong et al., unpublished data); Taihang Mountain (Liu et al., 2015b); Shuangliao (Chen et al., 2015).

2.2.2 Water contents in the asthenospheric mantle

The water contents of the asthenospheric mantle can be estimated by its partial melts and by geophysical approaches. Studies on water contents in clinopyroxene phenocrysts have shown that Cenozoic basalts in eastern China have highly variable water content; some are comparable to arc basalts (Figure 4b; Liu et al., 2015a, 2015b; Chen et al., 2015). The water contents in basalts are controlled by many factors, including components in mantle source and degree of partial melting. For example, the Shuangliao basanites and tholeiites that were formed via low and high degree of partial melting, respectively, have >3 wt.% and ~1 wt.% H_2O, respectively (Chen et al., 2015). The heterogeneity of the mantle source renders large uncertainties with estimation of the degree of partial melting, and this in turn hampers any convincing result of water contents in the mantle source. Because H_2O and Ce have comparable partition coefficients, partial melting and crystal fractionation cannot fractionate H_2O from Ce. Accordingly, the H_2O/Ce ratios of basalts can be considered as those in their source. Applying the H_2O/Ce ratios of basalts, together with other geochemical index, to trace mantle materials in the source, provides an alternative approach to constrain water contents of mantle materials (Dixon et al., 2002). For example, the co-variations between H_2O/Ce and other geochemical index (Ba/Th, Eu^*, Ce/Pb and O isotopes) suggest that the recycled oceanic crust has low H_2O/Ce ratios ($H_2O/Ce<200$; Liu et al., 2015a, 2015b; Chen et al., 2015). If this is correct, given the mature oceanic crust with ~6 ppm Ce and ~2–3 wt.% H_2O (Dixon et al., 2002), and the 50% mobility of Ce during subduction (Kogiso et al., 1997), we can estimate ~3 ppm Ce and < 600 ppm H_2O for the recycled oceanic crust. So the recycled oceanic crust in basalt source may have been strongly dehydrated.

As shown in Figure 4c, some basalts in eastern China have H_2O/Ce up to 800 (Liu et al., 2015a; Chen et al., 2015), much higher than the asthenospheric mantle (150±78; Salters and Stracke, 2004). This suggests that there must be a relatively water-rich component in the mantle source. Based on Ba/Th, Ce/Pb and O isotopic compositions, this water-rich component is suggested to be recycled sediments (Chen et al., 2015; Liu et al., 2015a). Nevertheless, the Shuangliao basalts have high H_2O/Ce ratios but depleted Sr-Nd isotopes, ruling out significant amount of recycled sediments in magma source. The high water contents of Cenozoic basalts in eastern China therefore are not related to recycled sediments. In addition, the basalts with high H_2O/Ce ratios have Ba/Th close to 110, and for the higher Ba/Th basalts, the H_2O/Ce ratios gradually decrease (Hong et al., in preparation), also arguing against the contribution of recycled sediments. Here, we propose two other possibilities. (1) High H_2O/Ce features may be related with incompletely dehydrated recycled oceanic crust. The Shuangliao basanites have slightly positive Eu anomalies, suggesting their source contain recycled cumulate gabbro (Xu Y G et al., 2012). The gabbro was located in the lower part of the oceanic crust and thus within the interior of the subducted plate, preventing from complete dehydration during subduction (van Keken et al., 2011). (2) The water-rich component in the basalt source may be peridotite from the MTZ modified by fluid/melt released from the stagnant slabs. In this schema, their high H_2O/Ce features inherit from the peridotite in the MTZ which has high water content and hard to be modified, whereas other geochemical features could result from modification of recycled materials during geological processes.

It is worth pointing out that not all the Cenozoic basalts in the eastern China have high water contents; some of them have low water contents comparable to the MORBs (Figure 4b). We measured the water contents of the olivine-hosted melt inclusions from Shandong and Chifeng Cenozoic basalts. The results show that all the melt inclusions have <1 wt.% H_2O. We consider that the lack of high water melt inclusions may be due to either water loss of melt inclusions via diffusion or biased sampling.

Water in the upper mantle can also be constrained by deep electrical conductivity. Karato (2011) detected electrical conductivity of the global mantle, revealing the highest values for the deep mantle (250–600 km) beneath eastern China. He also found that the electrical conductivity of the shallow mantle (100–250 km) beneath eastern China is lower than the average of global mantle. Given the experimental observations that hydrous peridotites have much higher electrical conductivity than anhydrous ones, the variable electrical conductivity might reflect vertical variation of water contents in the upper mantle beneath eastern China (Ichiki et al., 2006; Karato, 2011). As claimed by Karato (2011), the MTZ beneath eastern China contains a huge amount of water. This is consistent with the inference that the MTZ is potentially a large water reservoir (Hirschmann, 2006), and the observation that the subducted oceanic crust stagnates in the MTZ under eastern Asia (Huang and Zhao, 2006). Based on the electrical conductivity values, Ichiki et al. (2006) estimated > 500–1000 ppm H/Si within the upper mantle beneath eastern China. It is necessary to point out that such estimation only counts the effect of water on electrical conductivity of the mantle but ignores the role of other factors such as CO_2 (Gaillard et al., 2008). As a result, large uncertainty exists as to water content estimation based on electrical conductivity of the mantle.

2.3 Recycled sedimentary carbonates or carbonated peridotite in the BMW under eastern Asia

In most cases, carbonates carried by subducting slab would cumulate, melt and metasomatize the upper mantle at depths of 300–700 km near the MTZ. They cannot penetrate through the MTZ into the lower mantle. Hence deep carbon cycling most likely only occurs in the upper mantle (Thomson et al., 2016). In this sense, carbonates may represent the dynamic link between stagnant Pacific slab within the MTZ and the heterogeneity of the BMW beneath eastern Asia. Several lines of geochemical evidence are now available for abundant recycled carbonates in the BMW under eastern Asia.

(1) The spider-diagram of highly alkaline basalts such as that from Dashan in Shandong Province is characterized by negative anomalies of K, Pb, Zr, Hf and Ti, very similar to igneous carbonatites. Meanwhile these rocks have low SiO_2 and Al_2O_3 but high CaO contents, resembling low degree melts of carbonate-bearing peridotites. Based on these characteristics, Zeng et al. (2010) proposed that high alkaline basalts may have been derived from a carbonate-bearing peridotite source. This was followed by Sakuyama et al. (2013) who suggested that the strong alkali basalts from Shandong were originated from melting of carbonate-bearing Pacific slabs stagnant within the MTZ. On the basis of a study on melt inclusions, Li et al. (2016a) constrained the composition of primary magmas of the strong alkali basalts from Shandong and compared them with experimental results. They concluded that the primary magmas were derived from melting of carbonated peridotites and eclogites.

(2) Li Shuguang's group has carried out intensive Mg isotope measurements on intraplate basalts from east Asian continental margins and some basalts from circum-Pacific arcs (Li S G et al., 2017). They show that the Late Cretaceous and Cenozoic continental basalts from eastern China have low δ^{26}Mg isotopic compositions, and outline a large-scale mantle low in δ^{26}Mg in eastern China, ranging from Wudalianchi in Heilongjian Province in north to Hainan Island in south. Since recycled sedimentary carbonate through plate subduction is the main light-δ^{26}Mg reservoir within deep Earth and does not fractionate Mg isotopes during subduction, the observed low δ^{26}Mg anomaly in basalts is largely attributed to the contribution of sedimentary carbonates recycled into the upper mantle, but limited into the lower mantle (Yang et al., 2012; Huang et al., 2015). However, sedimentary carbonates also have relatively high ^{87}Sr/^{86}Sr (0.706–0.730), in contrast with depleted Sr isotopic compositions of the Cenozoic basalts (0.706–0.730). A possible explanation for this is that selective dissolution process of carbonates may result in the removal of most of the Ca-rich carbonates from, and leaving Mg-rich carbonates in, the subducting slabs (Huang and Xiao, 2016). Under high pressure, dolomite and magnesite become stable such that the proportion of Mg-rich carbonate retained in the subducted slabs and carried into the deep mantle could be significant (Li S G et al., 2017). Sr in magnesite is low (~1.84 ppm) so its effect on the mantle source is insignificant (Huang and Xiao, 2016). Alternatively, carbonates may be derived from carbonate vein in oceanic crust basalts (Li H Y et al., 2017). Given the similar Sr contents, in carbonatite vein (~100 ppm; Kelley et al., 2003) and MORB (~130 ppm; Gale et al., 2013), carbonate would melt first and extract Sr from eclogite. Since silicate melts have similar partition coefficients of trace elements (except for Zr-Hf-Ti; Dasgupta et al., 2009), the initial melts generated in this way fits that of nephelinite from Dashan, Shandong Province (0.703−0.704;

Zeng et al., 2011; Li et al., 2016a). Recently discovered carbonatite inclusions in peridotite xenoliths in Shandong Cenozoic basalts show relatively depleted Sr isotopic composition (~0.703; Deng et al., 2017), similar to the Dashan nephelinite.

(3) The carbonatitic source for the Cenozoic basalts is further supported by Zinc isotopic analyses. Liu S A et al. (2016) found that all of the basalts with ages of <110 Ma have systematically heavy δ^{66}Zn ranging from 0.30‰ to 0.63‰ compared to the mantle (0.28±0.05‰). Given the limited Zn isotope fractionation (≤0.1‰) during magmatic differentiation and the heavy δ^{66}Zn of sedimentary carbonates (δ^{66}Zn=~0.91‰), the elevated δ^{66}Zn values thus reflect the involvement of carbonates in the mantle source. The relatively high Zn concentration in Cenozoic basalts in eastern China is attributable to the presence of magnetite or dolomite in the source which has higher Zn contents than other low-pressure facies carbonates. Therefore, Zinc isotopes and concentration of Cenozoic basalts from eastern China indicate the widespread presence of recycled carbonates in the mantle beneath eastern China, which is possibly linked to subduction of the west Pacific plate during the Late Mesozoic to Cenozoic. The recycled carbonates are mainly composed of Mg and Zn enriched species (e.g., magnesite ±dolomite), in good agreement with the conclusions reached on the basis of Mg isotopes.

2.4 Roles of H_2O and CO_2 in the BMW under eastern Asia

As mentioned above, there are abundant recycled materials in the BMW under eastern Asia, including oceanic crust, water and sedimentary carbonates. These components played important roles in crust-mantle interactions in the BMW system. Which is more important, H_2O or CO_2, in the dynamic and melting processes in the BMW system? The role of CO_2 is emphasized here over H_2O, given the following considerations.

(1) Not all Cenozoic basalts from eastern China have high water contents. However, almost all the basalts show light-Mg isotopes and heavy-Zn isotopes, indicating a ubiquitous sedimentary carbonate-bearing source.

(2) The water contents in peridotite xenoliths are extremely low (Xia et al., 2013), suggesting that the lithospheric mantle was not significantly metasomatized by water. Deng et al. (2017), on the other hand, have identified carbonatite inclusions in peridotite xenoloths captured by Cenozoic basalts from Shandong, indicating that carbonatite metasomatism is not only confined to the asthenosphere, but also extended to the shallow lithospheric mantle.

(3) Although it is widely believed that the high electrical conductivity of the upper mantle beneath eastern China is due to hydrous olivines, the effect of carbonatitic peridotites cannot be ignored. Gaillard et al. (2008) have demonstrated through experiments that the electrical conductivity of molten carbonatite is higher by 10^5 times than that of hydrous olivines. Consequently, minor pervasive CO_2 could account for the high electrical conductivity of the upper mantle beneath eastern China. This model overcomes the difficulty encountered by the hydrous mantle model because of the unrealistic amount of H_2O requested to account for the measured electrical conductivity. The hydrous mantle model is also questioned by the anisotropy study. Jung and Karato (2001) suggested that the presence of H_2O enhances the anisotropy of the mantle. However, Yang (2012) found no correlation between electrical conductivities of olivines along different preferred orientation of 001, 010 and 100 and water contents.

3. The chemical heterogeneity of the BMW beneath Eastern Asia

3.1 Binary mixing model for Cenozoic basalts from the East China

Li H Y et al. (2016a, 2016b, 2017) carried out systematic investigations on whole rock geochemistry and melt inclusion in olivine phenocryst of the basalt erupted after 23 Ma in eastern North China. Since the composition of the basalts is highly related to the SiO_2 content, three groups, namely low-Si (SiO_2<42%), moderate-Si and high-Si (SiO_2>45%) basalts are distinguished. They found that the basalts in eastern North China represent mixture of two melt end-members, and their chemistry and recycled materials in their source are in close relationship with their SiO_2 contents (Figure 5).

As shown in Figure 5, the low-Si basalts have high alkali contents, CaO, FeO^T and TiO_2, whereas the high-Si basalts show the opposite. The moderate-Si basalts show features suggesting a mixture of the low-Si and high-Si end members (Li et al., 2016a). Moreover, the high-Si basalts have low trace element concentrations, low La/Yb, Sm/Yb and Ce/Pb but high Ba/Th ratios, low ^{176}Hf/^{177}Hf, ^{143}Nd/^{144}Nd and ^{206}Pb/^{204}Pb but high ^{87}Sr/^{86}Sr ratios, delineating EM1 type trace element and radiogenic isotopic features. In addition, they have relatively high δ^{11}B (−4.9‰ to −1.4‰) and Hf-Nd isotopes resembling the Indian Ocean mantle signature. The low-Si basalts show HIMU (high U/Pb) type trace element patterns, but with lower ^{206}Pb/^{204}Pb ratios than typical HIMU basalts. They have lower δ^{11}B (−6.9‰ to −3.9‰) than that of high-Si basalts, and have Hf-Nd isotopes with affinities of the Pacific mantle signature (Figure 6). Collectively, Sr-Nd-Hf-B isotope compositions suggest that the source of the high-Si basalts has recycled sediments together with altered oceanic crust or lithospheric mantle with old ages (>1 Ga), whereas that of the low-Si basalts has recycled Pacific

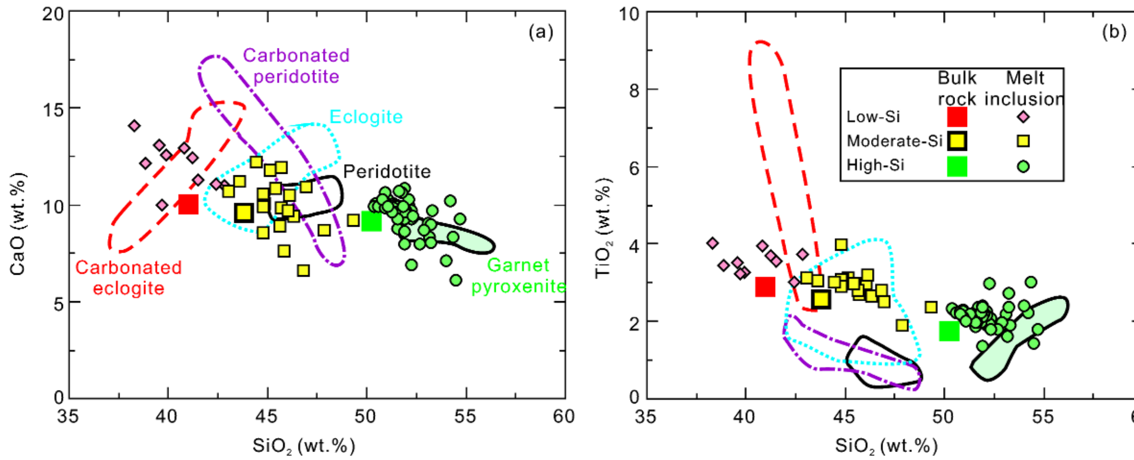

Figure 5 Chemistry of olivine hosted melt inclusions for Cenozoic basalts from Shandong (Li et al., 2016a). Experimental results: Garnet Pyroxenite, 3.5 GPa, Px-1 (Sobolev et al., 2007); Carbonated Eclogite, 3.0 GPa, SLEC1+5.0 wt.% CO_2 (Dasgupta et al., 2006); Peridotite, 2.5–3.0 GPa, HK-66 and KLB-1 (Hirose and Kushiro, 1993); Carbonated Peridotite, 3.0 GPa, KLB-1+1.0% CO_2 (Dasgupta et al., 2007); Eclogite, 2.0–5.0 GPa, KLB-1+MORB (Kogiso et al., 1998); MIX1G (Hirschmann et al., 2003); BECL (Kogiso and Hirschmann, 2006).

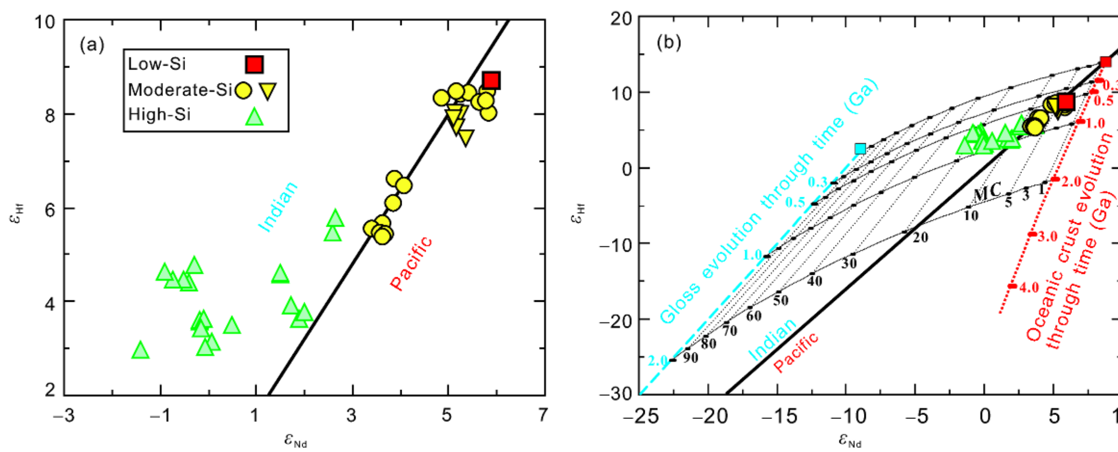

Figure 6 Hf-Nd isotope compositions for Cenozoic basalts from Shandong. Data from Zeng et al. (2011) and Li et al. (2016a). Numbers marked on the mixing curves (MC) represent the sediments proportions in percentage. The boundary of Hf-Nd isotopic composition between the Indian and Pacific Ocean mantle domains is from Pearce et al. (1999).

mantle components. These imply the upper mantle beneath eastern North China has experienced multiple enrichment events (Li et al., 2016b).

In order to further test whether this model could apply to the origin of Cenozoic basalts from the entire Eastern China region, we compile the data of Cenozoic basalts from Northeast China, North China and South China, which are illustrated in Figure 7.

(1) There is a clear negative correlation between Si and Fe contents in Cenozoic basalts from the entire Eastern China (Figure 7a), which can be interpreted as a result of binary mixing involving high-Si and low-Si basalt end-members. Except for ultrapotassic basalts from northeast China, all the basalts from eastern China, no matter erupted in North China, Northeast China or South China, share a common low-Si component. However, their high-Si components show diversity for different regions (Figure 7b–f). The high-Si component for North China has low $^{143}Nd/^{143}Nd$ and $^{206}Pb/^{204}Pb$ ratios similar as EM1 component, whereas that of South China presents moderately low $^{143}Nd/^{143}Nd$ and high $^{206}Pb/^{204}Pb$ ratios comparable to EM2 component, in good agreement with the observation of Zou et al. (2000). Both EM1 and EM2 components are observed in the basalts from Northeast China.

(2) The high-Si component in basalts from North China, especially those from Northeast China, shows variable Ba/Th ratios, possibly resulted from different proportions of EM1 and EM2 components involved or heterogeneous slabs which experienced variable extent of dehydration.

(3) Ultrapotassic basalts from Northeast China show compositional patterns which are significantly different from Na-series basalts, implying their distinct and complex petrogenesis. For this reason, they are not considered further in this paper.

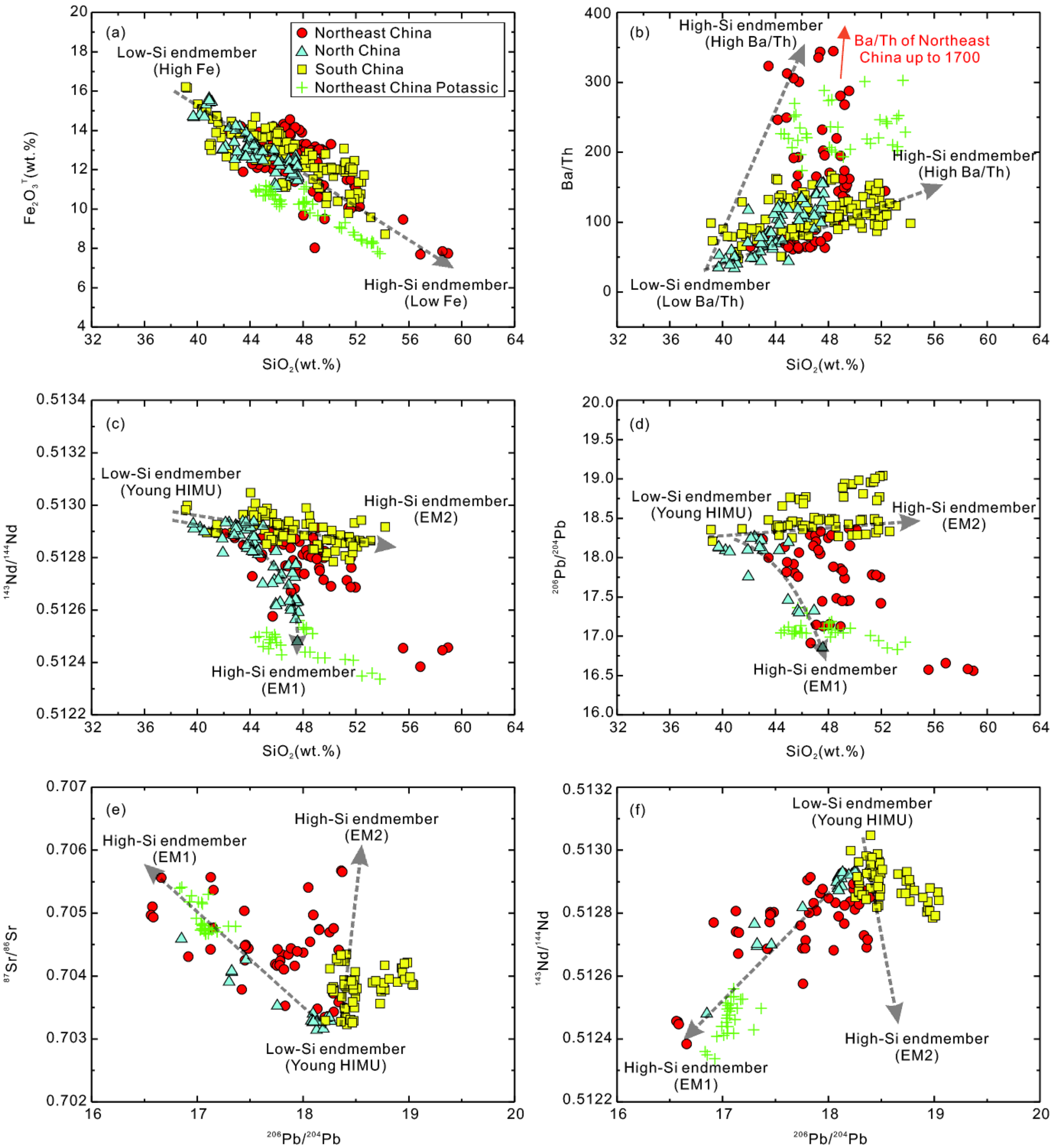

Figure 7 $Fe_2O_3^T$ (a), Ba/Th (b), $^{143}Nd/^{144}Nd$ (c) and $^{206}Pb/^{204}Pb$ (d) versus SiO_2, and $^{87}Sr/^{86}Sr$ (e) and $^{143}Nd/^{144}Nd$ (f) versus $^{206}Pb/^{204}Pb$ correlations for basalts from eastern China. Data Source: Northeast China (Xu Y G et al., 2012; Zhang et al., 2006; Qin et al., 2008; Kuang et al., 2012); North China (Qian et al., 2015; Li S G et al., 2017; Zeng et al., 2010, 2011; Xu Z et al., 2012; Sakuyama et al., 2013); South China (Huang et al., 2013, 2015; Li et al., 2015; Li S G et al., 2017; Zeng et al., 2017; Liu S C et al., 2016; Yu et al., 2015, 2017); K-rich basalts (Liu J Q et al., 2017; Wang et al., 2017).

3.2 Source characteristics of the high-Si and low-Si basalts

Olivine phenocrysts in the high-Si basalts have higher Ni and lower Mn and Ca contents than those crystallized from melts of peridotitic mantle source (Figure 8), being consistent with a garnet pyroxenitic source (Herzberg, 2011), whereas those in low-Si basalt show lower Ni but higher Mn contents, and have lower Ca contents under high Fo condition, all pointing to a pyroxene-rich mantle source (pyroxene-rich peridotitic

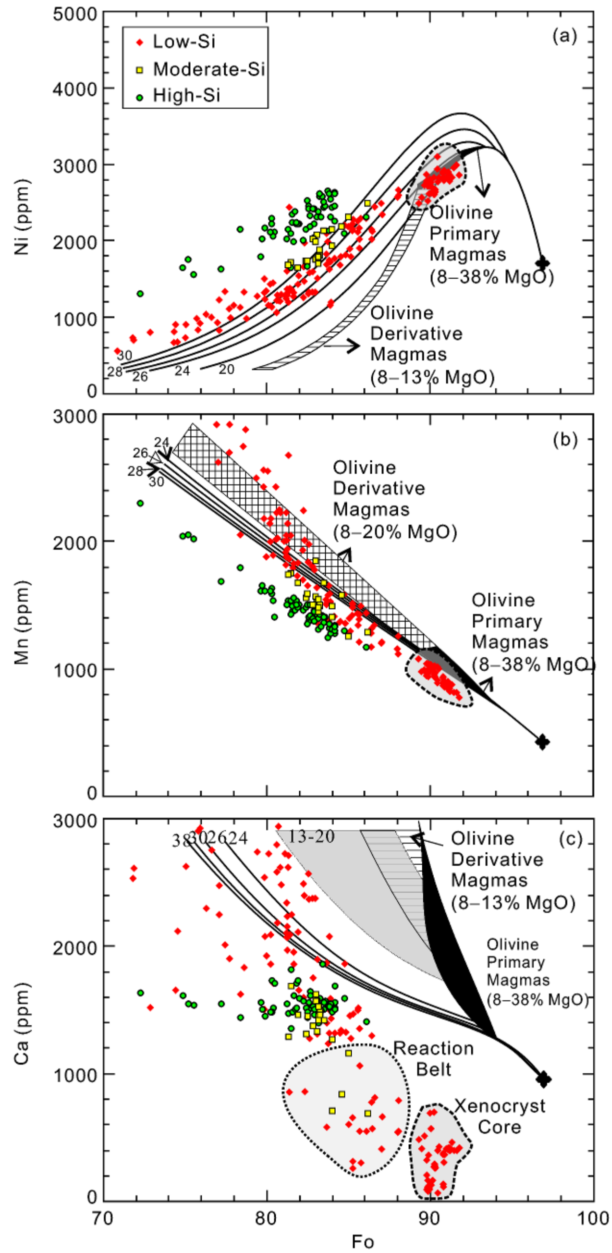

Figure 8 Compositions of olivine for Cenozoic basalts from Shandong (Li et al., 2016a). The compositions of olivines crystallized from peridotite melts are after Herzberg (2011).

mantle or olivine-rich pyroxenitic mantle). Melt inclusions hosted in olivine in high-Si basalt have relatively low CaO and high SiO_2 contents, in agreement with a garnet pyroxenitic source generated by melt-peridotite reaction (Sobolev et al., 2007). In contrast, melt inclusions hosted in olivine in low-Si basalt have relatively low SiO_2 and high CaO. The low-Si basalts might be derived from a carbonated eclogitic source, judging from the correlation between SiO_2 and CaO. However, the fact that their TiO_2 contents are lower than those from pure carbonated eclogitic source but higher than those from pure carbonated peridotites (Figure 5) indicates the source is most likely a hybrid of these two types of lithology. Therefore, the source of the high-Si basalts with EM1-type elemental and isotopic characteristics is a garnet pyroxenite while that of low-Si basalts with HIMU type trace elemental signature is a hybrid of carbonated eclogite and peridotite (Figure 5).

Major element composition and olivine chemistry of the high-Si basalts and the low-Si basalts are similar and characterized by low CaO and $Fe_2O_3^T$ but high SiO_2 contents (Figure 7a; Liu et al., 2015). In addition, olivines in these basalts exhibit low Ca and Mn contents coupled with high Ni contents (Liu et al., 2015). These characteristics imply that the mantle source of EM2-type high-Si basalts is similar as EM1-type ones, both of which are garnet pyroxenite (Liu et al., 2015). The different trace elemental and isotopic characteristics between EM1 and EM2 type high-Si basalts are interpreted as involvement of variable recycled sediment in the source. Small amount of recycled sediment cannot significantly modify the petrology of the mantle source.

4. Origin of recycled components in and vertical heterogeneity of the BMW under eastern Asia

4.1 Residence depths of recycled components

The residence of recycled crustal components in the BMW is a fundamental issue. It can be constrained through geochemical study of intraplate basalts which carry a wealth of information about the composition and melting depth of their mantle source rocks.

(1) Experiments have revealed that SiO_2 of basaltic melt increases, but FeO decreases with increasing melting depth of the mantle rocks (Jaques and Green, 1980). We therefore propose that Cenozoic high-Si basalts from eastern China were derived from a shallower mantle than the low-Si basalts. That is, the EM1 and EM2 components were derived from a shallower mantle, while HIMU component was derived from a deeper mantle.

(2) Figure 9 shows the solidus of the mantle of different lithology. Considering the absence of evidence for mantle plumes underneath eastern China in the Cenozoic, we assume a 1350°C potential temperature of the upper mantle (McKenzie et al., 2005). In this case, garnet pyroxenite starts to melt at depth of ~70 km and carbonated garnet pyroxenite/peridotite initially melts at depth of ~ 300 km (Dasgupta et al., 2007). It should be pointed out that the models in Figure 9 are simplified without considering the role of water in mantle melting. As discussed previously, the mantle sources of some Cenozoic basalts in eastern China are hydrous. Presence of water in the mantle would facilitate partial melting at greater depths. Nevertheless, the involvement of carbonates is considered more important in the melting of

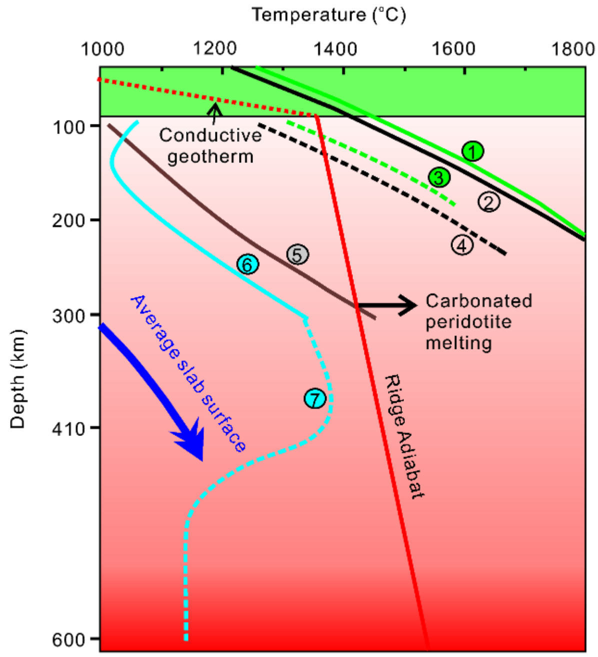

Figure 9 Solidus of different mantle lithologies. Solidus: Mantle solidi: ① peridotite (Hirschmann, 2000); ② garnet pyroxenite (Kogiso et al., 2003); ③ carbonated silicate melting of peridotite (Dasgupta et al., 2007); ④ carbonated silicate melting of pyroxenite (Dasgupta et al., 2007); ⑤ carbonated peridotite (Dasgupta et al., 2006); ⑥ carbonated eclogite (Dasgupta et al., 2004); ⑦ carbonated eclogitic oceanic slab (Thomson et al., 2016).

BMW under eastern Asia.

4.2 Origin of recycled components in the BMW

Although it is now widely accepted that there are abundant recycled materials in the source of Cenozoic basalts in eastern China, the origins of these recycled components such as oceanic crust, water and sedimentary carbonates remain poorly understood and are difficult to constrain. The presence of the stagnant slab within the MTZ confines the source of Cenozoic basalts to the upper mantle, rather than in the lower mantle (Xu Y G et al., 2012). This prompts many researchers to link the genesis of Cenozoic basalts with the flat-lying Pacific slab in the MTZ (Zhao, 2004; Ohtani and Zhao, 2009; Xu Y G et al., 2012; Kuritani et al., 2011; Sakuyama et al., 2013; Li H Y et al., 2016a, 2016b, 2017), and to postulate that recycled components are likely derived from the slabs in the MTZ. Two different recycled components are further identified in this paper and may have different provenance. They are respectively captured by high-Si and low-Si basalts and therefore deserve separate consideration.

4.2.1 Recycled components in low-Si basalts from the stagnant slab in the MTZ

(1) Highly alkaline basalts from eastern China (e.g., Dashan, Shuangliao) exhibit trace element and Sr-Nd isotopic compositions identical to young HIMU basalts, pointing to a petrogenesis closely related to recycled altered oceanic crust (Xu Y G et al., 2012). In addition, these basalts are characterized by moderate, MORB-like $^{206}Pb/^{204}Pb$, rather high $^{206}Pb/^{204}Pb$ expected for classic HIMU-type basalts. These features again suggest that the recycled components are young (Thirlwall, 1997), probably derived from the subducted Pacific oceanic crust stored in the MTZ (Xu Y G et al., 2012). The highly alkaline and low-Si basalts from Shandong Province show a Pacific mantle affinity (Figure 5), in support of the conclusion reached based on Pb isotopes.

(2) Water contents in the source of Cenozoic basalts from eastern China exhibit a salient spatial distribution pattern. The samples from the east of the Daxin'anling-Taihangshan gravity lineament (DTGL) have significantly higher water contents than those from the west of the DTGL (Xia et al., 2017). Given the coincidence of the western end of stagnant slab with the DTGL (Huang and Zhao, 2006; Niu, 2005; Xu, 2007), this suggests that the high water contents might be related to dehydration of stagnant slabs in the MTZ (Xia et al., 2017).

(3) Cenozoic basalts from the east of the DTGL have low $\delta^{26}Mg$ isotopic compositions, while the Chaihe-A'ershan basalts, which are located to west of the DTGL have mantle-like Mg isotopic characteristics. As discussed previously, the low Mg isotopic compositions imply recycled sedimentary carbonates in the source of basalts (Yang et al., 2012; Huang et al., 2015). Following the same logics used to constrain water origin, we infer that sedimentary carbonates are probably only present in the BMW, most likely related to the decarbonization of the stagnant slab within the MTZ (Li S G et al., 2017).

(4) The deep part (660 to 250 km depth) of the upper mantle under eastern China shows the highest electrical conductivity, in contrast the shallow part (<250 km) of the upper mantle is the second lowest electrical conductivity measured on the global scale (Karato, 2011). If the mantle electrical conductivity is positively correlated with H_2O and CO_2 (Karato, 2011; Gaillard et al., 2008), it implies a vertical decrease in H_2O+CO_2 contents from bottom to top of the BMW under eastern Asia. Such a vertical distribution pattern is not contradictory with the deviation of these volatiles from the MTZ.

4.2.2 Recycled components in high-Si basalts from shallow lithospheric mantle

Two different enriched components are present in high-Si basalts. The enriched component in the Cenozoic basalts from North China is EM1-like, whereas that in basalts from South China is EM2-like. Both EM1 and EM2 components are present in basalts from northeast China. No consensus has been reached so far as regard the provenance of these enriched components. In considering the provinciality of these enriched components, we tend to believe that they inherited from the continental lithospheric mantle.

4.3 Vertical heterogeneity of the BMW beneath Eastern Asia

If the above hypotheses are correct, it is reasonable to envisage that the BMW beneath eastern Asia has a stratified chemical heterogeneity (Figure 10). The shallower mantle has EM1/EM2 components with radiogenic isotope compositions showing affinities with that of Indian mantle domain, exhibited as scattered garnet pyroxenites, possibly originating from an old lithospheric mantle. The deeper mantle, on the other hand, contains more contribution from the Pacific slab, might be related to metasomatism by carbonatite melts from the stagnant Pacific slab in the MTZ. This opinion is in good agreement with Huang et al. (2015), in which they found that the lower SiO_2 contents the samples have, the lighter Mg isotopes are for Cenozoic basalts in South China. Because low degree partial melting preferentially captures more fusible carbonated component, low-Si basalts tend to have a light Mg isotopic compositions. In contrast, relatively high degree partial melting would capture both carbonated and silicate components, hence high-Si basalts display rather heavy Mg isotopic compositions due to the dilution effect.

5. Formation of intraplate basalts in a BMW system

Figure 10 schematically depicts the generation of intraplate basalts in the BMW under eastern Asia. In this model, the BMW is vertically heterogeneous in terms of H_2O and CO_2 concentrations, and melting of the BMW to generate Cenozoic intraplate basalt is triggered by decarbonization and dehydration of the slabs stagnated in the MTZ. This new model explains the three long-lasted scientific questions posed in the Introduction Section.

5.1 Why do Cenozoic basalts in eastern China have OIB compositions despite their occurrence in a continental setting?

This question can be now easily answered given the widespread recycled oceanic crust components in the source of Cenozoic basalts in eastern China. The oceanic recycling model proposed for OIBs (Hofmann and White, 1982) is equally applicable to the genesis of Cenozoic intraplate basalts in eastern China.

5.2 Why do Cenozoic basalts in eastern China predominantly exhibit an Indian Mantle signature despite their location in the Pacific tectonic realm?

This question can also be answered if the BMW under eastern Asia is vertically heterogeneous. Hf-Nd isotopic study of the Cenozoic basalts in eastern China shows that both Indian and Pacific mantle components are present in the Pacific tectonic realm, with the former in the shallow mantle and the later in the deep mantle. If the behavior of mantle melting follows the melting column model, the low-Si basalts can capture more Pacific Mantle components than the high-Si basalts. With further mantle upwelling, increasing mantle melting would capture Pacific mantle components from depth and Indian mantle components from shallow level. Since melting degree increases with mantle upwelling, the resultant melts (i.e., high-Si basalts) have much more abundant Indian mantle components than Pacific mantle components which reside at the shallow mantle. The con-

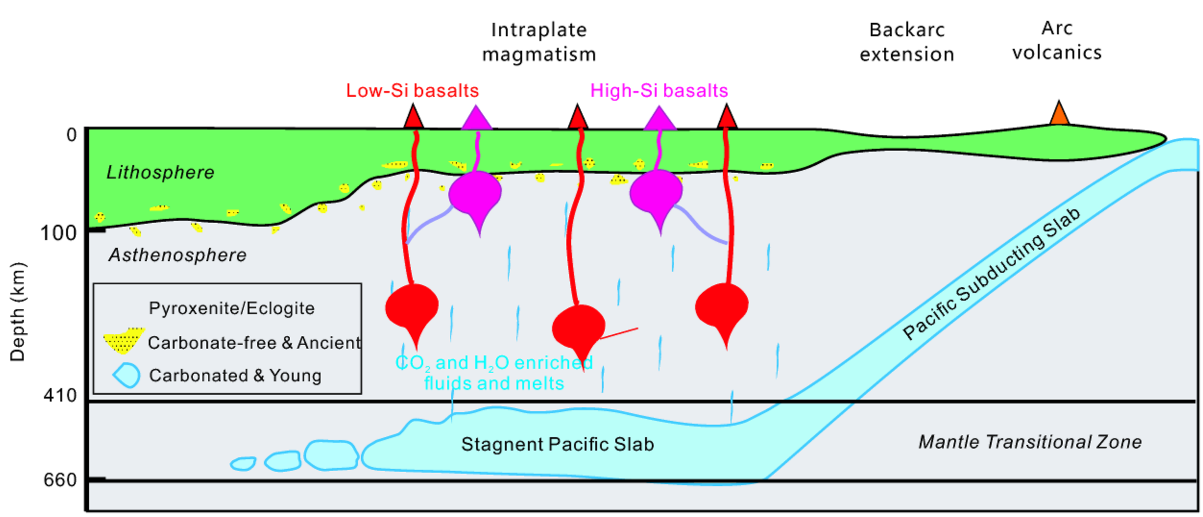

Figure 10 Cartoon illustrating the composition of the big mantle wedge and the generation of continental intraplate basalts in eastern Asia.

sequence is that the high-Si basalts exhibit Indian mantle-like isotope characteristics. The following two factors may have resulted in the wide occurrence of Indian Mantle components in the Pacific tectonic realm

(1) The thickness of the lithosphere beneath eastern China is generally <80 km, due to the destruction of the North China Craton and related lithospheric thinning. Under this circumstance, the generated basalts are mostly moderate in alkali contents with only minor highly alkaline basalts.

(2) The residence of Indian mantle components in the shallow mantle may be related to the erosion of the ancient continental lithospheric mantle by convective asthenosphere in the process of lithospheric thinning (Xu et al., 2005). Since the continental lithosphere underneath eastern Asia was the part of Gondwana which was originally located in the southern hemisphere (i.e., with an Indian mantle signature), it better explains why Cenozoic basalts in eastern China exhibit Indian Mantle signature despite their location in the Pacific tectonic realm.

5.3 How were recycled materials in the MTZ transported into the shallow level?

Zhao et al. (2004) were the first to propose that Changbai volcano was triggered by dehydration of the stagnant slabs within the MTZ, on the basis of their seismic tomographic images in which low velocity column beneath the Changbai volcano can be continuously traced from a depth equivalent to the MTZ. This model was further extended by Ohtani and Zhao (2009) to account for the genesis of intraplate basalt in the entire east Asian continental margin. However, these models suffer some weaknesses.

(1) Although many Cenozoic basalts from eastern China have high water contents, some others have fairly low water contents, even similar to that of the depleted mantle (Figure 4c).

(2) Mantle melting assisted by water ingression likely produces Si-saturated magmas, in contrast to the presence of Si-undersaturated basalts in this region.

(3) Kuritani et al. (2011) found that Ba/Th ratios of volcanic rocks decrease gradually from the Changbai volcano to its surroundings. Since the higher Ba/Th is, the higher contents of sediment and water are in magma source, this observation prompted Kuritani et al. (2011) to propose that the formation of the Changbai volcano is related to dehydration of the stagnant slab. The weakness of their model in that the distribution of Cenozoic volcanoes in eastern China is not centered with the Changbai volcano. In other words, if the eruption of Changbai volcanoes is related to slab dehydration, do other volcanoes, especially for those with low Ba/Th ratios, have nothing to do with dehydration processes?

(4) Given its relatively high density, oceanic crust in the MTZ can hardly reach to the shallow mantle. Dehydration and decarbonization of the stagnant slab would release H_2O and CO_2 into the overlying upper mantle. It is unclear how these volatiles migrate from a depth of 440 km to the initial melting depth for production of low-Si basalts (i.e., ~300 km), in particular when the very strong reactivity of these volatiles is considered. All these considerations imply that dehydration may have played an important role in generation of Cenozoic intraplate basalts, but it does not present a universally applicable factor in petrogenesis.

Since the BMW beneath eastern Asia is a huge carbon reservoir (Li S G et al., 2017), the role of carbon is emphasized here in mantle melting. According to Thomson et al. (2016), the thermal gradient of subducted slab, whether hot or cold, would intersect the solidi of carbonated peridotite/eclogite in the MTZ. The subducted slab is gradually warmed so that it melts, leasing water and carbonatitite into melts. In their recent experimental studies, Zhang Y F et al. (2017) demonstrated that low-Si hydrous melts can be formed in the MTZ conditions. In addition, the presence of hydrous melts in return would promote the melting of materials in the MTZ. Because of its relatively small density, carbonatite melt would leave the MTZ and migrate upward into the upper mantle. Meanwhile, these melts have strong reactivity and would react with surrounding mantle to generate carbonated peridotites. For a normal mantle with a potential temperature of 1350°C (McKenzie et al., 2005), carbonatite-bearing peridotites start to melt at a depth of ~300 km (Dasgupta et al., 2007) to generate carbonaititic melts (< 10% SiO_2, ~40% CO_2). Recently discovered carbonatitic melts in seamount basalt in South China Sea just represent products of initial melting of deep carbonated peridotite (Zhang G L et al., 2017). Once recycled into deep mantle, carbonatite is capable of triggering mantle melting. For instance, Dasgupta et al. (2007) found that, under 3 GPa and 1325–1350°C, melting of carbonatitic peridotites generate silicate melts (>25% SiO_2, <25% CO_2). The melting temperature is by ~150°C lower than the dry mantle solidi. Partially molten mantle is considered as the driving force for mantle upwelling due to its relatively small density.

One of possible difficulty for deep carbonatitic melts to migrate upward to the shallow mantle is the oxidation state of the mantle. Although carbonatitic melts are low in density and in viscosity, which are favorable for their upward migration and metasomatism of the upper mantle above the MTZ, experiments show that the mantle below 250 km is largely reduced and even have free Fe ion (Rohrbach and Schmidt, 2011). Under such circumstance, carbonatitic melt can be easily reduced to form diamond and reside in deep mantle, hampering its upward migration to ~70 km as such silicate melts cannot be formed (Kiseeva et al., 2013). Meanwhile this reaction would induce the increase of oxidation state of the deep mantle (Kiseeva et al., 2016; Thomson et al., 2016). For example, Kiseeva et al. (2018)

found that the garnets included in diamonds show a pronounced increase in oxidation state with depth, with Fe^{3+}/(Fe^{3+}+Fe^{2+}) increasing from 0.08 at approximately 240 km depth to 0.30 at approximately 500 km depth. Among these garnets, those Fe^{3+} rich garnets within the MTZ are genetically related to recycled oceanic crust, most likely resulted from interaction of carbonatitic melts/fluids with mantle peridotites. The occurrence of these Fe^{3+} rich minerals suggest that the MTZ modified by subduction would be in a high oxidation state (Kiseeva et al., 2018). The presence of abundant recycled carbonates in the source of Cenozoic basalts implies a possibly high oxidation state for the lowermost upper mantle in this region. Although it remains unclear as to the mechanism to increase its oxidation state of the lowermost mantle, following Kiseeva et al. (2018), we suggest here that the stagnant Pacific slabs within the MTZ, especially their released carbonatitic melts/fluids are the principle triggers.

6. Conclusions and perspectives

It has been over ten years since the concept of the BMW has been put forward. Geophysists not only provide us with clear pictures as to deep earth structure, but also provide new research opportunities. Systematic geochemical and isotopic studies on Cenozoic basalts from eastern China, together with experimental petrology and deep seismic survey, greatly advanced our understanding of the composition and structure of the BMW under eastern Asia and the generation of intraplate basalts in this BMW system.

(1) Abundant recycled materials, including oceanic crust, water and sedimentary carbonates are present in the BMW under eastern Asia. They mostly come from the stagnant slab in the MTZ, and subordinately from the ancient continental lithospheric mantle.

(2) Cenozoic basalts from eastern China are interpreted as a mixture of high-Si and low-Si end-member melts. The high-Si basalts are characterized either by EM1 or EM2 isotopic signature, showing Indian mantle-type composition and a garnet pyroxenitic source. The low-Si basalts show HIMU-type trace element compositions delineating a Pacific mantle provenance, and come from a source composed of carbonated eclogites and peridotites.

(3) The BMW under eastern Asia is vertically heterogeneous, with the upper part containing EM1 and EM2 components and isotopically resembling the Indian mantle domain, whereas the lower part containing components derived from Pacific mantle domain.

(4) A new model is proposed to account for the generation of intraplate basalt in the BMW system, in order to explain why these basalts have compositions similar to OIBs despite their occurrence in a continental setting, and why they exhibit an Indian mantle signature despite their location in the Pacific tectonic realm. Melting of the BMW to generate Cenozoic intraplate basalts is likely triggered by decarbonization and dehydration of slab stagnated in the MTZ.

Despite these new progresses, a number of important problems remain to solve in this field. The subducted slab with sediments and serpentinites stagnant within the MTZ may be dehydrated and decarbonized, releasing water and CO_2, or melts/fluids into the upper mantle above the MTZ and consequently resulting in metasomatism at the bottom of the upper mantle. This deep mantle metasomatism in the BWM system is significantly different from those taking place at the small mantle wedge system near trenches. Relevant knowledge is not available yet. It is pivotal to understand the mechanism triggering dehydration and decarbonization of the stagnant slab within the MTZ, melting of the upper mantle caused by volatiles released from the MTZ, and interaction between melts and the upper mantle above the MTZ. The answers to these questions can be found through geochemical investigations into Late Cretaceous-Cenozoic basalts and high-pressure and high-temperature experimental simulations. It has been approved that the BMW under eastern Asia is a huge carbon reservoir. The contribution of the BMW to the deep carbon cycling bears great significance, in particular in understanding global carbon cycling and their effects on climate changes. The transport flux of sedimentary carbonates into deep mantle during the formation of the BMW, the CO_2 emission rate via volcanism into the atmosphere, and their relevance to global and regional climate changes deserve attentions in the future.

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