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The evolution and ascent paths of mantle xenolith-bearing magma: Observations and insights from Cenozoic basalts in Southeast China

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ABSTRACT

Studies have shown that mantle xenolith-bearing magmas must ascend rapidly to carry mantle xenoliths to the surface. It has thus been inferred inadvertently that such rapid ascending melt must have undergone little crystallization or evolution. However, this inference is apparently inconsistent with the widespread observation that xenolith-bearing alkali basalts are variably evolved with Mg$^{\#}$ ≤72. In this paper, we discuss this important, yet overlooked, petrological problem and offer new perspectives with evidence.

We analyzed the Cenozoic mantle xenolith-bearing alkali basalts from several locations in Southeast China that have experienced varying degrees of fractional crystallization (Mg$^{\#}$ = ~48–67). The variably evolved composition of host alkali basalts is not in contradiction with rapid ascent, but rather reflects inevitability of crystallization during ascent. Thermometry calculations for clinopyroxene (Cpx) megacrysts give equilibrium temperatures of 1238–1390 °C, which is consistent with the effect of conductive cooling and melt crystallization during ascent because $T_{Melt} > T_{Lithosphere}$. The equilibrium pressure (18–27 kbar) of these Cpx megacrysts suggests that the crystallization takes place under lithospheric mantle conditions. The host melt must have experienced limited low-pressure residence in the shallower levels of lithospheric mantle and crust. This is in fact consistent with the rapid ascent of the host melt to bring mantle xenoliths to the surface.

1. Introduction

Our present-day knowledge on the thermal structure of subcontinental lithospheric mantle (SCLM) largely comes from petrological, geochemical, experimental and thermodynamic studies of mantle xenoliths brought to the surface by kimberlite eruptions, and most abundantly by eruptions of alkali basalts (e.g., Herzberg, 1993; Mather et al., 2011; Menzies, 1983; Nickel and Brey, 1984; O'Hara, 1967; O'Hara and Schairer, 1963; Rudnick et al., 1998; Sleep, 2005; Wood and Banno, 1973). The worldwide observation that apart from kimberlite, it is alkali basalt (vs. tholeiite) that carries mantle xenoliths to the surface, points to a genetic link between mantle xenoliths and alkali basaltic magmatism. Because mantle xenoliths are lithospheric mantle materials whereas basaltic melts are derived from the asthenosphere at greater depths, it follows that alkali basaltic melts that are enriched in volatiles and alkalis have the capacity to collect and transport lithospheric mantle materials during ascent.

Indeed, reduced solubility of volatiles in the melts with decreasing pressure will result in volatile exsolution during alkali melt ascent, causing the bulk magma volume expansion and viscosity increase with destructive power to break magma conduits in the lithospheric mantle (Gonnermann and Manga, 2013; Lensky et al., 2006; Spera, 1984; Woods and Cardoso, 1997). These broken fragments of lithospheric material are the familiar “mantle xenoliths” carried in alkali basalts during eruption. However, mantle xenoliths are physically denser than, and compositionally not in equilibrium with the host melt, which requires the host melts ascend rapidly, with the aid of increased viscosity due to volatile exsolution and bubble formation, to transport mantle xenoliths to the surface. The ascending rates of mantle xenolith-bearing alkali magmas have been estimated to be 6 ± 3 m/s and 0.2–2 m/s by Demouchy et al. (2006) and O'Reilly and Griffin (2010), respectively, which is consistent with the anticipation of the rapid ascent of xenolith-bearing melt.

The “primary” basaltic melt after being extracted from the asthenospheric source region will undergo varying extent of crystallization during ascent, mostly as a consequence of magma cooling (Niu, 1997, 2005;

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Niu and O'Hara, 2008; O'Hara and Herzberg, 2002). One may anticipate that the rapid ascending xenolith-bearing melt would undergo little crystallization (Higgins and Allen, 1985; McBride et al., 2001; O'Reilly and Griffin, 1984; Sigmarsson et al., 1998; Wass, 1980). However, this inference is inconsistent with the widespread observation that the xenolith-bearing alkali basalts are variably evolved with $Mg^{\#} \leq 72$, which is the minimum value required for the melt to be in equilibrium with mantle olivine in both asthenospheric source region and lithospheric mantle magma conduit. Irving and Price (1981) interpreted some evolved lherzolite-bearing phonolitic lavas from Nigeria, Australia, East Germany and New Zealand as originating from fractional crystallization of basanitic magmas in the upper mantle, which is reasonable and likely. However, this apparent problem still remains rarely addressed until recently when pyroxenites were popularly invoked as source for ocean island basalts (OIB) and alkali basalts (Sobolev et al., 2005, 2007; Yang and Zhou, 2013) with the conclusion that the more evolved host magmas must have derived from pyroxenites, which has many more problems than certainties (see Niu, 2016; Niu et al., 2011, 2012; Niu and O'Hara, 2003, 2007).

We consider that the variably evolved nature of host melts does not negate the rapid ascent of mantle xenolith-bearing melt but emphasizes the importance of melt crystallization during ascent. In this paper, we use bulk-rock major and trace elements and clinopyroxene thermobarometry of several sample suites from Southeast (SE) China as a case study to address the above fundamental yet overlooked petrological problems of global significance. We conclude that the varying extent of crystallization during rapid ascent is inevitable for mantle xenolith-bearing basaltic melts, which in SE China largely take place in magma chambers in lithospheric mantle.

2. Geological background and analytical procedures

2.1. Geological background

Cenozoic basaltic volcanism is widespread in eastern China (Fig. 1a). These basalts have been identified as typical continental-intraplate basalts derived from the asthenosphere, with trace element signatures similar to ocean island basalts (OIB) (Meng et al., 2015; Tu et al., 1991; Wang et al., 2011; Zou et al., 2000). A significant low-degree melt metasomatism within the asthenospheric mantle has been invoked to explain the incompatible element enrichment in these basalts (Guo et al., 2016; Niu, 2005, 2014; Sun et al., 2017).

In SE China, the Cenozoic basaltic volcanism is spatially associated with three extensional fault systems parallel to the coastline (Fig. 1b; Chung et al., 1994; Ho et al., 2003; Huang et al., 2013; Sun et al., 2017). Basalts containing abundant mantle xenoliths were collected from several localities (i.e., Xiadai, Xiahuqiao, Dayangke and Jiucaidi) (see Fig. 1b and Appendix A for sample locations). The mantle xenoliths are 4–10 cm in size (Fig. 2a & b) and are dominated by spinel lherzolite and harzburgite with minor dunite. Clinopyroxene (Cpx) megacrysts with varying size of ~1–6 cm are common in these samples except for those from Xiahuqiao (Fig. 2c & d). They are optically homogeneous with 0.5–1.0 mm gray or brown reaction rims (Fig. 2e & f). In addition to xenoliths, these basalts contain abundant euhedral to subhedral olivine (Ol) and relatively less Cpx phenocrysts in a fine-grained and microlite-bearing groundmass (Fig. 2g & h). The Ar–Ar dating gives eruption ages of 20.2 ± 0.1 Ma for basalts from Jiucaidi, 23.3 ± 0.3 Ma from Xiadai, 9.4 ± 0.1 Ma from Xiahuqiao, 2.2 ± 0.1 Ma from Dangyangke (Ho et al., 2003; Huang et al., 2013).

2.2. Analytical procedures

As we endeavored to study melt compositions by choosing glasses if any, or quenched matrix materials, we crushed fresh samples to chips of ≤5 mm to exclude phenocrysts, xenocrysts and weathered surfaces before repeatedly washing the chips in Milli-Q water, drying them and then ground them into powders with an agate mill. Despite the effort, our analyses still contain contributions from olivine micro-phenocrysts (Fig. 2g & h), rather than melt compositions we endeavored to obtain. In our case, we made corrections for this problem using the method described in Sun et al. (2017) and also a new method to verify the validity of the correction results (see Appendix B).

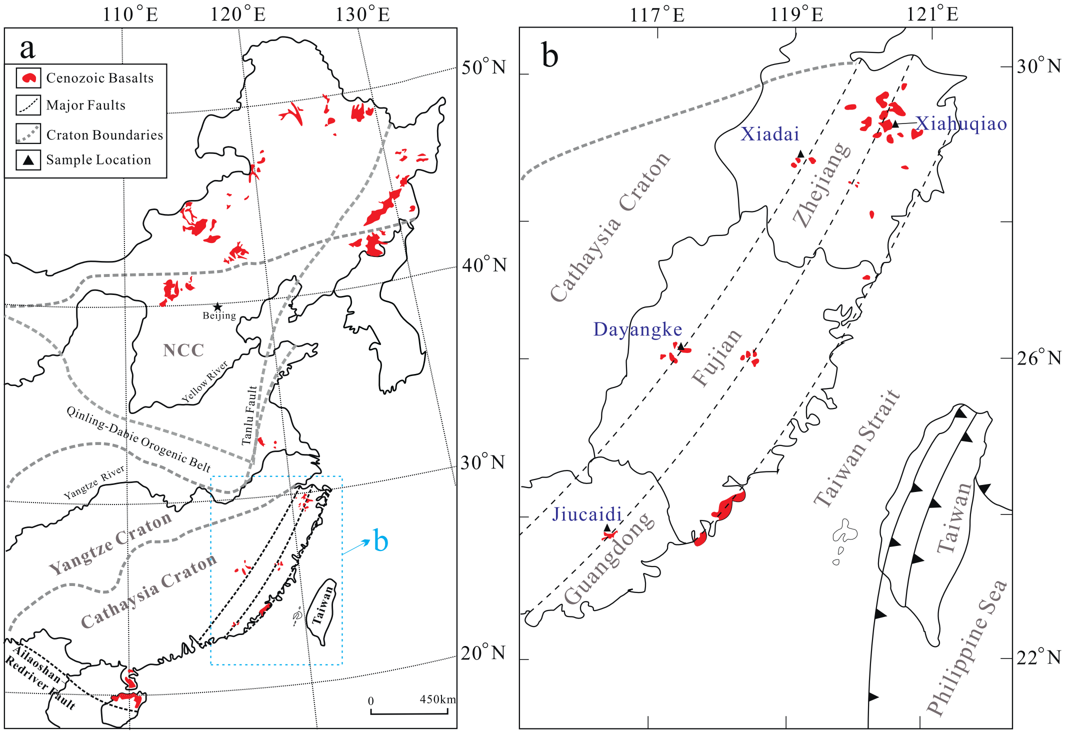

Fig. 1. (a) Distribution of the Cenozoic volcanism in eastern China. (b) Locations of our samples from Southeast (SE) China. Modified from Sun et al. (2017).

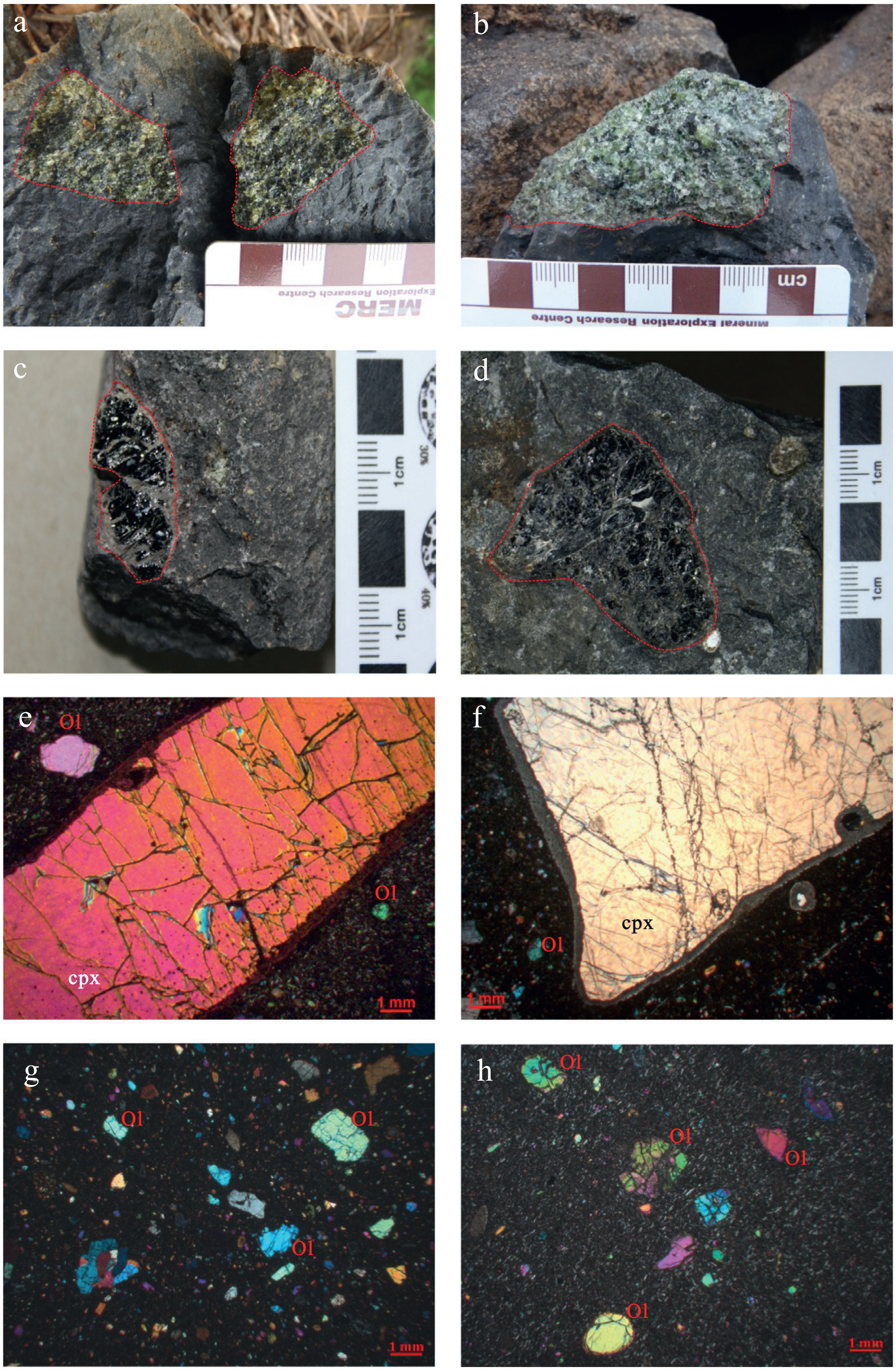

Fig. 2. Hand specimens of mantle xenoliths (a & b) and clinopyroxene megacrysts (c & d) hosted in basalts from SE China. Photomicrographs of the clinopyroxene megacrysts (e & f) and abundant olivine phenocrysts of varying size (g & h) in these basalts.

Major and trace element analysis of glasses/matrix powders was done at China University of Geosciences in Beijing (CUGB). The major element analysis was done using a Leeman Prodigy Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) and trace element analysis was done using an Agilent 7500a Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Repeated analyses of USGS reference rock standards AGV-2, W-2, BHVO-2 and national geological standard reference materials GSR-1, GSR-3 give analytical precision better than 15% for Ni, Co, Cr and Sc and better than 5% for other trace elements. The analytical details are given in Song et al. (2010).

Major elements and Cr contents of Cpx megacrysts were analyzed in thin sections using LA-ICP-MS in Institute of Oceanology, Chinese Academy of Sciences. Laser sampling was performed using a Photon Machines Excite 193 nm excimer Ar–F laser system, and an Agilent 7900a ICP-MS instrument was used to acquire ion-signal intensities. The samples were analyzed using a 40 μm spot and 7.42 J/cm^2 energy density at a repetition rate of 6 Hz. Each analysis includes 25 s background acquisition (gas blank) followed by 50s data acquisition. USGS glasses (BCR-2G, BHVO-2G and BIR-1G) are used as external standards for calibration. Every five sample analyses were followed by two analyses of GSE-1G (one as QC to correct for the time-dependent drift of sensitivity and the other as an unknown sample to check for analytical accuracy and precision). The raw data were processed using ICPMSDataCal (Liu et al., 2008). Repeated analysis of GSE-1G give analytical precision and accuracy generally better than 5% for major elements and Cr except for P_2O_5. The analytical data include 231 spot analyses from 26 single Cpx megacrysts, with 5 to 16 points in a profile per Cpx crystal. The analytical details are given in Xiao et al. (in preparation).

3. Data and interpretations

3.1. The geochemistry of mantle xenolith-bearing basalts

The analytical data are given in Appendix A. After correction for the olivine phenocryst effects (see Appendix B for correction results), these basalts have variably high alkali contents with total alkalis ($Na_2O + K_2O$) of 2.47–8.03 wt%, and range from tephrite/basanite, trachybasalt to alkali basalt in the TAS diagram (Fig. 3). They show a wide MgO range (5–12 wt%) with varying $Mg^{\#}$ ($=100 \times Mg / [Fe^{2+} + Mg]$) of 48–67, indicating variable extent of evolution from the expected primary magma (i.e., $Mg^{\#} \geq 72$) in equilibrium with mantle olivine. Although scattered, there exist first order systematic variations as a function of $Mg^{\#}$ (Fig. 4) using samples from Jiucaidi (also see below). These correlated variations of major elements, trace elements and their ratios are to a first order consistent with varying extents of fractional crystallization dominated by olivine and Cpx.

As shown in Fig. 5a, mantle xenolith-bearing alkali basalts have rare earth element (REE) patterns similar to that of the present-day OIB, but most of them are more enriched in light REEs with high $[La/Sm]_N$ (2.68–4.33), $[La/Yb]_N$ (14.4–40.4) and $[Dy/Yb]_N$ (2–3) ratios. In Fig. 5b, they have multi-element patterns similar to that of OIB but are more enriched in the progressively more incompatible elements with significantly greater $[Nb/Th]_N$, $[Ta/U]_N$ and $[P/Sm]_N$ than unity (i.e., positive Nb, Ta and P anomalies common to oceanic basalts; Niu and Batiza, 1997). Even though fractional crystallization can result in the enrichment of progressively more incompatible elements (i.e., increasing La, Sm, La/Sm and Sm/Yb with decreasing $Mg^{\#}$; Fig. 4), this process is apparently inadequate to explain the overall extremely enriched incompatible elements and depleted heavy REEs in these basalts (Fig. 5). Therefore, the characteristics of these mantle xenolith-bearing basalts are most consistent with an origin of low extent of partial melting from an enriched mantle source with garnet present as a residual phase as indicated by heavy REE depletion with high $[Dy / Yb]_N > 1$ (Sun et al., 2017).

3.2. Geochemistry of clinopyroxene (Cpx) megacrysts

The compositions of Cpx megacrysts are given in Appendix C. They have relatively low SiO_2 (47.3–53.6 wt%), Cr_2O_3 (0.00–0.62 wt%), $Mg^{\#}$ (64.5–85.2) and TiO_2 (0.38–1.69 wt%) but high Al_2O_3 (6.34–9.22 wt%), which is different from mantle-derived Cr-diopside (high SiO_2, Cr_2O_3 and $Mg^{\#}$), but similar to Al-augite crystallized at high pressures (Irving and Frey, 1984; Wass, 1979). Overall, variations in Cpx components are limited to the range of $Wo_{35–47}$, $En_{35–53}$, $Fs_{9–19}$, which are classified as diopside and augite (Fig. 6a). In addition, the composition for a single Cpx megacryst is generally homogeneous (Fig. 6b). In the following, multiple analyses in an individual Cpx megacryst are averaged to obtain the mean composition of the Cpx crystal.

These Cpx megacrysts show significant correlations of $Mg^{\#}$ with major elements (e.g., SiO_2, TiO_2, Al_2O_3, FeO and Na_2O) and Cr (Fig. 7), showing their derivation from melts that had experienced variable extent of fractional crystallization. Three Cpx megacrysts (XD11-11A, XD11-11C and JC11-03A) have apparently lower $Mg^{\#}$ (65–69), SiO_2 and Cr, and higher TiO_2, Al_2O_3, FeO and Na_2O, compared with other Cpx megacrysts ($Mg^{\#} = 75–84$), reflecting their crystallization from compositionally more evolved melts.

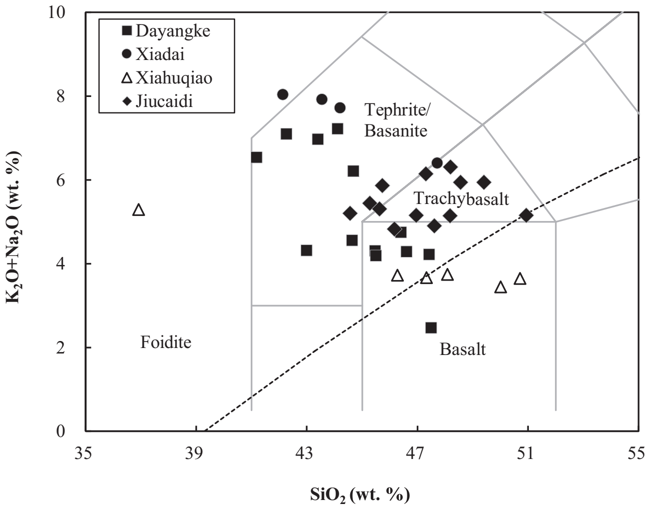

Fig. 3. TAS diagram showing compositional variations of the SE China basalts of this study.

4. Discussion

4.1. Fractional crystallization reflected from basalt compositions

Mantle xenolith-bearing basaltic magma has been inferred to ascend rapidly (Demouchy et al., 2006; O'Reilly and Griffin, 2010), which would suggest less heat loss, less temperature drop and less crystallization during ascent. This reasoning is logical. However, the mantle xenolith-bearing basalts in SE China have $Mg^{\#}$ of 48–67, which manifests in simple clarity that they must have experienced significant crystallization from their primary state ($Mg^{\#} \geq 72$) in equilibrium with mantle olivine. Because mantle melting processes exert the primary control on the compositions of basalts from different locations in SE China (Sun et al., 2017), we select basalts from a single location of Jiucaidi where sufficient samples with a large compositional spectrum exists to evaluate the effect of fractional crystallization during magma ascent.

In Fig. 4, these samples show negative correlations between $Mg^{\#}$ and incompatible major and trace elements ($K_2O + Na_2O$, TiO_2, P_2O_5, La and Sm), and positive correlations between $Mg^{\#}$ and Cr and Ni. All these elemental systematics are consistent with olivine and Cpx being the dominant liquidus phases during cooling and fractional crystallization, most likely at high pressures without plagioclase on the liquidus as manifested by decreasing CaO/Al_2O_3 ($\boldsymbol{Kd}_{\boldsymbol{cpx}}^{\frac{\boldsymbol{CaO}}{\boldsymbol{Al2O3}}} >> \boldsymbol{Kd}_{\boldsymbol{plagioclase}}^{\frac{\boldsymbol{CaO}}{\boldsymbol{Al2O3}}}$) and increasing La/Sm and Sm/Yb with decreasing $Mg^{\#}$ ($\boldsymbol{Kd}_{\boldsymbol{Yb}}^{\boldsymbol{cpx/melt}} > \boldsymbol{Kd}_{\boldsymbol{Sm}}^{\boldsymbol{cpx/melt}} > \boldsymbol{Kd}_{\boldsymbol{La}}^{\boldsymbol{cpx/melt}}$; e.g. Blundy et al., 1998); Sm/Yb is essentially constant in the course of low-pressure fractional crystallization dominated by olivine + plagioclase with Cpx appearing late (MgO < ~8 wt%) on the liquidus (Niu and O'Hara, 2009), but in the basalts under consideration here, Sm/Yb increases with decreasing $Mg^{\#}$. This is consistent with our petrological observation of abundant olivine phenocrysts and Cpx phenocrysts and megacrysts entrained in these basalts.

4.2. Is variably high extent of crystallization possible during ascent of xenolith-bearing magma?

4.2.1. Cpx thermobarometer

There are generally two kinds of thermobarometers to calculate the equilibrium temperature and pressure of Cpx phenocryst and megacryst crystallization. The most widely used thermobarometer is based on the jadeite-diopside/hedenbergite exchange equilibria between Cpx and host melt (Cpx-melt thermobarometer; Putirka et al., 1996, Putirka et al., 2003), which is most precise with least systematic error. The other thermobarometer is based only on the Cpx components (single Cpx thermobarometer; Nimis, 1995, 1999; Nimis and Taylor, 2000), which is also valid but contains systematic errors (Putirka, 2008).

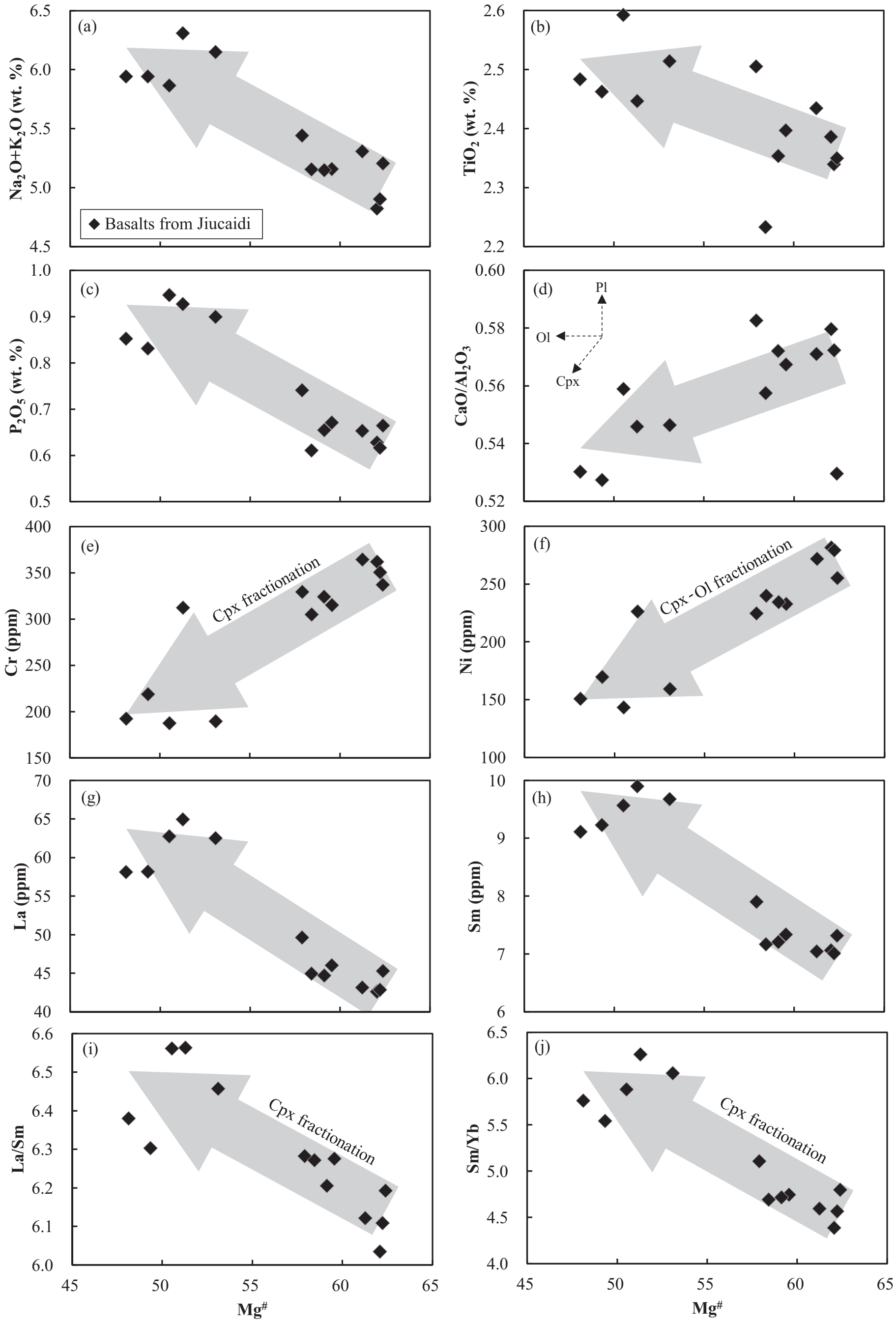

Fig. 4. Mg# variation diagrams of $Na_2O + K_2O$, TiO_2, P_2O_5, CaO/Al_2O_3, Cr, Ni, La, Sm, La/Sm and Sm/Yb of basalt samples from Jiucaidi as an example (more samples with larger compositional variation available than other locations), which is consistent with varying extent of Ol-Cpx crystallization.

The Cpx-melt thermobarometer needs approximation of the melt compositions in equilibrium with the Cpx. Bulk-rock compositions have been most commonly approximated as representing the melt. However, the bulk-rock could represent melt only when the bulk-rock acted as a closed system (Putirka, 2008). The presence of mantle peridotite xenoliths in these rocks clearly negates the bulk-rock as a closed system. As stated above, bulk-rock compositions rarely represent pure melt, but mixture of crystals (e.g. olivine and Cpx) and melts. Therefore, using bulk-rock compositions in Cpx thermobarometer calculation may give misleading results.

Using Cpx from Jiucaidi as an example, we illustrate the above problem in Fig. 8 by using the Cpx-melt thermobarometer in Putirka et al. (2003). The standard error of estimate (SEE) for this method is ±33 °C and ± 1.7 kbar. Nominal melts needed by this thermobarometer are approximated by the uncorrected bulk-rock compositions (samples with Mg# of 56, 60 and 65; Fig. 8a) and bulk-rock compositions corrected for the olivine effect (samples with Mg# of 48, 53 and 59; Fig. 8b), respectively. Although our corrected "melts" may not be perfect due to minute olivine and minor Cpx effect, they are adequately close to melt compositions. We consider that Cpx crystals plotted within the $K_D[Fe\text{-}Mg]^{Cpx\text{-}melt} = 0.28 \pm 0.08$ interval are in equilibrium with the nominal melts (Putirka, 2008; Fig. 8a & b). Fig. 8c shows the results calculated using uncorrected bulk-rock compositions as "melts", which gives crystallization temperatures and pressures of 1250–1304 °C and 16–21 kbar, respectively. Fig. 8d shows the results calculated using the corrected "melt", which gives lower crystallization temperatures and pressures

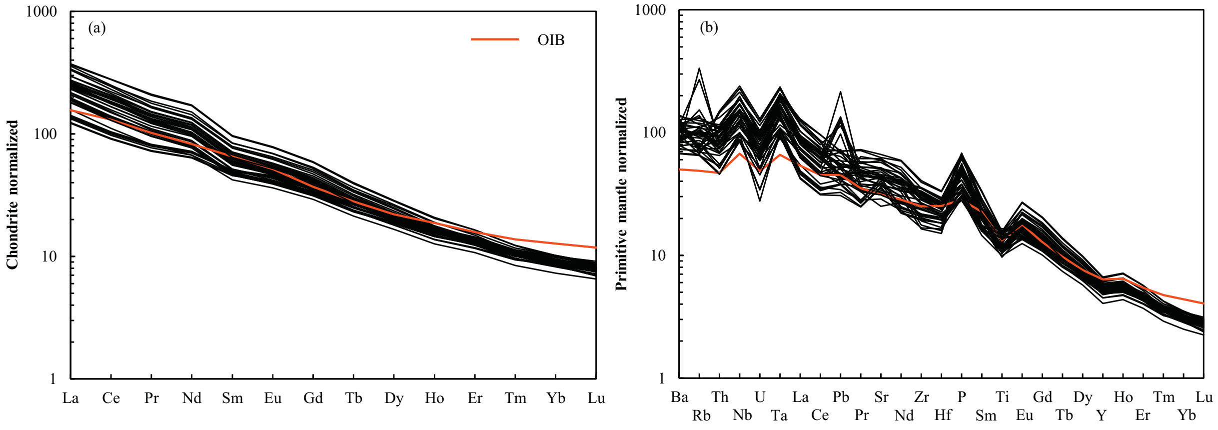

Fig. 5. Chondrite-normalized REE patterns (a) and primitive mantle-normalized multiple incompatible element abundances (b). For comparison, average composition of present-day OIB (Sun and McDonough, 1989) are plotted. These basalts are extremely enriched in incompatible elements, indicative of their enriched source character.

of 1213–1270 °C and 12–16 kbar, respectively. These calculation results indicate that (1) the calculated temperature and pressure values using the Cpx-melt thermobarometer highly depend on the nominal melt compositions chosen (Fig. 8c & d); (2) compared with the thermobarometry calculations using corrected "melt" compositions, calculations using uncorrected bulk-rock compositions give overestimated temperature and pressure results (Fig. 8c & d). Therefore, using uncorrected bulk-rock compositions in the Cpx thermobarometer calculation may give misleading results; (3) although the Cpx-melt thermobarometer is considered as most precise with least systematic error, choosing different nominal melts can introduce significant errors in this thermobarometer. For example, in Fig. 8d, except for the systematic errors of ±33 °C and ± 1.7 kbar, uncertainties in the nominal melt compositions would lead to additional 57 °C and 4 kbar derivations in the calculated temperature and pressure values, which is geologically rather significant. Therefore, caution is needed when using the Cpx-

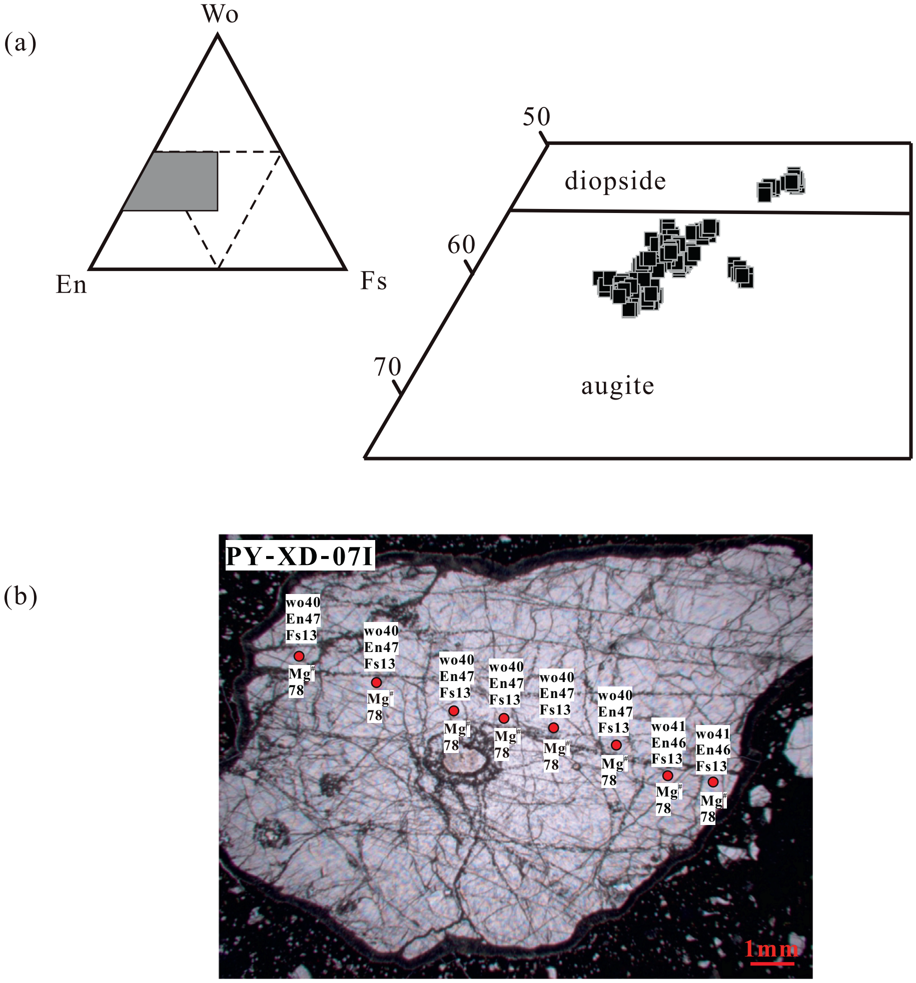

Fig. 6. (a) Compositions of all analyzed clinopyroxene data points ($n = 231$). These clinopyroxenes vary compositionally in the range of $Wo_{35–47}$, $En_{35–53}$, $Fs_{9–19}$. (b) Chemical profile of clinopyroxene megacryst interior (sample PY-XD-07I as an example) to show homogeneous compositions in a given clinopyroxene crystal.

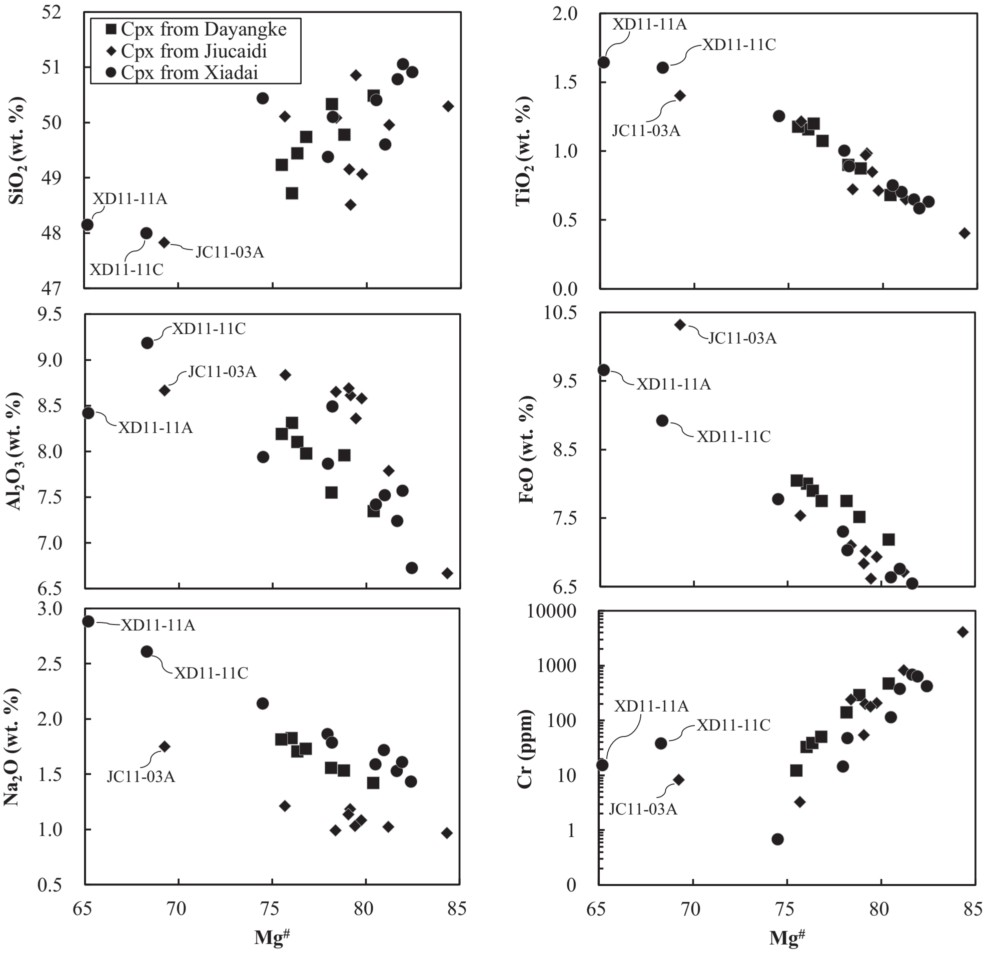

Fig. 7. Co-variations of $Mg^\#$ with major elements (SiO_2, TiO_2, Al_2O_3, FeO, Na_2O) and Cr of the clinopyroxene megacrysts. These clinopyroxene megacrysts were crystallized from melts that had experienced variable extent of fractional crystallization. Three clinopyroxene megacrysts from Jiucaidi and Xiadai (JC11-03A, XD11-11A and XD11-11C) have apparent lower $Mg^\#$ (65–69), SiO_2 and Cr, and higher TiO_2, Al_2O_3, FeO and Na_2O, compared with other Cpx megacrysts ($Mg^\# = 75–84$), reflecting their crystallization from compositionally more evolved melts.

melt thermobarometer to obtain precise temperature and pressure values.

Considering the potential errors of the Cpx-melt thermobarometer, we choose to use the single Cpx thermobarometer to calculate the crystallization temperatures and pressures of these Cpx megacrysts. The Cpx barometer and thermometer we use are recalibrated from Nimis (1995) and Nimis and Taylor (2000), respectively (Putirka, 2008; eq. 32a/32d), which are more precise than their original forms, but still contain systematic errors (~ ± 3.1 kbar and ±58 °C). The calculated *P*-*T* results are listed in Appendix D and shown in Fig. 9. These Cpx megacrysts from SE China crystallized under conditions of 18–27 kbar and 1238–1390 °C. Given the uncertainties in these thermobarometers, we do not intend to rely on *P* and *T* values, but to emphasize the similarities and differences between Cpx samples and sample suites for comparison.

4.2.2. Cooling-induced crystallization during ascent

Fig. 9 shows our calculated *P*-*T* conditions using the Cpx-thermobarometry (see above). For comparison, the lithosphere geotherm of eastern China (Menzies et al., 2007) and the solidus and liquidus of alkali olivine basalt (Green and Ringwood, 1967) are also plotted. Three Cpx megacrysts with lower $Mg^\#$ (XD11-11A, XD11-11C and JC11-03A; Fig. 7) have lower calculated crystallization temperatures more close to the lithosphere geotherm than other Cpx megacrysts (Fig. 9), which is consistent with our explanation of their crystallization from more evolved melts (Niu et al., 2002). According to the Fe–Mg exchange equilibrium ($Kd^{Cpx\text{-}Melt}_{[Fe\text{-}Mg]} = 0.28 \pm 0.08$; Putirka, 2008), the melts in equilibrium with these three Cpx megacrysts have low $Mg^\#$ of 34–38, compared with $Mg^\# = 48–67$ of our basalt samples. We infer these three Cpx megacrysts crystallized from highly evolved melts that experienced long-time thermal equilibrium with ambient lithosphere wall-rock. Therefore, the calculated *P*-*T* results of these three Cpx megacrysts do not represent the *P*-*T* conditions of rapidly ascending mantle-xenolith bearing melt.

In comparison, most of Cpx megacrysts show much higher temperatures than the ambient lithosphere, which is consistent with their parental melts crystallization during ascent because of the inevitable conductive heat loss to the cooler ambient mantle. Hence, the observed variably highly evolved composition of xenolith-bearing alkali basalts is not in contradiction with the rapid ascent, but an unavoidable consequence of melt crystallization because of cooling (heat loss to the ambient mantle).

4.2.3. Where does the crystallization take place?

To convert pressure (kbar) to depth (km), we estimated the approximate densities of the representative crustal and mantle layers beneath SE China (Appendix E; Zheng et al., 2001; Zhang and Wang, 2007) and created an equation relating depth to calculated pressure:

$$D\ (\text{km}) = 3.04^{*}P\ (\text{kbar}) + 5.35 \qquad (1)$$

The calculated pressures (18–27 kbar) translate into Cpx crystallization depth of 59–88 km (Appendix D). According to Li et al. (2006), the

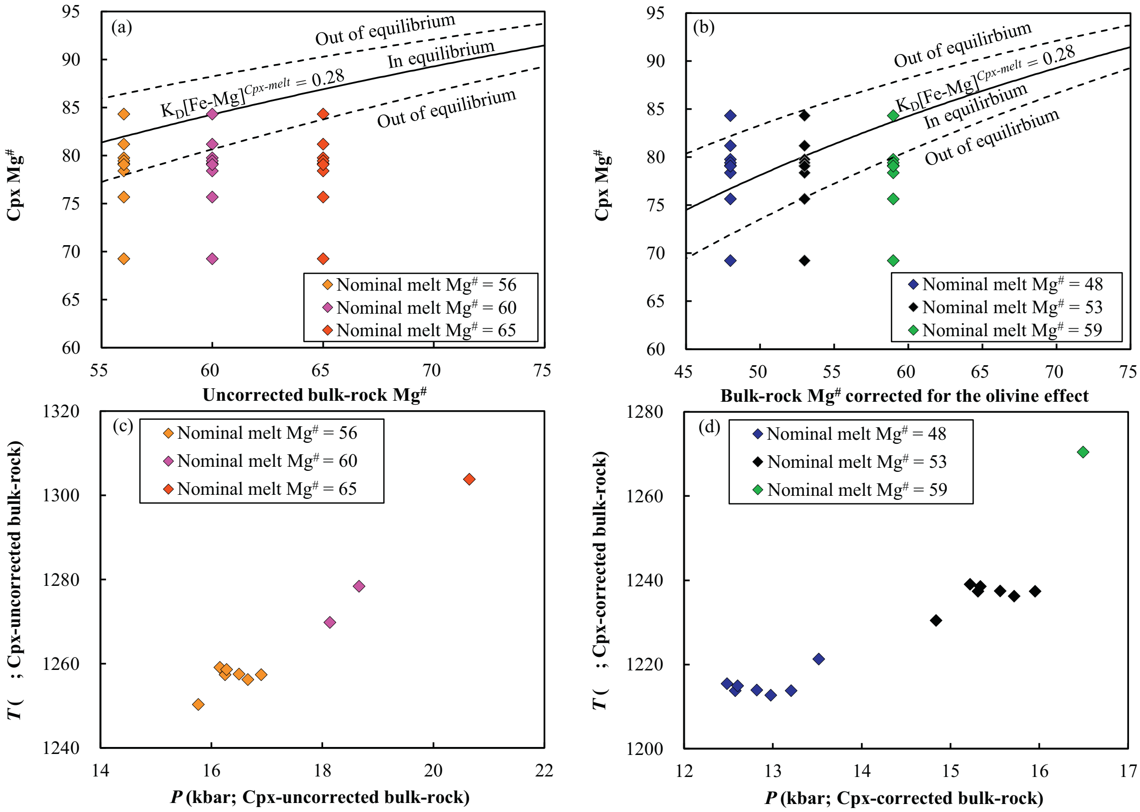

Fig. 8. (a) Equilibrium tests between Cpx megacrysts from Jiucaidi as an example and host bulk-rock uncorrected for the olivine effect with Mg# of 56, 60 and 65. (b) Equilibrium tests between Cpx megacrysts from Jiucaidi and host bulk-rock corrected for the olivine effect with Mg# of 48, 53 and 59. Both tests (a, b) use a $K_D[Fe\text{-}Mg]^{Cpx\text{-}melt} = 0.28 \pm 0.08$ to define the equilibrium envelope (Putirka, 2008) and only data points falling within the equilibrium envelope are used for further thermobarometry calculations. (c) Calculated Cpx temperatures and pressures using uncorrected bulk-rock compositions. (d) Calculated Cpx temperatures and pressures using bulk-rock compositions corrected for the olivine effect. The Cpx thermometer and barometer we use are from Putirka et al. (2003), with systematic errors of ~ ± 33 °C and ± 1.7 kbar, respectively.

crustal thickness of South China is about 30–34 km and is 30–32 km in the coastal region, which means that all Cpx megacrysts must have crystallized at lithospheric mantle depths. This is consistent with previous thermobarometric calculations on Cpx megacrysts in eastern China (Chen et al., 2009; Huang et al., 2007).

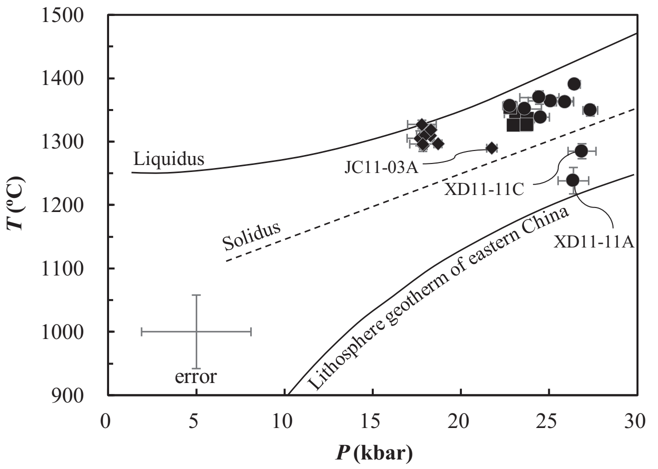

Fig. 9. Calculated equilibrium temperatures and pressures of clinopyroxene megacrysts in *P-T* space. The Cpx barometer and thermometer we use are recalibrated from Nimis (1995) and Nimis and Taylor (2000), with systematic errors of ~ ± 3.1 kbar and ± 58 °C, respectively (Putirka, 2008; eq. 32a/32d). Standard errors of *P* and *T* results calculated from multiple analyses in a single Cpx are also plotted, respectively. For comparison, the lithosphere geotherm of eastern China (Menzies et al., 2007) and the solidus and liquidus of alkali olivine basalt (Green and Ringwood, 1967) are also plotted. The significantly higher temperatures of xenolith-bearing melts relative to the ambient mantle lithosphere ensure cooling-induced crystallization to be an unavoidable consequence during ascent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

During melt ascent with cooling, melt crystallization can take place both in the conduit and in a magma chamber. In Irving's "flow crystallization" model, crystallization takes place along the walls of magma conduits from a flowing melt (Irving, 1978, 1980). This is possible and likely, but the rapid melt ascent in magma conduits with continued decompression (1) does not guarantee sufficient time for crystal-melt equilibrium to form large compositionally uniform megacrysts (Fig. 6b); (2) crystallization on the conduit wall surface could further prevent the conduit wall destruction, xenolith generation and transport. Thus, under the conditions of rapid ascent, a magma conduit may not be the ideal place for crystallization. Furthermore, Irving's "flow crystallization" model discussed composite xenoliths in which the pyroxenites are composed of coarse but not megacryst-sized veins. Hence, magma conduit is not a likely site for megacryst growth. It follows indeed that magma chambers in a stable environment are required to allow slow cooling and the growth of compositionally uniform large crystals, that is, megacrysts (O'Hara, 1977; O'Hara and Mathews, 1981; Sparks et al., 1984). The abundant Cenozoic volcanism in eastern China and frequent melt supply from the source regions could ensure the existence of long-lived magma chambers in the lithospheric mantle (Niu and O'Hara, 2008). All this leads us to the proposal that xenolith-bearing alkali basalts in SE China must have evolved in magma chambers developed in the lithospheric mantle depths.

4.3. Ascent of mantle xenolith-bearing magmas beneath SE China

The calculated *T-P* results of the Cpx megacrysts suggest that their parental magmas must have crystallized under high pressures in lithospheric mantle and did not experience long-time stay at crustal levels. This conclusion can also be inferred from the homogenous compositional profile of these Cpx megacrysts (Fig. 6b) and the absence of low-pressure overgrowth-induced compositional zonation (Dobosi, 1989; Geiger et al., 2016; Nakagawa et al., 2002; Neumann et al., 1999; Stock et al., 2012). In addition, the petrological observation of widespread mantle xenoliths entrained in these basalts indicates that the host melts may have ascended too rapidly to experience any residence in the shallow levels (>20 m/s through shallow crust and >300 m/s in the uppermost crust; O'Reilly and Griffin, 2010).

Based on the above observations and inferences, we provide a model for the ascent of mantle xenolith-bearing magmas beneath SE China (Fig. 10). That is, 1) low extent of partial melting of a fertile mantle source enriched in incompatible elements and volatiles produced alkali basaltic melts with elevated abundances of volatiles (Sun et al., 2017); 2) these melts migrated upwards from the source region, percolated through the base of the lithospheric mantle and focused in a magma chamber in the lithospheric mantle where variable extent of mineral crystallization (including Cpx megacryst) happened, (3) periodically melt replenishment in the magma chamber forced the residual melt together with the crystallized Cpx megacrysts to ascend from the magma chamber. Such alkali basaltic melts during ascent through the mantle lithosphere will exsolve volatiles (reduced volatile solubility in the melt due to decompression), resulting in bulk magma volume expansion, viscosity increase, and development of power to fragment the conduit wall-rock to produce "mantle xenoliths", and rapidly transport them to the surface with limited residence in shallow levels. In addition, volatile exsolution during magma ascent and decompression can also increase liquidus temperatures, which may further facilitate melt crystallizations (Blundy and Cashman, 2001, 2005; Cashman and Blundy, 2000; Sparks et al., 2000).

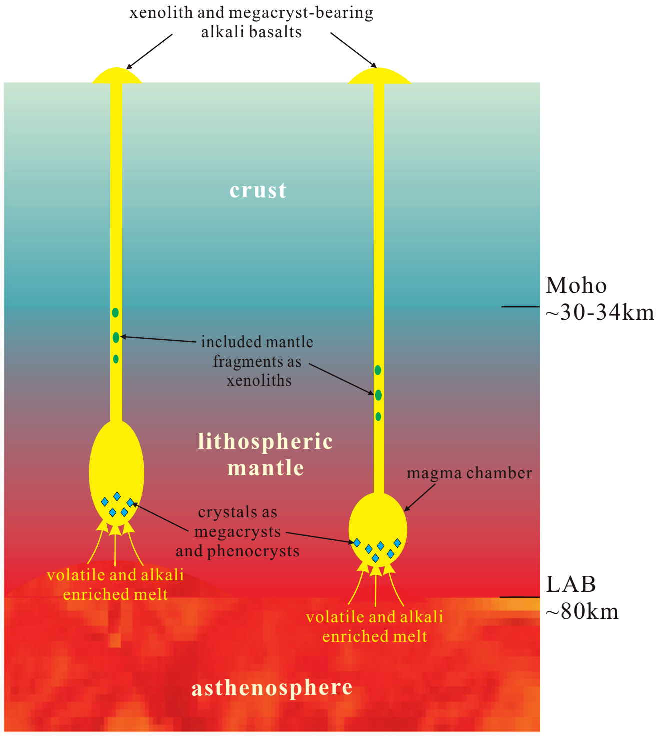

Fig. 10. Cartoon showing the evolution and ascent paths of mantle xenolith-bearing magmas prior to their eruption. Incompatible element- and volatile-(H_2O and CO_2) enriched melts are generated from low extent melting of a fertile mantle source. These melts are then extracted and gathered in the magma chambers under the conditions of lithospheric mantle, where variable extent of crystallization of olivine and clinopyroxene happens. After extraction from the magma chambers, these melts will exsolve volatiles, resulting in bulk magma volume expansion, and development of power to fragment the conduit wall-rock to produce "mantle xenoliths", and rapidly transport them to the surface with limited residence in shallow levels.

5. Conclusions

1. After correction for the effect of olivine micro-phenocrysts in the samples, we obtained the compositions of melt with $Mg^{\#} = 48–67$ for the Cenozoic xenolith-bearing alkali basalts from Southeast China. These highly evolved compositions are consistent with olivine-Cpx crystallization during ascent.
2. Calculations for equilibrium temperatures (1238–1390 °C) of Cpx megacrysts show that their parental melt are hotter than the ambient lithosphere, which is consistent with cooling-induced crystallization during ascent.
3. The equilibrium pressures (18–27 kbar) of Cpx megacrysts suggest that the crystallization takes place under lithospheric mantle conditions. This could occur in magma conduits, but lithospheric mantle magma chambers are required to provide a stable environment for crystallizing megacrysts (1–6 cm) of uniform composition.
4. Melts entraining megacrysts after extracted from the magma chamber should experience limited residence in the shallow levels to rapidly transport mantle xenoliths to the surface.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lithos.2018.04.015.

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