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ARTICLE



Magma–magma interaction in the mantle recorded by megacrysts from Cenozoic basalts in eastern China

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ABSTRACT

Recently, besides magma–rock and rock–rock reaction, magma–magma interaction at mantle depth has been proposed as an alternative mechanism to produce diverse compositions of mantle. Clinopyroxene and garnet megacrysts can be formed at this condition since this process is suggested to trigger the high-pressure crystallization of these minerals. Studying on this type of megacrysts provides us important information on the genesis of intraplate basalts and the chemical heterogeneity of mantle, which has not been reported before. Here we present major, trace elements and Sr isotopes of clinopyroxene and garnet megacrysts hosted by Cenozoic basalts from Penglai, Shandong province of eastern China. The megacrysts are suggested to be formed by crystallization from magma because of their moderate $Mg^{\#}$ (74.0–79.9 for clinopyroxene and 58.8–65.0 for garnet) and good correlations between $Mg^{\#}$ and other elements (e.g. CaO, TiO_2 , Nd and Lu). The potential crystallized temperature and pressure are estimated to be $\sim 1156^{\circ}C$ at 2.6–3.2 GPa, which should occur at the top of asthenosphere or lithosphere–asthenosphere boundary based on the lithospheric thickness in this area (~ 60 – 70 km). Since the megacrysts show variable Sr isotopes, and their primary magmas show negative correlation between $^{87}Sr/^{86}Sr$ and Hf/Sm ratios, as well as positive correlation between Ba/Th and Nb/U for clinopyroxenes, it indicates a mixing origin. Cenozoic basalts from Shandong show a mixing trend, and high-pressure fractionation of clinopyroxene and garnet is suggested to occur during the mixing process because some basalts show significantly higher Sm/Yb and lower Ca/Al ratios than others, which again supports our interpretations. When compared to megacrysts and host basalts from other locations of eastern China, similar geochemical variations and a deviation trend relative to the mixing trend are also observed. It indicates that magma–magma interaction can be a common process for formation of intraplate basalts and basalt-borne megacrysts.

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KEYWORDS

Megacryst; magma–magma interaction; high-pressure fractional crystallization; intraplate basalt; eastern China

1. Introduction

Clinopyroxene and garnet megacrysts are commonly found in intraplate basaltic eruptions (e.g. Liotard *et al.* 1988; Shaw and Eyzaguirre 2000; Rankenburg *et al.* 2004; Akinin *et al.* 2005; Ashchepkov *et al.* 2011). It is invoked that they are originated from the magma as the crystallized phases during the fractionation process (e.g. Green and Ringwood 1964; Liotard *et al.* 1988; Shaw and Eyzaguirre 2000; Rankenburg *et al.* 2004; Akinin *et al.* 2005; Smith *et al.* 2008; Ashchepkov *et al.* 2011), though they may also represent the fragments of disaggregated mantle xenoliths (e.g. Zhang *et al.* 2007; Yu *et al.* 2010) or the metasomatic products of melt/fluid–mantle reaction (e.g. He *et al.* 2013; Li *et al.* 2002a). The crystallization of clinopyroxene and garnet

megacrysts from magma can be induced by near-liquidus phase precipitation (e.g. Green and Ringwood 1964; Green and Hibberson 1970; Smith *et al.* 2008; Ashchepkov *et al.* 2011) or mingling between primitive melts and their fractionated derivatives (Rankenburg *et al.* 2004), and the latter would buffer the temperature ($\sim 1400^{\circ}C$) of magma in the lithospheric mantle (~ 2 GPa) (e.g. Liotard *et al.* 1988). Recently, studies on oceanic island basalts (Herzberg 2011) and intraplate continental basalts (Zeng *et al.* 2017) proposed that magma–magma mingling at mantle depth (~ 4 GPa) can also trigger high-pressure crystallization of clinopyroxene and garnet, which provides us an alternative mechanism to form the megacrysts. Up to now, there is no report of megacrysts that are relevant to such high-pressure mixing–crystallization process, though

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studying on this type of megacrysts can provide us important information on the genesis of intraplate basalts and the chemical heterogeneity of mantle.

Since Cenozoic, eastern China is characterized by widespread eruption of intraplate basalts from north of Heilongjiang province to south of Hainan island (e.g. Liu *et al.* 1992b). Compositional variation of these intraplate basalts is inferred to reflect chemical heterogeneity in the mantle, which owes to the variable contributions of recycled crustal materials (e.g. Chen *et al.* 2009; Zeng *et al.* 2010; Xu *et al.* 2012; Sakuyama *et al.* 2013; Xu 2014; Liu *et al.* 2016; Sun *et al.* 2017; Wang *et al.* 2017; Yu *et al.* 2017). Crustal-derived components like eclogite and pyroxenite source rocks thus are considered to play important roles in forming these intraplate basalts (e.g. Chen *et al.* 2009; Zeng *et al.* 2011; Sakuyama *et al.* 2013; Sun *et al.* 2017). In addition, an olivine-free secondary pyroxenite formed by melt-rock reaction was proposed to be the source of SiO₂-saturated basalts (e.g. Liu *et al.* 2015b; Zhang *et al.* 2009); while carbonated peridotite was proposed to be the source rock of SiO₂-undersaturated alkaline basaltic melts (e.g. Chen *et al.* 2009; Yu *et al.* 2015; Zeng *et al.* 2017). Recent study on Fujian basalts indicated that formation of intraplate basalts is closely related to the process of magma–magma interaction by SiO₂-saturated melt and SiO₂-undersaturated melt in deep which causes high-pressure crystallization of clinopyroxene and garnet megacrysts along with the mixing of

magmas (Zeng *et al.* 2017). This magma–magma interaction proposal can challenge our understanding about the formation of intraplate basalts as it can cause the garnet or clinopyroxene effect of basaltic magmas which shows similar geochemical variations to partial melting of eclogitic or pyroxenitic rock sources. Besides the intraplate basalts, basalt-borne megacrysts are also widely seen from eastern China (Figure 1(a)). As most of them are magmatic crystallization origins (e.g. Chen *et al.* 1997; Du *et al.* 2006; He *et al.* 2013; Li and Ma 2002; Xia *et al.* 2004; Yu and O'Reilly 2001; Yu *et al.* 2003), eastern China is an ideal place to search for high-pressure crystallized megacrysts.

Here, we present major, trace elements and Sr isotope data for clinopyroxene and garnet megacrysts hosted in Penglai basalts from Shandong, North China. Based on these data, we argue that these megacrysts were formed by high-pressure crystallization at mantle depths, triggered by magma–magma interaction. This magma–magma interaction model at mantle depth provides not only an important mechanism to form the high-pressure megacrysts, but also a way to explain compositional variation of intraplate basalts, in addition to magma–rock and rock–rock interactions (e.g. Sobolev *et al.* 2005, 2007; Liu *et al.* 2008; Chen *et al.* 2009; Herzberg 2011; Zeng *et al.* 2013, 2017). In the meantime, we compare our observations with megacrysts and hosted basalts from other locations in eastern China and obtain the implications that magma–

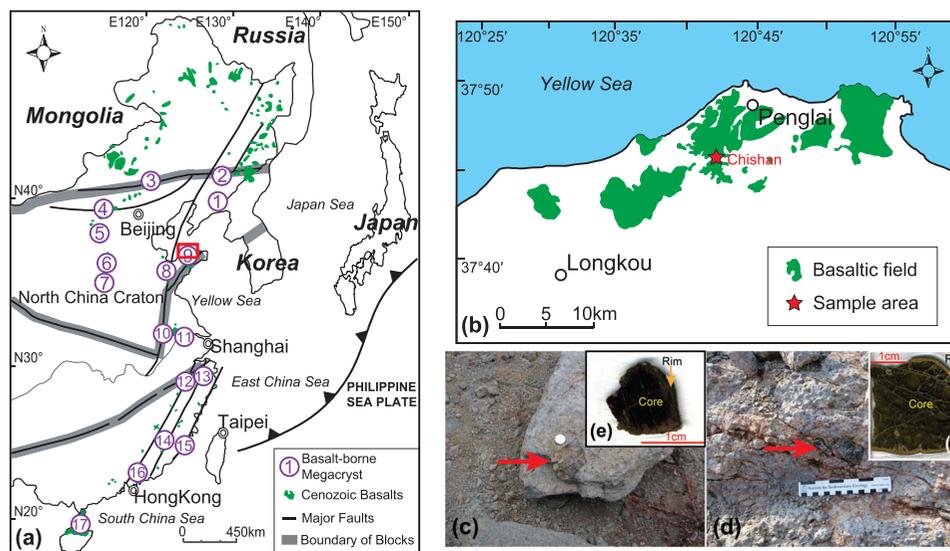


Figure 1. (a) Simplified geological map of eastern China. Distribution of Cenozoic basalts and basalt-borne megacryst outcrops are shown. (b) Distribution of Cenozoic basalts in Penglai area and the sample location of megacrysts, Chishan. (c) and (d) are photographs of garnet and clinopyroxene in field observations, and (e) and (f) are thin sections for garnet and clinopyroxene megacrysts. In (a), different numbers stand for different megacryst outcrops which are listed as follows: 1-Kuandian, 2-Longgang, 3-Chifeng, 4-Jining and Hannuoba, 5-Pingquan, 6-Zuoquan, 7-Hebi, 8-Changle and Linqu, 9-Penglai and Qixia, 10-Nushan, 11-Luhe, 12-Xilong, 13-Xinchang, 14-Mingxi, 15-Longhai, 16-Puning, and 17-Leiqiong.

magma interaction should be a common phenomenon for genesis of intraplate basalts and mantle heterogeneity from eastern China.

2. Geologic background and sample description

Eastern China is composed of the Xing-Meng Block (XMB), the North China Craton (NCC), the Yangtze Craton (YC), and the Cathaysia Block (CB) from north to south (Figure 1(a)). Basalt-borne megacrysts can be sampled from all the four blocks (Figure 1(a)) wherein K–Ar age of the host intraplate basalts varies from ~35 Ma to <1 Ma (Liu *et al.* 1992b). Among megacrysts, clinopyroxene is the most common mineral which can be observed from all the megacryst outcrops. Clinopyroxene and garnet megacrysts only coexist at locations like Kuandian from Liaoning province, Hannuoba from Hebei province, Penglai from Shandong province, Xilong from Zhejiang province, and Mingxi from Fujian province and Hainan Island (e.g. Chen *et al.* 1997; He *et al.* 2013; Huang *et al.* 1991; Liu *et al.* 1992a; Yu *et al.* 2001; Yu *et al.* 2003). In this study, we sampled clinopyroxene and garnet megacrysts from Penglai which is located at the North China Craton (Figure 1(a)).

The North China Craton is composed of two Archaean blocks (eastern and western blocks) and a Proterozoic orogenic belt (the central part) (e.g. Wilde and Zhao 2005; Zhao *et al.* 2010). Penglai is located at the east end of the eastern block of the North China Craton (Figure 1(b)), where Cenozoic basalts are widely distributed and <6 Ma old (Liu *et al.* 1992b; Lee *et al.* 2006). Magmatism is closely associated with major regional faults, for example, the Tan-Lu fault (Figure 1(a)). Penglai basalts are mainly trachybasalts and alkali olivine basalts (Lee *et al.* 2006; Sakuyama *et al.* 2013). Megacrysts were sampled from Chishan in Penglai city (hereafter termed Chishan megacrysts) where host lavas are basanites/tephrites (SFig. 1). The age of host basalts is about 5 Ma (Enami *et al.* 1988). Besides of megacrysts, abundant, fresh xenoliths of Iherzolite and pyroxenite, with minor harzburgite and wehrlite were observed from Penglai (Enami *et al.* 1988; Chu *et al.* 2009).

Megacrysts are clinopyroxene and garnet, with clinopyroxene predominating. Garnet is brown in color and about 2 cm in radius with reaction rims (Figure 1(c) and 1(e)) while clinopyroxene is black in color and about 1 cm in radius with common reaction rims (Figure 1(d) and 1(f)). Clinopyroxene is mainly composed of rounded shape while garnet is out-of-shape. For the cores of both garnet and clinopyroxene, no inclusions

and zoning are observed. We selected five pieces of fresh garnet and seven pieces of fresh clinopyroxene for geochemical measurements.

3. Methods

The major elemental compositions for minerals and *in situ* trace elemental measurements for garnets were carried out at the State Key Laboratory for Mineral Deposits Research, Nanjing University in Nanjing, China. Quantitative analyses (major elements) for clinopyroxene and garnet used a JEOL JXA-8100M electron-microprobe. The operating conditions were as follows: an accelerating voltage of 15 kV and a probe current of 2×10^{-8} A. The diameter of the electron beam was 1 μm for the rims of garnet and 10 μm for the cores of garnet. The counting times at the peaks were 20 s for major elements. All data were corrected with standard ZAF correction procedures. Natural minerals were used as standards. *In situ* trace elemental analyses of garnet were performed by laser-ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS, Agilent 7500a) equipped with a New Wave 213 nm laser ablation system. External standards used for LA-ICP-MS analysis were NIST (National Institute of Standard and Technology) SRM 610 and USGS (United States Geological Survey) BCR-2G. Ca was used for internal standardization. Laser ablation was conducted with a fluence of 10 to 20 J/cm², 5 Hz frequency, and 55 μm spot size.

Whole mineral trace elemental compositions were obtained at the Department of Geology, Northwest University in Xi'an, China. The cores of garnet and clinopyroxene grains were crushed into gravel-size chips and washed with distilled water. After drying, the freshest pieces of the chips were selected under binocular microscope. Only the chips without inclusions were picked up. After that, the selected chips were grounded into powders in an agate mortar. Trace elements, including the rare earth elements, were then determined using an ELANG100DRC inductively coupled plasma mass spectrometer (ICP-MS) after acid digestion of samples in Teflon bombs. Analyses of the USGS rock standards (BHVO-2, BCR-2, AGV-2, and GSP-1) indicate precision and accuracy better than 5% for V, Ni, Cu, Zn, Sr, Y, Nb, Cs, Ba, Hf, and REEs, and 10% for Li, Sc, Cr, Co, Ga, Ta, and U.

Isotopic analyses were performed at the State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering at Nanjing University, Nanjing, China. All chemical digestion and separation were carried out in a Class 100 ultra-clean laboratory and the mass spectrometric analyses were performed in a Class 1000 clean laboratory. All reagents used for leaching, dissolution and separation were twice-distilled, extra-pure grade. All dilutions were made using

$\geq 18.2 \text{ M}\Omega \text{ cm}^{-1}$ de-ionized water, and all labware was acid-washed prior to use. 100 mg megacryst powder was leached for 12 h in warm 2.5 N HCl and dissolved in a hot HF-HNO₃ mixture followed by ion exchange procedures. Isotope ratios of Sr were measured on a TRITON (Thermo Finnigan) thermal ionization mass spectrometer on single W filaments. Sr isotopic compositions were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. Detailed analytical procedures for Sr isotope can be seen elsewhere (e.g. Yu *et al.* 2017; Zeng *et al.* 2017). During the analytical session for our samples, the measured value for the NIST SRM 987 Sr standard was 0.710248 ± 0.000004 for $^{87}\text{Sr}/^{86}\text{Sr}$. The total procedure blank for Sr isotopes was less than 100 pg.

All measured data for samples are shown in Tables S1 and S2, and trace elemental data for standards are shown in Table S3. Trace elemental compositions obtained by whole mineral solution method are used in the following discussion part. LA-derived trace element data are only used for comparison between cores and rims of garnet and to validate the significance of whole mineral data by solution method (SFig. 2).

4. Compositional variations of Chishan megacrysts

Chishan clinopyroxenes are augite in composition without zoning, which is similar to the composition of basalt-borne clinopyroxenes from eastern China (Figure 2(a)). In comparison, clinopyroxenes from mantle xenolith are mainly diopside (Figure 2(a)). Clinopyroxene megacrysts have low $\text{Mg}^\#$ ($100 \times \text{molar Mg}/(\text{Mg} + \text{Fe}^{2+})$; 74.0–79.9) and negative correlations between $\text{Mg}^\#$ and CaO, TiO₂ (Figure 3(a,b)). In

comparison, basalt-borne clinopyroxenes from eastern China are characterized by lower $\text{Mg}^\#$ and CaO with higher TiO₂ than mantle xenoliths-derived megacrysts from eastern China (Figure 3(a,b)). For compatible elements, clinopyroxenes contain 178–339 ppm Ni and 14–95 ppm Sc. In chondrite-normalized (Anders and Grevesse 1989) rare earth element (REE) diagrams and primitive mantle-normalized (McDonough and Sun 1995) trace element diagrams, clinopyroxenes are enriched in middle rare earth elements (MREE) and depleted in both light (LREE) and high (HREE) rare earth elements (Figure 4(a,b)). Negative anomaly of Zr is observed for clinopyroxenes. In addition, clinopyroxenes show large variations of Hf/Sm (0.51–0.59), Ba/Th (47–166), and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70376–0.70408). Sr isotopic variation of clinopyroxenes is within the range of Sr isotopic variation of Cenozoic basalts from Shandong (Lee *et al.* 2006; Chen *et al.* 2009; Zeng *et al.* 2010, 2011; Sakuyama *et al.* 2013).

Chishan garnets are mainly pyrope in composition without obvious zoning (Figure 2(b)). They have low $\text{Mg}^\#$ (58.8–65.0). A negative correlation is observed between $\text{Mg}^\#$ and TiO₂, and a positive correlation between $\text{Mg}^\#$ and CaO (Figure 3(d,e)). In comparison, basalt-borne garnets from eastern China present lower $\text{Mg}^\#$ and higher CaO and TiO₂ than garnets originated from mantle xenoliths (Figure 3(d,e)). For compatible elements, garnets contain 67–197 ppm Ni and 47–90 ppm Sc. In terms of trace elements, all garnets are enriched in HREE over LREE (Figure 4(c,d)). Positive anomalies of various extents in Sr and Zr are seen for garnets. In contrast to basalt-borne garnets, our samples are characterized by enrichment of some LREE (Figure 4(c)), the same features can be seen in strongly incompatible elements like Rb

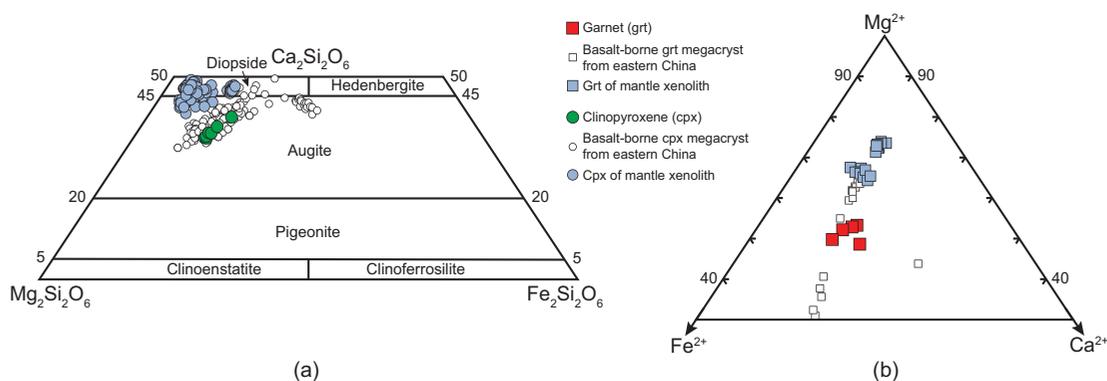


Figure 2. Compositional characteristics of the clinopyroxenes (A) following Morimoto *et al.* (1988) and ternary compositions in mole percent for garnets (B). Cation mole percent for Almandine (Fe²⁺), Pyrope (Mg²⁺), and Grossular (Ca²⁺) are shown in (B). Basalt-borne megacrysts and minerals of mantle xenolith from eastern China are shown as comparison. Basalt-borne garnets are from Kuandian (Huang *et al.* 1991; Liu *et al.* 1992a), Hannuoba (Huang *et al.* 1991), and Hainan (Yu and O'Reilly 2001), while clinopyroxene megacrysts are from Kuandian (Huang *et al.* 1991; Liu *et al.* 1992a; Li and Ma 2002), Jining (Du *et al.* 2006), Hannuoba (Liu *et al.* 1992a; Chen *et al.* 1997; He *et al.* 2013), Nushan (Chen *et al.* 1997; Xia *et al.* 2004; Zhang 1986) and Hainan (Yu *et al.* 2003). Clinopyroxene and garnet within mantle xenoliths are from (Fan *et al.* 2000; Rudnick *et al.* 2004; Zheng *et al.* 2005a, 2005b, 2006, 2010; Ying *et al.* 2006; Tang *et al.* 2008; Chu *et al.* 2009). Cited data can be referred to STable 4.

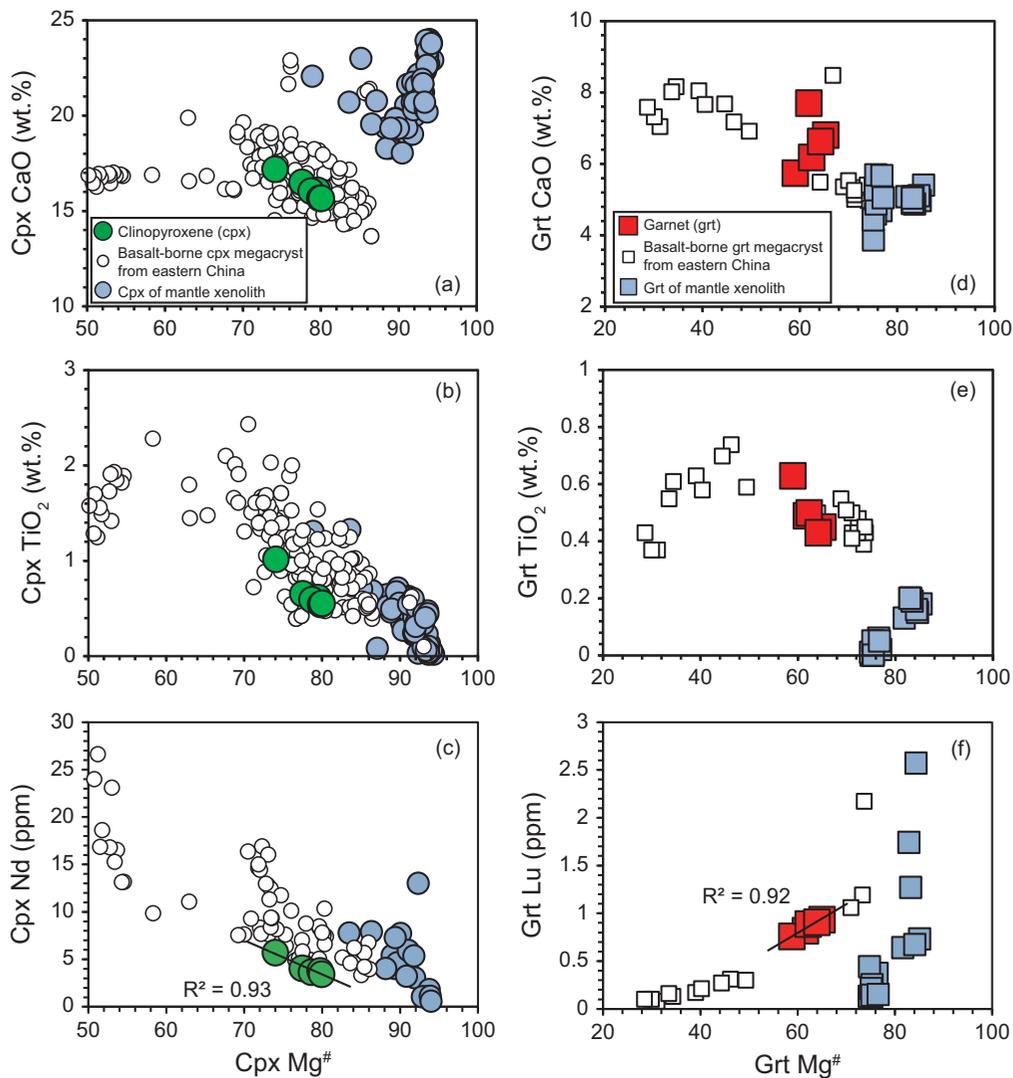


Figure 3. Major and trace elemental compositions for clinopyroxene (a, b, c) and garnet (d, e, f) megacrysts. Data for basalt-borne clinopyroxene and garnet megacrysts and clinopyroxene and garnet of mantle xenoliths from eastern China are the same as those in Figure 2. Cited data can be referred to STable 4. Symbols of samples are the same as in Figure 2.

and Th (Figure 4(d)). *In situ* trace elemental measurements further show that the garnet rims differ from the cores, the rims being more enriched in LREE and less enriched in HREE than the cores (SFig. 2). In addition, garnets show large variations of Rb/Sr (0.04–0.35) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70431–0.70627) ratios. Sr isotopic variation of garnets is over the range of Sr isotopic variation of Cenozoic basalts from Shandong (Lee *et al.* 2006; Chen *et al.* 2009; Zeng *et al.* 2010, 2011; Sakuyama *et al.* 2013).

5. Discussion

5.1. Effect of shallow processes on the geochemical compositions of megacrysts

Before we discuss the genesis of basalt-borne megacrysts by geochemical variations, effect of shallow

processes like interaction between megacrysts and host basaltic melts, contamination by wall rocks during upwelling should be considered. Both processes can enrich the strongly incompatible elements in the megacrysts (e.g. Depaolo 1981; Hoal *et al.* 1994; Ashchepkov *et al.* 2011). For Chishan megacrysts, garnets show enrichment of LREE and part of LILE (Figure 4(c,d)). It indicates that shallow processes might affect the elemental compositions of garnets. To examine the sources of enrichments, we measured the trace elements of cores and rims of garnets (STable 2). In comparison to cores, rims show obvious variable LREE and depletion of HREE (SFig. 2). Relative to garnets, host basaltic melt is characterized by enrichment of LREE and depletion of HREE (SFig. 2). The trends of elemental variations of rims are similar to the elemental pattern of host basaltic magmas (SFig. 2). It indicates that

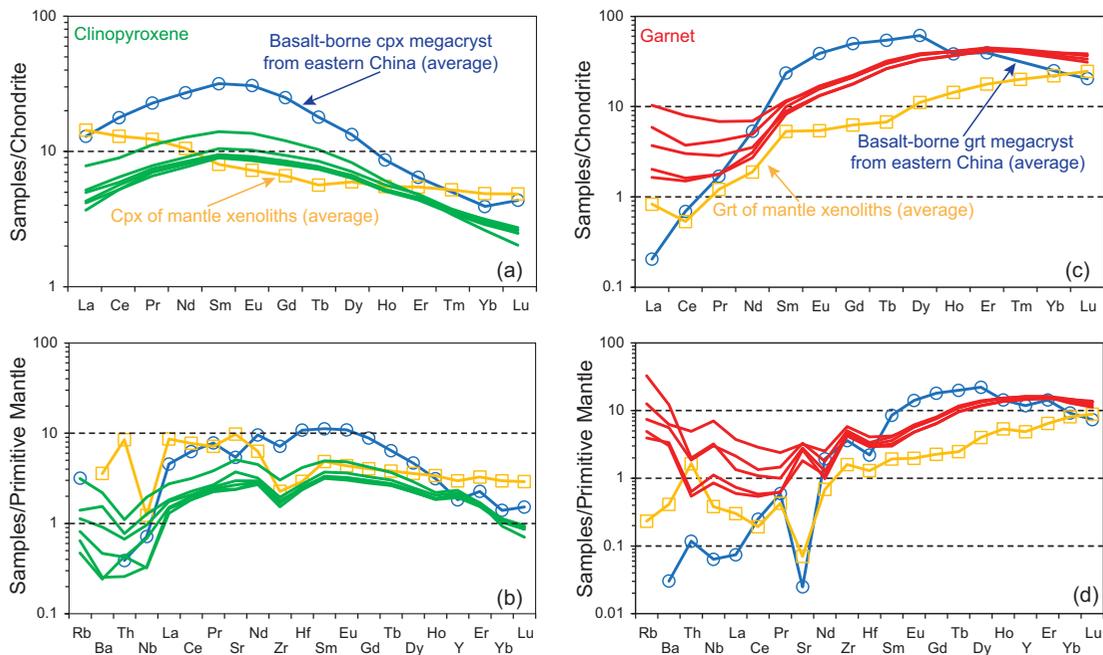


Figure 4. Chondrites-normalized rare earth element diagram and primitive mantle-normalized trace element diagrams for clinopyroxene and garnet megacrysts. Chondrites data are from Anders and Grevesse (1989) and the primitive mantle values are from McDonough and Sun (1995). Average trace elemental composition of basalt-borne megacrysts from eastern China (Chen *et al.* 1997; Du *et al.* 2006; He *et al.* 2013; Huang *et al.* 1991; Li and Ma 2002; Liu *et al.* 1992a; Xia *et al.* 2004; Yu *et al.* 2003; Zhang 1986). is shown as blue line with circle symbol, and average trace elemental composition of megacrysts from mantle xenolith (Fan *et al.* 2000; Zheng *et al.* 2005b, 2006, 2010; Ying *et al.* 2006; Tang *et al.* 2008) is shown as orange line with square symbol. The green lines represent the clinopyroxenes and the red lines stand for the garnets.

megacrysts and host melt are disequilibrium and rims of garnets were affected by melt-megacryst reaction. However, for cores of garnets, except for some LREE and strongly incompatible elements, MREE and HREE are consistent and homogeneous (Figure 4 and SFig. 2). Trace elemental data of garnets by solution method are located into the data area of garnet cores, indicating that the garnet samples we measured by solution method can represent the cores of garnets and most of the elemental compositions of them were not influenced by disequilibrium between megacrysts and host melt (SFig. 2).

In addition, we propose that wall rock contamination should also be excluded. First, besides of megacrysts, mantle xenoliths were also observed from Penglai basalts, indicating that ascending of basaltic melts and megacrysts should be fast and have no time to be contaminated (Chu *et al.* 2009). Second, according to geochemical studies of Penglai basalts, no signal of crustal contamination was observed (e.g. Lee *et al.* 2006; Sakuyama *et al.* 2013). Third, contamination of crustal wall rock should also enrich the strongly incompatible elements of clinopyroxene and garnet megacrysts (e.g. Depaolo 1981; Hoal *et al.* 1994; Ashchepkov *et al.* 2011). As continental crust is featured by high Sr with radiogenic Sr isotopes, contamination of crustal wall rock

could form good correlation between $1/\text{Sr}$ and Sr isotopes (SFig. 3). However, for Chishan megacrysts, no elemental enrichment is found for clinopyroxenes (Figure 4(a,b)) and no correlation is observed between $1/\text{Sr}$ and Sr isotopes for megacrysts (SFig. 3), indicating the negligible role of crustal contamination in the formation of Chishan megacrysts. Therefore, the geochemical variations of Chishan megacrysts can record the deep processes when they formed.

5.2. Origin of Chishan megacrysts: magmatic fractionation, rock fragments, or melt/fluid-rock reaction?

Previous studies have proposed three different models to explain the formation of basalt-borne megacrysts: (1) magmatic phases formed by fractional crystallization of magmas (e.g. Green and Ringwood 1964; Liotard *et al.* 1988; Shaw and Eyzaguirre 2000; Rankenburg *et al.* 2004; Xia *et al.* 2004; Akinin *et al.* 2005; Smith *et al.* 2008; Ashchepkov *et al.* 2011); (2) captured fragments of lithospheric mantle (e.g. Zhang *et al.* 2007; Yu *et al.* 2010); and (3) products of melt/fluid-rock reaction (e.g. He *et al.* 2013; Li *et al.* 2002a). Megacrysts formed by different processes are distinguishable in geochemistry, though they are similar in hand specimen (e.g. Liotard

et al. 1988; Dobosi and Jenner 1999; Shaw and Eyzaguirre 2000; Yu and O'Reilly 2001; Li and Ma 2002; Yu *et al.* 2003; Rudnick *et al.* 2004; Xia *et al.* 2004; Akinin *et al.* 2005; Zheng *et al.* 2005a, 2005b, 2006, 2010; Chu *et al.* 2009). The elemental compositions of megacrysts formed by magmatic fractionation should be affected by the temperature and composition of residual melts during crystallization (e.g. Lindsley and Andersen 1983; Johnson 1998; Adam and Green 2006). Ca and Ti, as well as $Mg^\#$ values, can be good indicators to trace above processes (e.g. Johnson 1998; Adam and Green 2006). In order to facilitate the comparison, we collected major and trace elemental data of clinopyroxenes and garnets in lithospheric mantle xenoliths and basalt-borne megacrysts from eastern China (Figures 2 (a) and 3). Most clinopyroxenes hosted in Penglai basalts show low $Mg^\#$ values (74.0–79.9), and their $Mg^\#$ values are negatively correlated to CaO contents (Figure 3(a)). These characteristics are similar to those of basalt-borne clinopyroxenes (Figure 3(a)) and are obviously different from those clinopyroxenes in mantle xenoliths. Garnets hosted in Penglai basalts show moderate $Mg^\#$ (58.8–65.0) and high TiO_2 contents (0.43–0.63 wt. %), and their $Mg^\#$ values are negatively correlated to TiO_2 contents (Figure 3(e)). These characteristics are also similar to those of basalt-borne garnets from eastern China (Figure 3(e)) and are obviously different from those garnets in xenoliths.

Megacrysts crystallized from magma should also obey the rules of Rayleigh fractional crystallization. For trace elements, Nd is incompatible into clinopyroxene, while Lu is compatible into garnet (e.g. Johnson 1998; Adam and Green 2006). Therefore, during fractional crystallization, the residual melt would be enriched in Nd and depleted in Lu, which would result in forming clinopyroxenes with negative correlations between $Mg^\#$ and Nd (Figure 3(c)), and garnets with a positive correlation between $Mg^\#$ and Lu (Figure 3(f)). However, fragments of lithospheric mantle are not affected by magmatic fractionation, so that they should be characterized by high $Mg^\#$ values with variable Nd or Lu contents based on the degree of depletion of the lithospheric mantle (e.g. Chu *et al.* 2009). Additionally, for the garnet megacrysts, basalt-borne garnets are characterized by enrichment of MREE, HREE but depletion of LREE and strongly incompatible elements (Figure 4(d)), which is caused by differences in partition coefficients during fractionation (e.g. Johnson 1998). In comparison, garnets in mantle xenoliths are characterized by lower MREE enrichment (Figure 4(c)), which may be the result of their complex geologic history (Zheng *et al.* 2005b, 2006). Garnet megacrysts from Penglai basalts are

more enriched in MREE and HREE than garnets from mantle xenoliths presenting similarities to the basalt-borne garnets (Figure 4(c)). In summary, we suggest that Chishan megacrysts are originated from magma by crystallization rather than the fragments of the lithospheric mantle, similar to most of the reported megacrysts from eastern China (e.g. Chen *et al.* 1997; Du *et al.* 2006; He *et al.* 2013; Li and Ma 2002; Xia *et al.* 2004; Yu and O'Reilly 2001; Yu *et al.* 2003).

Although megacrysts formed by melt/fluid-mantle reaction would show similar geochemical features to magmatic megacrysts in major elements (e.g. $Mg^\#$), they have much higher Cr contents (>2000 ppm) (e.g. Bodinier *et al.* 2008; He *et al.* 2013; Li *et al.* 2002a). Chishan megacrysts are characterized by low Cr contents (STable 1), indicating negligible role of the lithospheric mantle during their formation. In addition, megacrysts formed by melt/fluid-mantle reaction are mainly clinopyroxenes which show significant deformation (e.g. Bodinier *et al.* 2008; Zhang *et al.* 2012), which is different from the characteristics of Chishan megacrysts. Here we modelled the elemental variations for clinopyroxenes formed from melt-lithospheric mantle interaction by AFC model (e.g. Depaolo 1981; Lee *et al.* 2014). Lherzolite from Penglai was selected to represent the lithospheric mantle (Chu *et al.* 2009), while the equilibrated melt of sample 09CS-80 was regarded as the starting melt. Modelling results show that melt-peridotite interaction would decrease the HREE of clinopyroxenes. However, this process would not affect the strongly incompatible elements too much because these elements are highly incompatible in clinopyroxenes (SFig. 4a; e.g. Johnson 1998; Adam and Green 2006). Interaction between melt and low degree partial melts of mantle peridotite can modify both LREE and HREE (SFig. 4b). The enrichment of HREE for clinopyroxenes would also occur during this process because low degree partial melting of peridotite can form melts with enrichment in incompatible elements (SFig. 4b). Chishan clinopyroxenes except for 09CS-80 show variable contents of LREE/LILE and homogeneous HREE, suggesting that most of megacrysts were not affected by the melt-lithospheric mantle interaction, and therefore melt/fluid-mantle reaction cannot be the main mechanism forming the megacrysts of study area.

5.3. Pressure–temperature estimation of mineral crystallization

Because HREE and Zr are more compatible in garnet than in clinopyroxene ($D_{grt}^{Yb} > D_{cpx}^{Yb}$, $D_{grt}^{Zr} > D_{cpx}^{Zr}$; e.g. Johnson 1998), simultaneous crystallization of them would produce the enrichment of HREE and Zr in garnet

but depletion of these elements in clinopyroxene. The complementary trace element features between clinopyroxene and garnet megacrysts of Chishan (Figure 4) strongly indicate that they crystallized almost at the same time. In order to further affirm this conclusion, we modelled the fractional crystallization trend of an assumed basaltic melt and so crystallized clinopyroxene and garnet in plots of MgO versus Ni and Sm/Yb ratios (SFig. 5). Ni is more compatible in clinopyroxene than in garnet (Duke 1976) so that crystallization of these minerals simultaneous can generate higher Ni in clinopyroxene than in garnet with similar MgO content, as well as positive correlation between MgO and Ni (SFig. 5a). In addition, $D^{Sm/Yb}$ of garnet ($D^{Sm/Yb} = 0.04$) is much more incompatible than clinopyroxene ($D^{Sm/Yb} = 0.7$) (Johnson 1998). Thus, crystallization of clinopyroxene and garnet simultaneous can generate negative correlation between MgO and Sm/Yb ratios with higher Sm/Yb ratios in clinopyroxene (SFig. 5b). Chishan clinopyroxenes present higher Ni and Sm/Yb than garnets, as well as the consistent geochemical trend similar to the modelling results, suggesting that clinopyroxenes and garnets should crystallize at the same time.

Experimental results suggest that the Na₂O content of clinopyroxene and CaO content of garnet are dominantly controlled by the pressure of crystallization rather than temperature (Kogiso *et al.* 1998; Yaxley 2000; Barth *et al.* 2002; Hirschmann *et al.* 2003; Pertermann and Hirschmann 2003; Dasgupta *et al.* 2004, 2005; Keshav *et al.* 2004; Pertermann *et al.* 2004; Yaxley and Brey 2004), and therefore they can be used to estimate the crystallization pressure. For clinopyroxene, the crystallization pressure is generally positively correlated with the Na₂O content (Figure 5(a)). Clinopyroxenes in Penglai basalts contain 1.28 to 1.67 wt. % Na₂O, which reflect that their crystallization at pressure of 2.6 ± 0.4 GPa (Figure 5(a)). For garnets, a positive correlation is observed between the crystallization pressure and CaO content (Figure 5(b)). Therefore, high CaO contents (5.75–7.70 wt. %) for garnets in Penglai basalts also suggest that they crystallized at a high pressure (3.2 ± 1.0 GPa; Figure 5(b)). An additional estimation for the crystallization pressure of megacrysts is obtained based on the clinopyroxene-melt barometer (Table S1), where we need to assume a primary magma for Chishan megacrysts (Putirka 1999). Because the

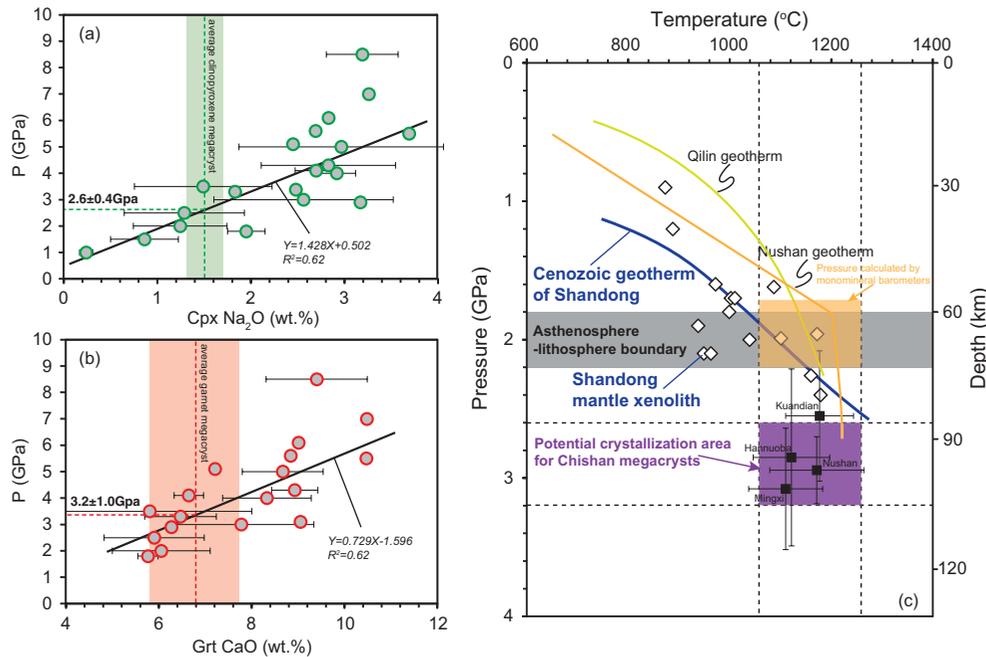


Figure 5. Na₂O content in experimental clinopyroxene (a) and CaO content in experimental garnet (b) in equilibrium with melt derived from experimental work as a function of pressure (Kogiso *et al.* 1998; Yaxley 2000; Barth *et al.* 2002; Hirschmann *et al.* 2003; Pertermann and Hirschmann 2003; Dasgupta *et al.* 2004, 2005; Keshav *et al.* 2004; Pertermann *et al.* 2004; Yaxley and Brey 2004), and average elemental compositions are shown for each pressure with one standard error. (c) Cenozoic geotherm beneath eastern North China craton. The green shaded area in (a) and the red shaded area in (b) mean the Na₂O and CaO elemental compositions for clinopyroxene and garnet megacrysts, respectively. Cenozoic geotherm of Shandong in (c) is estimated by mantle peridotites from Zheng *et al.* (2005a) and Zheng *et al.* (2006). Geotherm lines for Qilin and Nushan are from Xu *et al.* (1996) and Liu *et al.* (2012). The grey shaded area in (c) represents the lithosphere-asthenosphere boundary as estimated from Chen *et al.* (2008). And the purple shaded area in (c) represents the pressure-temperature we calculated from Chishan megacrysts. Estimated pressure and temperature for megacrysts from Kuandian, Hannuoba, Nushan, and Mingxi are shown, the details of which can be found in Table 1.

primary magma of the Chishan megacrysts is unknown, we picked the basalt samples showing the least effect of fractional crystallization from the Cenozoic Shandong basalts (Lee *et al.* 2006; Zeng *et al.* 2010; Sakuyama *et al.* 2013). Then we used the PRIMELT2 software (Herzberg and Asimow 2008) to calculate the average composition of the primary magma for these selected basalt samples. The calculated pressure by clinopyroxene-melt barometer is 2.6 ± 0.1 GPa (Table S1), which agrees well with the results above (Figure 5(a,b)). Therefore, the crystallization pressure for Chishan megacrysts is inferred to range from 2.6 GPa to 3.2 GPa. In addition, we calculated the pressures for clinopyroxene and garnet by monomineral barometers (e.g. Ashchepkov *et al.* 2013, 2017, 2017). Results show that clinopyroxene might crystallize at 1.7 ± 0.2 GPa and the garnets might crystallize at 2.1 ± 0.2 GPa. The crystallization temperature of megacrysts is calculated from the method of Nimis and Taylor (2000), which is about $1156 \pm 56^\circ\text{C}$. We also calculated the crystallization temperature (Table 1 and Table S1) by garnet-clinopyroxene geothermometer (Ravna 2000) to test the accuracy of the temperature estimated above. The result is $1175 \pm 72^\circ\text{C}$ which is close to the temperature as calculated by method of Nimis and Taylor (2000). Though the pressure as calculated by monomineral barometers is lower, we found that the pressure as calculated by cpx-melt barometer is similar to the pressure achieved by empirical equation by experimental data (Table 1). Thus, we prefer to select the higher pressure calculated. Furthermore, calculated results by monomineral barometer (e.g. Ashchepkov *et al.* 2013, 2017, 2017) show that Chishan megacrysts are located at the boundary of lithospheric mantle and

asthenosphere in study area (Figure 5(c)). This does not conflict with the conclusions we would achieve in the following discussions. We suggest that the accuracy of the pressure as calculated by different barometers should be put in the second order.

Based on this crystallization pressure, Chishan megacrysts could crystallize at depths of 85–105 km (Figure 5(c)). Because the boundary of lithosphere and asthenosphere in this area is about 60–70 km (e.g. Chen *et al.* 2008), the megacrysts formed at the top of the asthenospheric mantle. For comparison, the pressure and temperature of megacrysts from other locations in eastern China, including Kuandian (NCC), Hannuoba (NCC), Nushan (YC), and Mingxi (CB), are also estimated using the same empirical methods (Table 1). Relative to the geothermal lines of different blocks, these megacrysts show higher pressures, indicating that the origins of megacrysts should be deeper than or close to the lower boundary of the lithospheric mantle. This conclusion has also been mentioned in the previous studies of megacrysts from Jining, Hebi, and Nushan (Chen *et al.* 1997; Du *et al.* 2006; Xiao *et al.* 2008).

5.4. Magma–magma interaction in the mantle: mechanism for the formation of high-pressure megacrysts during crystallization

For megacrysts crystallized from magmas, three different mechanisms have been proposed, including (1) near-liquidus fractionation of basaltic magma (e.g. Green and Ringwood 1964; Shaw and Eyzaguirre 2000; Smith *et al.* 2008; Ashchepkov *et al.* 2011; He *et al.* 2013), (2) temperature buffering by mixing of magmas

Table 1. Estimated pressure and temperature for representative megacrysts from eastern China.

Location	Penglai, Shandong	Kuandian, Liaoning	Hannuoba, Hebei	Nushan, Anhui	Mingxi, Fujian
^a Cpx-Na ₂ O (wt.%)	1.4	1.4	1.6	1.8	1.7
stdev (wt.%)	0.1	0.3	0.4	0.3	0.2
^b Pressure (GPa)	2.6	2.5	2.8	3.1	2.9
stdev (GPa)	0.4	0.5	0.6	0.4	0.2
^c Temperature (°C)	1156.2	1175.6	1120.3	1108.8	1170.1
stdev (°C)	55.6	66.7	75.3	72.7	92.7
^d Grt-CaO (wt.%)	6.6	5.3	6.8	-	-
stdev (wt.%)	0.7	0.2	1.0	-	-
^e Pressure (GPa)	3.2	2.3	3.4	-	-
stdev (GPa)	1.1	0.1	0.7	-	-
^f Temperature (°C)	1174.9	1255.5	-	-	-
stdev (°C)	72.4	29.5	-	-	-

^aNa₂O data for Kuandian clinopyroxenes can be referred to Huang *et al.* (1991); Li and Ma (2002); Liu *et al.* (1992a). Na₂O data for Hannuoba clinopyroxenes can be referred to Chen *et al.* (1997); He *et al.* (2013); Li and Ma (2002); Liu *et al.* (1992a). Na₂O data for Nushan clinopyroxenes can be referred to Xia *et al.* (2004); Zhang (1986). Na₂O data for Mingxi clinopyroxenes can be referred to Huang *et al.* (1991); Zhang (1986).

^bPressure calculated by relationship between pressure and Na₂O in clinopyroxene.

^cTemperature calculation can be referred to Nimis and Taylor (2000).

^dCaO data for Kuandian garnets can be referred to Huang *et al.* (1991); Liu *et al.* (1992a). CaO data for Hannuoba garnets can be referred to Huang *et al.* (1991); He *et al.* (2013).

^ePressure calculated by relationship between pressure and CaO in garnet.

^fTemperature calculation by grt-cpx geothermometer according to Ravna (2000).

from the same source with different evolved degrees in lithospheric mantle (e.g. Liotard *et al.* 1988; Rankenburg *et al.* 2004), and (3) magma–magma mixing at deep mantle depths (Herzberg 2011; Zeng *et al.* 2017). Based on the similar partition coefficients between Yb and Er for clinopyroxene and garnet ($D^{Yb/Er} \approx 1$) (e.g. Johnson 1998; Klemme *et al.* 2002), near-liquidus fractionation of megacrysts cannot produce significant variations of Yb/Er for clinopyroxene and garnet megacrysts. Positive correlations between $Mg^\#$ and Yb/Er for both clinopyroxenes and garnets (Figure 6) suggest that, though they crystallized from magmas, these megacrysts cannot simply be the result of near-liquidus fractionation of the same basaltic magma. This deduction can also be certified by the correlations between $^{87}Sr/^{86}Sr$ and different trace elemental ratios of megacrysts (SFig. 6). For clinopyroxene, Ca/Al ratio can be a good index to represent the crystallization degree of melt. Nonetheless, the negative correlation between $^{87}Sr/^{86}Sr$ and Ca/Al (SFig. 6a) suggests that mixing has affected the geochemical compositions of clinopyroxene besides of fractional crystallization. For garnet, Zr and Sm show similar partition coefficients (Johnson 1998) during mineral crystallization, thus Zr/Sm ratio together with $^{87}Sr/^{86}Sr$ can tell us the mixing information. The negative correlation between $^{87}Sr/^{86}Sr$ and Zr/Sm (SFig. 6b) indicates that mixing happened in the formation of garnets. Therefore, mixing should be considered. For the second scenario, crystallization of megacrysts is triggered by the replenishment of more primitive melts into fractionated derivatives, which would buffer the temperature of the magmas. Such a mechanism is proposed for magmas with high temperature ($\sim 1400^\circ C$) at depths of ~ 2 GPa (e.g. Rankenburg *et al.* 2004), which is higher than the crystallization temperature of Chishan megacrysts ($\sim 1156^\circ C$). In addition, this mechanism cannot explain the

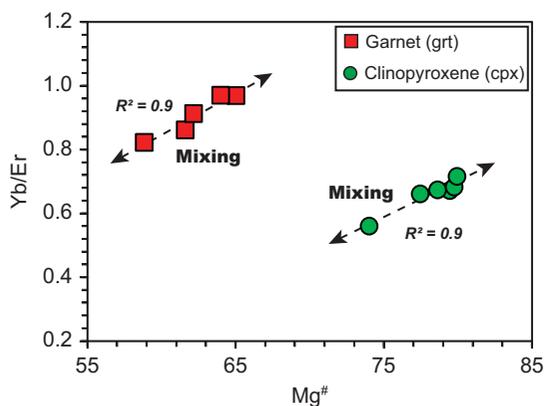


Figure 6. Plot of $Mg^\#$ versus Yb/Er for Chishan megacrysts. Symbols of samples are the same as in Figure 2.

correlations between $Mg^\#$ and Yb/Er (Figure 6) as well as variable Sr isotopic compositions (SFig. 6). Therefore, we suggest that Chishan megacrysts were most likely formed by crystallization triggered by magma–magma mixing at mantle depths.

Variable Sr isotopic compositions of these megacrysts and good correlations between $^{87}Sr/^{86}Sr$ ratios and Hf/Sm ratios of calculated primary magmas further support the mixing scenario in formation of them (Figure 7). The variation of $^{87}Sr/^{86}Sr$ ratios of Shandong basalts has been owed to heterogeneity of mantle sources, wherein the enriched end-member attributes to the recycled oceanic crust or lower continental crust in the mantle (e.g. Lee *et al.* 2006; Zeng *et al.* 2010, 2011; Sakuyama *et al.* 2013). Chishan clinopyroxenes and garnets show more than half scale of variation relative to the Shandong basalts in Sr isotopic ratios (Figure 7). Furthermore, clinopyroxene and garnet show similar partition coefficients when magmas experienced fractional crystallization in deep depth ($D_{cpx}^{Hf} = 0.20$, $D_{cpx}^{Sm} = 0.29$, $D_{grt}^{Hf} = 0.24$, $D_{grt}^{Sm} = 0.25$; Johnson 1998). Thus, the difference in mineral proportion

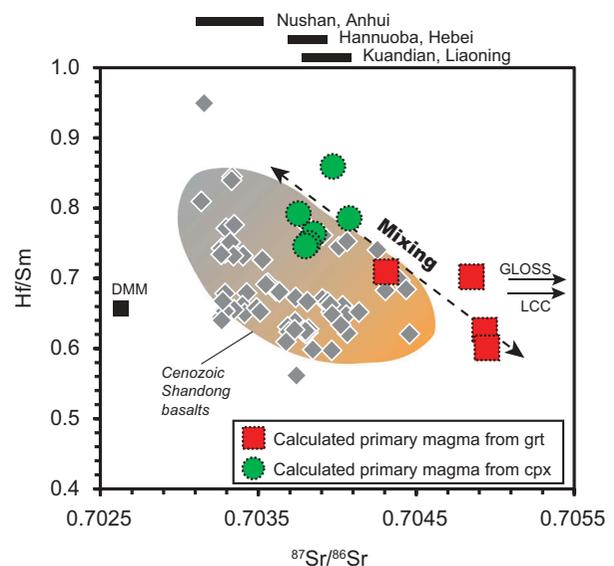


Figure 7. Sr isotopic variations against Hf/Sm ratios for primary magmas of megacrysts and Cenozoic Shandong basalts. Isotopic compositions of Cenozoic basalts from eastern Shandong are shown (Lee *et al.* 2006; Zeng *et al.* 2010, 2011; Sakuyama *et al.* 2013). Isotopic and elemental ratios of global subducting sediment (GLOSS), lower continental crust (LCC), and depleted MORB mantle (DMM) are derived from Plank and Langmuir (1998); Rudnick and Gao (2003) and Workman and Hart (2005). Sr isotopic variations for clinopyroxene megacrysts from Kuandian (Huang *et al.* 1991; Liu *et al.* 1992a), Hannuoba (Huang *et al.* 1991; He *et al.* 2013), and Nushan (Chen *et al.* 1997; Xia 2004) are also shown. The Hf/Sm ratios of primary magmas were back calculated based on the Rayleigh fractional crystallization equation. Symbols of Chishan megacrysts are the same as in Figure 2.

between clinopyroxene and garnet, as well as the weak difference between the ratios of fractional crystallization, would not fractionate Hf/Sm ratios when we back calculated the primary magmas of megacrysts. Therefore, in this study, we can assume that 20% of clinopyroxene and garnet megacrysts (8:2) were crystallized, and then we back calculated the Hf/Sm ratios of primary magmas before the crystallization of Chishan clinopyroxene and garnet. Remarkably, negative correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and Hf/Sm is observed for primary magmas of megacrysts which is consistent with the mixing trend of Shandong basalts (Figure 7). It further suggests a mixing origin for Chishan megacrysts. In addition, the signal of magma–magma mixing can be confirmed by elemental compositions of clinopyroxene megacrysts (Figure 8(a)). Strongly incompatible element ratios like Nb/U and Ba/Th are used to discuss the source components of basalts. For example, the positive correlation between Nb/U and Ba/Th of Cenozoic Shandong basalts indicates mixing of two end-members in their source, containing an eclogite/pyroxenite rock source and a peridotite rock source (e.g. Lee *et al.* 2006; Chen *et al.* 2009; Zeng *et al.* 2010, 2011; Sakuyama *et al.* 2013). For Chishan clinopyroxenes, a positive correlation is seen in the plot of Nb/U and Ba/Th (Figure 8(a)) and is similar to the mixing trend as shown by Cenozoic Shandong basalts, which confirms the mixing origin of these megacrysts.

As highlighted, previous studies have revealed that mixing process between two types of magmas (SiO_2 -saturated and SiO_2 -undersaturated) at mantle depth can trigger the high-pressure crystallization of clinopyroxene and garnet (Kato and Kumazawa 1985; Herzberg and Zhang 1998; Herzberg 2011). Based on the studies

on the Cenozoic basalts from Shandong, the mantle beneath the area is suggested to be composed of recycled crustal and carbonated lithology (e.g. Chen *et al.* 2009; Liu *et al.* 2015a; Sakuyama *et al.* 2013; Zeng *et al.* 2010, 2011). The recycled crustal source is characterized by high Nb/U and Ba/Th ratios with low Ca/Al and Sm/Yb ratios (Figure 8). In addition, the recycled crustal source presents high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with low ϵ_{Nd} and ϵ_{Hf} values (e.g. Zeng *et al.* 2011; Sakuyama *et al.* 2013). In comparison, the carbonated source is characterized by low Nb/U and Ba/Th ratios with high Ca/Al and Sm/Yb ratios (Figure 8), and their isotopic compositions are relatively depleted (with low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, high ϵ_{Nd} and ϵ_{Hf} values; Zeng *et al.* 2011; Sakuyama *et al.* 2013). It provides the possibility for the mixing between magmas derived from different source lithology. Furthermore, if the basaltic magma has undergone such high-pressure fractionation of clinopyroxenes and garnets, it is proposed to show high Sm/Yb (>4.0) but low Ca/Al (<0.8), because Yb is compatible to the garnet and Ca is compatible to the clinopyroxene (Zeng *et al.* 2017) (Figure 9). We modelled the fractionation of clinopyroxene and garnet for a mixed magma with Sm/Yb = 6 and Ca/Al = 1 in Figure 8(b). Different proportions of garnet relative to clinopyroxene (Grt:Cpx = 1:9, 2:8, 3:7) are assumed. No matter how we changed the proportion, the basaltic magmas experienced clinopyroxene and garnet fractionation show obvious deviation to the mixing trend of basalts. Wherein, the modelling trend is similar to the deviation of high-Sm/Yb, low-Ca/Al basalts from Shandong (Figure 8(b)), which further support our interpretation that Chishan megacrysts were formed by the high-

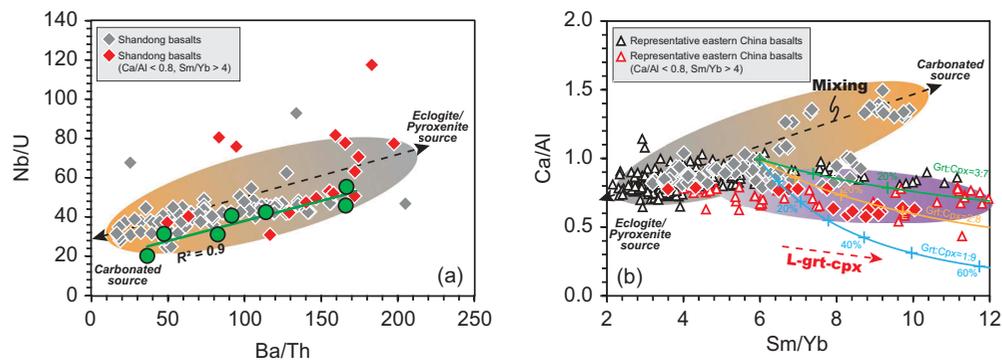


Figure 8. Plot of Ba/Th versus Nb/U and Sm/Yb versus Ca/Al for Cenozoic basalts from Shandong and representative basalts from eastern China. In both (a) and (b), Cenozoic Shandong basalts can be referred to Lee *et al.* (2006), Sakuyama *et al.* (2013), Zeng *et al.* (2010), and Zeng *et al.* (2011). In (b), basalt data from Hannuoba (Song *et al.* 1990; Zhi *et al.* 1990; Basu *et al.* 1991; Liu *et al.* 1994; Guo *et al.* 2016), Leiqiong (Zou and Armstrong 1982; Tu *et al.* 1991; Flower *et al.* 1992; Ho *et al.* 2000; Wang *et al.* 2012, 2013), and Jining (Ho *et al.* 2011; Guo *et al.* 2014) are also shown. Rayleigh fractional crystallization is modelled for Shandong basalts to show the influence of clinopyroxene and garnet fractionation on basalt geochemistry. Assumed starting primary melt is derived from the mixing trend which is characterized by Sm/Yb = 6 and Ca/Al = 1. During the modelling, partition coefficients for Sm, Yb, Ca and Al were referred to Adam and Green (2006) and Johnson (1998). Symbols of Chishan megacrysts are the same as in Figure 2.

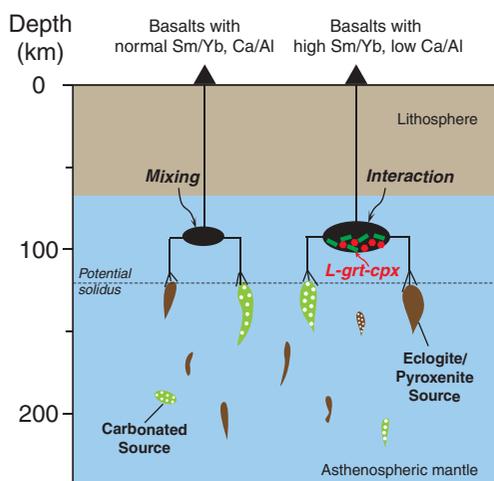


Figure 9. Cartoon illustrating the formation of basalt-borne megacrysts and host intraplate basalts from eastern China. Carbonated component and eclogitic/pyroxenitic component melted subsequently at upper mantle level. Mixing of the magmas from different sources forms basalts with normal Sm/Yb and Ca/Al ratios, while magma–magma interaction causes the generation of basalt-borne megacrysts. The basalts formed by magma–magma interaction show higher Sm/Yb and lower Ca/Al ratios, which deviate from the trend of mixing.

pressure fractional crystallization triggered by magma–magma mixing at the mantle depth (Figure 9).

5.5. Implications for the genesis of intraplate basalts and mantle heterogeneity

The effect of high-pressure fractional crystallization during the formation of intraplate basalts was rarely mentioned in previous studies, because such mechanism has not been fully understood and it is still unknown whether this mechanism is common or not. In order to make it clear, we compared both megacryst data and basalt data from eastern China. In Figure 5(c), pressure estimations have already shown that basalt-borne megacrysts from eastern China should have a deeper origin than the lithospheric mantle. It is difficult for us to compare the trace element ratios for megacrysts due to the lack of high quality trace element data. However, the diversity of Sr isotopic ratios for clinopyroxene megacrysts from different places (Figure 7; 0.70382–0.70401 for Kuandian, 0.70374–0.70387 for Hannuoba, and 0.70309–0.70346 for Nushan) indicates that, similar to Chishan megacrysts, they may be formed by magma–magma mixing process. In other words, high-pressure crystallization of megacrysts triggered by magma–magma mixing could be a common phenomenon for intraplate basalts from eastern China. The same deduction can be achieved from the view of host basalts. Basalt data from some typical megacryst

outcrops from eastern China such as Jining, Hannuoba, and Leiqiong are shown in Figure 8(b). Mantle heterogeneities have been reported for the sources of these basalts (e.g. Wang *et al.* 2012, 2013; Guo *et al.* 2014, 2016). In the plot of Sm/Yb versus Ca/Al, most of the basalts are located on the trend of mixing between two end-members, one is a SiO₂-saturated end-member and the other one is a SiO₂-undersaturated end-member (Figure 8(b)). However, the basalts with high Sm/Yb (>4.0) but low Ca/Al (<0.8) show obvious deviation from the trend of mixing, which is consistent with the feature we observed from Shandong basalts and the fractionation trend we modelled (Figure 8(b)). It means that high-pressure fractional crystallization of clinopyroxene and garnet has already influenced the compositions of basalts in these areas. Therefore, it further indicates that magma–magma interaction in depths is common in formation of intraplate basalts for the cited places from eastern China (Figure 8(b)).

Besides forming the megacrysts, high-pressure crystallization of clinopyroxene and garnet can also form eclogite/pyroxenite in the upper mantle or in the boundary between lithosphere and asthenosphere. Since such mafic lithology has been proposed to be a potential source for intraplate basalts (e.g. Sobolev *et al.* 2005, 2007; Liu *et al.* 2008; Chen *et al.* 2009, 2017; Zhang *et al.* 2009; Herzberg 2011; Xu *et al.* 2012), studying the high-pressure megacrysts provides us with a way to understand the mantle source of intraplate basalts. More importantly, if such high-pressure megacrysts formed during the magma–magma interaction are common in the upper mantle, the occurrence of clinopyroxene and garnet should be taken into consideration in the explanation of geophysical observations of the upper mantle.

6. Conclusion

Clinopyroxene and garnet megacrysts hosted in Cenozoic Penglai basalts provide a good view into understanding the process of magma–magma interaction in the asthenospheric mantle depth and formation of intraplate basalts. Major and trace elemental compositions and correlations suggest that all megacrysts were crystallized from the basaltic magma. Based on the local lithospheric thickness (~60–70 km), pressure and temperature estimations show that megacrysts were formed at the top of the asthenosphere or lithosphere–asthenosphere boundary. The variable Sr isotopes of megacrysts and positive correlation between ⁸⁷Sr/⁸⁶Sr and Hf/Sm of primary magmas, and positive correlation between Nb/U and Ba/Th of clinopyroxenes, confirm the

magma–magma mixing origin for these megacrysts, verifying the magma–magma interaction model in formation of intraplate basalts. When in comparison with megacrysts and basalts from other places of eastern China, similarities in geochemical variation are observed, indicating that magma–magma interaction can be a common mechanism in formation of intraplate basalts. Since magma–magma interaction process provides an alternative way to form eclogite/pyroxenite in the upper mantle, the geochemistry of high-pressure megacrysts can help us better understand the formation of intraplate basalts and geochemical heterogeneity of upper mantle.

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Disclosure statement

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