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Multiple exsolutions in a rare clinopyroxene megacryst from the Hannuoba basalt, North China: Implications for subducted slab-related crustal thickening and recycling

Detao He, Yongsheng Liu *, Xirun Tong, Keqing Zong, Zhaochu Hu, Shan Gao

State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China

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ABSTRACT

A rare large clinopyroxene megacryst (referred to as type 1) collected from the Hannuoba basalt, North China was studied. It is distinguished from the prevalent clinopyroxene megacrysts (type 2) by garnet and orthopyroxene exsolutions and by elemental and Sr–Nd isotopic compositions. The type 1 clinopyroxene megacryst has higher Cr and Nb contents and Mg# (82.9) than the type 2 clinopyroxene megacrysts as well as more evolved Sr and Nd isotopic compositions ($^{87}Sr/^{86}Sr = 0.704520$, $^{143}Nd/^{144}Nd = 0.512350$) than clinopyroxene megacrysts elsewhere. These characteristics suggest that the type 1 clinopyroxene megacryst could have been formed by a recycled crust-related melt–peridotite reaction and that the melt formed in the rutile unstable field. The type 2 clinopyroxene megacrysts exhibit good correlations between Mg# and major and trace element compositions. Type 2 Sr–Nd isotopic compositions cluster at the least evolved end of the Hannuoba basalt composition. These observations imply that the type 2 clinopyroxene megacrysts were crystallized from the host lava at high pressure.

The type 1 clinopyroxene megacryst contains abundant coherent cryptocrystalline lamellae and orthopyroxene exsolutions. The bulk composition of the cryptocrystalline lamellae, composed of fine plagioclase and olivine, shows typical chemical features of garnet with a Sr isotopic composition similar to the clinopyroxene host. These observations indicate that the cryptocrystalline lamellae are decomposition products of garnet exsolutions in the clinopyroxene megacryst. P–T estimates suggest that garnet exsolution in the clinopyroxene megacryst could have occurred at 2.75 GPa and 1290 °C. This garnet exsolution could be caused by increasing pressure or decreasing temperature, as indicated by experimental results. Although the temperature decreases during basalt eruption, the much quicker decrease in pressure will suppress the garnet exsolution in clinopyroxene. Therefore, we suggest that the type 1 clinopyroxene megacryst could have experienced pre-Mesozoic crustal uplifting and thickening at the north margin of the North China Craton. Garnet decomposition could have taken place prior to orthopyroxene exsolution during the eruption of the host lava.

1. Introduction

Clinopyroxene megacrysts commonly occur in alkaline basaltic lavas and kimberlites (Akinin et al., 2005; Dobosi and Jenner, 1999; Huang et al., 2007; Pivin et al., 2009; Shaw and Eyzaguirre, 2000) and have a variety of origins. They may precipitate at elevated pressures from basaltic magmas as near-liquidus phases (Akinin et al., 2005; Dobosi and Jenner, 1999; Shaw and Eyzaguirre, 2000), as supported by high-temperature–pressure experiments (Adam, 1990), or may have been entrained in the magma as accidental fragments of disaggregated mantle xenoliths (Righter and Carmichael, 1993). Thus, these clinopyroxene megacrysts can be used to trace both the evolution of parental magmas (Akinin et al., 2005; Shaw and Eyzaguirre, 2000) and the composition of melts and minerals at mantle conditions (Pivin et al., 2009).

Garnet exsolutions in pyroxene were first recognized in an eclogite xenolith from a South African kimberlite by Beck (1907). Since then, this exsolution texture has been found not only in eclogite xenoliths within kimberlite (Aoki et al., 1980), but also in eclogites within serpentinites in metamorphic complexes (Reiche and Bautsch, 1985), clinopyroxene megacryst (Huang et al., 2007), and clinopyroxenite xenoliths (Xu et al., 2004) within basaltic magmas, HP/UHP terranes (Hwang et al., 2011; Zhang et al., 2000), and ultra-mafic rocks (Faryad et al., 2009). The garnet exsolutions in clinopyroxene generally indicate

* Corresponding author. Tel.: +86 27 87483044; fax: +86 27 67885096.
E-mail addresses: yshliu@cug.edu.cn, yshliu@hotmail.com (Y. Liu).

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high P–T equilibrium (Faryad et al., 2009; Nishi et al., 2011; Xu et al., 2004). Clinopyroxene can incorporate significant amounts of aluminum by Ca-, Mg- and Fe-Tschermak substitutions (Wood and Banno, 1973). These substitutions occur within silicon–oxygen tetrahedron of a clinopyroxene crystal and may be promoted by low pressures and high temperatures. In other words, the aluminum content in clinopyroxene increases with decreasing pressure and increasing temperature (Gasparik, 2000). As a consequence, cooling or increasing pressure may result in the unmixing of excess aluminum by exsolving garnet (Aoki et al., 1980; Faryad et al., 2009; Reiche and Bautsch, 1985; Zhang et al., 2000).

The southward subduction of the Paleo-Asian oceanic crust beneath the North China Craton (NCC) (Chen et al., 2009; Xiao et al., 2003) could have induced widespread melt–peridotite interaction at the northern margin of the NCC, as suggested by the relatively high radiogenic Sr isotopic compositions of some garnet pyroxenite xenoliths (Xu, 2002), variable Li isotope ratios of peridotite xenoliths (Tang et al., 2007), and zircon U–Pb dating of composite xenoliths of garnet pyroxenite + peridotite (Liu et al., 2010b) from the Hannuoba basalts. Melt–peridotite reactions can generate pyroxene at the expense of olivine, as suggested by experiments (Mallik and Dasgupta, 2012; Rapp et al., 1999; Wang et al., 2010) and natural samples (Liu et al., 2005; Liu et al., 2010b).

In this paper, we report a unique clinopyroxene megacryst with evolved Sr–Nd isotopic compositions and multi-stage exsolutions. In-situ and bulk compositions of major and trace elements and Sr–Nd isotopes were analyzed to constrain the petrogenesis and P–T evolution of the megacryst.

2. Geological setting

The NCC is one of the oldest Archean cratons in the word and preserves crustal remnants as old as 3.8 Ga (Liu et al., 1992). It is bordered by the eastern part of the Central Asian Orogenic Belt to the north and the Qinling–Sulu–Dabie Orogen to the south. The NCC can be subdivided into the eastern block, the western block, and the intervening Trans-North China Orogen (Fig. 1, inset) (Zhao et al., 2001). Zhao et al. (2001) and Wilde et al. (2002) suggested that an ancient ocean existed between the eastern and western blocks and that the western block was subsequently subducted beneath the eastern block, resulting in the final amalgamation of the two blocks along the central zone at 1.85 Ga. However, Li et al. (2002) and Kusky et al. (2001) argued that the western and eastern blocks were amalgamated during a ~2.5 Ga collision event. The eastern block had a cold and thick lithosphere, typical of other Archean cratons, at least through the Ordovician, when the diamond- and garnet peridotite-bearing kimberlites erupted (Menzies et al., 1993). Garnet peridotite xenoliths carried by the kimberlites have Archean Os model ages (Gao et al., 2002; Wu et al., 2006). During the late Mesozoic and Cenozoic, however, the eastern part of the craton experienced widespread tectonothermal reactivation and lithospheric thinning accompanied by the replacement of the refractory cratonic root by a fertile lithospheric mantle (Gao et al., 2004; Griffin et al., 1998; Menzies et al., 2007; Wu et al., 2006; Xu, 2001).

The Hannuoba basalts are found along the northern margin of the NCC, covering an area of 1700 km^2. The basalts have been dated at 14 to 27 Ma by the K–Ar method (Zhu, 1998). Abundant lower crustal and upper mantle xenoliths were carried by the basalts and have been studied from various perspectives (e.g. Chen et al., 2001; Gao et al., 2000; Liu et al., 2001; Liu et al., 2003; Liu et al., 2010a; Rudnick et al., 2004; Tang et al., 2007; Xu, 2002; Zhou et al., 2002). Most of the xenoliths have been found near Damaping village, the clinopyroxene megacrysts studied herein were also collected from the same locality.

3. Samples

Two types of clinopyroxene megacrysts collected from the Hannuoba basalts were identified based on physical properties and geochemical compositions. Type 1 clinopyroxene megacryst is deep

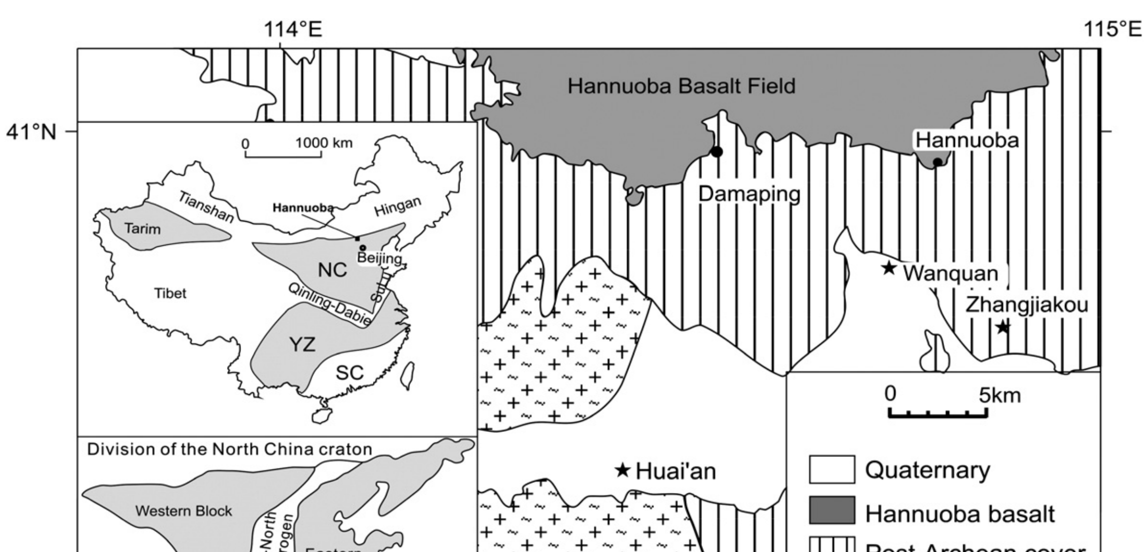

Fig. 1. Simplified geological map of the Hannuoba area. The clinopyroxene megacrysts were collected from the Damaping area. The divisions of the North China Craton (inset) are after Zhao et al. (2000).