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On the significance of temperatures derived from major element and REE based two-pyroxene thermometers for mantle xenoliths from the North China Craton

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ABSTRACT

Thermal evolution of the North China Craton (NCC) has been a subject of extensive geochemical and geophysical investigations. To better constrain the thermal state of lithospheric mantle beneath the NCC, we calculated and compared equilibrium or closure temperatures for peridotite and pyroxenite xenoliths from the NCC lithospheric mantle using major element-based two-pyroxene thermometers and a REE-based two-pyroxene thermometer. Samples included in this study are ancient refractory peridotites entrained by Early Cretaceous high-Mg diorites from Fushan within the central NCC, peridotites with varying chemical compositions and rhenium-depletion model ages entrained by younger than 100 Ma alkali basalts from the central and eastern NCC, and pyroxenites entrained by Early Cretaceous alkali basalts from Feixian and Fangcheng within the eastern NCC. The Fushan peridotites have low major element-derived temperatures and slow cooling rates, owing to the shallow intrusion of their host diorites. The peridotites in younger than 100 Ma alkali basalts have a more complicated thermal history. The Fexian and Fangcheng pyroxenites have relatively high temperatures and moderate to fast cooling rates. The present thermometric data, combined with the published petrologic, geochemical, and seismic observations, provide new insight into the thermal state and thermal evolution of the NCC lithospheric mantle in the Mesozoic and Cenozoic.

1. Introduction

The discoveries of Archean garnet peridotite xenoliths in Ordovician diamond-bearing kimberlites (e.g., Gao et al., 2002; Lu et al., 1991; Zhang et al., 2008; Zheng, 1999, Fig. 1) and spinel peridotite xenoliths in alkali basalts younger than 100 Ma (e.g., E and Zhao, 1987; Rudnick et al., 2004; Xu et al., 1999; Zheng et al., 2007, Fig. 1) reveal a more than 100 km reduction of lithosphere of the central and eastern North China Craton (NCC) after Ordovician and a replacement of a refractory lithospheric mantle by a fertile one (e.g., Fan and Menzies, 1992; Menzies et al., 1993). Recent studies on the destruction of the NCC have indicated that this transition took place in the Mesozoic (e.g., Zhu et al., 2012). Our current understanding of thermal state of the NCC lithospheric mantle during the Phanerozoic mainly relies on the applications of thermobarometers to mantle-derived xenoliths (e.g., Chi, 1988; E and Zhao, 1987; Huang and Xu, 2010; Rudnick et al., 2004; Xu et al., 1993, 1999; Zheng, 1999; Zheng et al., 2007). These standard thermobarometers are based on major element compositions of coexisting minerals in mantle rocks and well suited to characterize equilibrium temperatures of well-equilibrated mantle rocks (e.g., Brey and Köhler, 1990; Fabriès, 1979; Krogh, 1988; Wells, 1977).

It is well known that the distribution of rare earth element (REE) between coexisting minerals depends on temperature, pressure, and major element compositions of the minerals and can also be used as a thermometer or thermobaromter (e.g., Eggins et al., 1998; Hellebrand et al., 2005; Lee et al., 2007; Liang et al., 2013; Seitz et al., 1999; Stosch, 1982; Sun and Liang, 2015; Witt-Eickschen and O'Neill, 2005). Recently, Liang et al. (2013) presented a REE-in-two-pyroxene thermometer that is based on the parameterized lattice-strain models for REE partitioning between clinopyroxene and basalt (Sun and Liang, 2012) and between orthopyroxene and basalt (Yao et al., 2012). Using this REE-based thermometer, Liang et al. (2013) calculated temperatures (designated as T_{REE}) for cratonic peridotite xenoliths, abyssal peridotites, and pyroxenites from a number of localities. They observed that T_{REE}'s are in excellent agreement with temperatures derived from major element-based pyroxene thermometers (e.g., Brey and Köhler, 1990; Putirka, 2008; Wells, 1977) for peridotites from stable cratonic mantle, whereas T_{REE}'s are 50–300 °C higher than major element-derived temperatures for abyssal peridotites and pyroxenites. Liang et al. (2013) attributed the differences in temperature to the differences in diffusion rates between trivalent REEs and divalent Fe, Mg, and Ca in pyroxene, as closure temperatures for the trivalent and divalent cations in the same mineral are different for a

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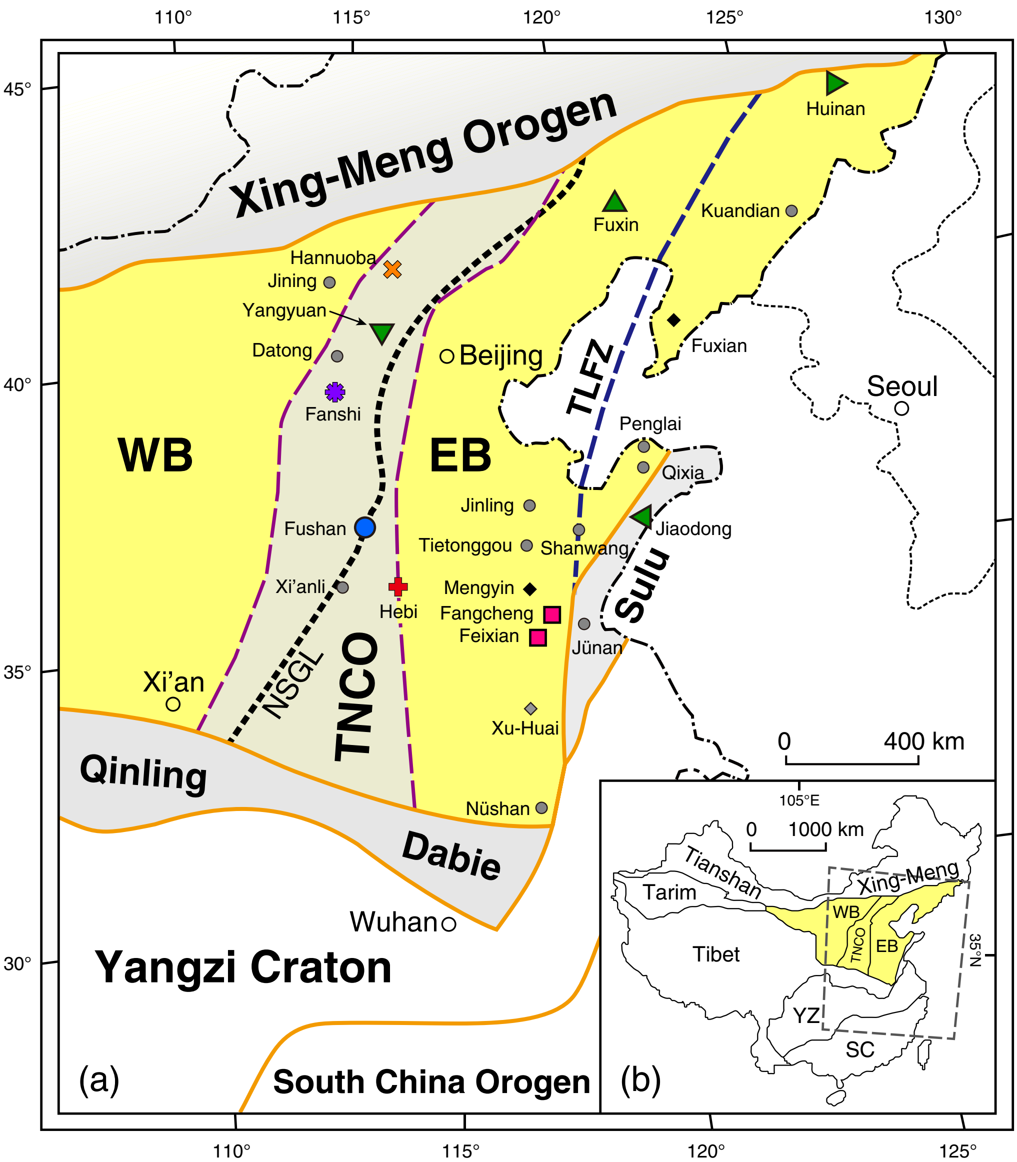

Fig. 1. Schematic geologic map of the North China Craton (NCC) (a) and major tectonic divisions of China (b), where the NCC is shaded in yellow. Larger colored symbols (identical to those in Figs. 2, 5–7) mark the localities of mantle xenoliths included in this study, and smaller gray circles represent other mantle xenoliths reported in literature. Also marked are localities of diamond-bearing kimberlites [Fuxian (Lu et al., 1991; Zheng, 1999; Gao et al., 2002) and Mengyin (Zheng and Lu, 1999)] and eclogite-bearing adakites [Xu–Huai (Xuzhou–Huaibei, Xu et al., 2006, 2009)]. WB: Western Block, TNCO: Trans-North China Orogen, EB: Eastern Block (Zhao et al., 2000, 2001), NSGL: North–South Gravity Lineament (Griffin et al., 1998), TLFZ: Tancheng–Lujiang Fault Zone (Xu and Zhu, 1994).

given cooling rate (e.g., Dodson, 1973). Thus, a comparative REE- and major element-based two-pyroxene thermometry study can shed new light on the thermal history of two pyroxene-bearing mafic and ultramafic rocks. In this study, we apply the REE-in-two-pyroxene thermometer and major element-based two-pyroxene thermometers to peridotite and pyroxenite xenoliths from the NCC. The new thermometric data help us to better understand thermal state of the NCC lithospheric mantle and how it changed in the Mesozoic and Cenozoic.

2. Geological background and sample description

The NCC is composed of three tectonic divisions: the Eastern Block, the Western Block, and the Trans-North China Orogen (TNCO) which was formed by collision of the two blocks in the Paleoproterozoic (e.g., Zhao et al., 2000, 2001, Fig. 1). The NCC was magmatically quiescent from the Neoproterozoic to the mid Ordovician. Since the Mesozoic, the TNCO and Eastern Block have experienced an intensive tectono-thermal reactivation, resulting in widespread intrusions of high-Mg diorites (e.g., Xu et al., 1993, 2008a, 2010) and eruptions of alkali basalts (e.g., Liu et al., 2008 and references therein). A variety of mantle xenoliths were entrained by these diorites and basalts, providing a unique opportunity for studying the NCC lithospheric mantle.

Forty samples are included in this study. They are (1) peridotites entrained by Early Cretaceous high-Mg diorites from Fushan in the middle segment of the TNCO (5 samples), (2) peridotites entrained by younger than 100 Ma (denoted as <100 Ma hereafter for short) alkali basalts from Huinan, Fuxin, Jiaodong, Hannuoba, Yangyuan, Fanshi, and Hebi in the Eastern Block and TNCO (28 samples), and (3) pyroxenites entrained by Early Cretaceous alkali basalts from Feixian and Fangcheng on the eastern margin of the NCC (7 samples). Localities of the samples are marked in Fig. 1. Key petrologic and chemical features of the xenoliths from the NCC are summarized below. Additional information for samples included in this study can be found in the Supplementary material (Table S1 and Fig. S1).