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Precisely dating Paleozoic kimberlites in the North China Craton and Hf isotopic constraints on the evolution of the subcontinental lithospheric mantle

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ABSTRACT

Kimberlite, a deep-sourced ultramafic potassic rock, carries not only diamond, but also invaluable mantle xenoliths and/or xenocrysts, which are important for tracking the evolution of subcontinental lithospheric mantle (SCLM). However, it is challenging to accurately determine the emplacement age of kimberlite and its compositions of primary magma because of modifications by crustal and/or mantle contamination and post-emplacement alteration. This paper reports emplacement ages of diamondiferous kimberlites in Mengyin and Fuxian of the North China Craton (NCC) using three different dating methods. For Mengyin kimberlite, single-grain phlogopite Rb–Sr dating yields an isochron age of 485 ± 4 Ma, U–Th–Pb analyses on perovskite give a ^{238}U–^{206}Pb age of 480.6 ± 2.9 Ma and a ^{232}Th–^{208}Pb age of 478.9 ± 3.9 Ma, and baddeleyite yields a ^{207}Pb–^{206}Pb age of 480.4 ± 3.9 Ma. For Fuxian kimberlite, baddeleyite gives a ^{207}Pb–^{206}Pb age of 479.6 ± 3.9 Ma, indicating that the Paleozoic kimberlites in the NCC were emplaced at ~480 Ma. Numerous lines of evidence indicate that the studied baddeleyites are xenocrysts from the SCLM, and can be used to constrain Hf isotope compositions ($\varepsilon_{Hf}(t) \sim -6$) of the SCLM when kimberlite erupted. Combined with data from Mesozoic–Cenozoic mantle-derived rocks and xenoliths, the Hf isotope evolution trend of the SCLM beneath NCC before craton destruction was tentatively constructed, which suggested that the Archean SLCM was enriched by metasomatism at ~1.3 Ga. Further Hf isotope investigations on additional SCLM-derived materials could be used to compare with the constructed Hf isotope evolution trend before craton destruction to determine when lithospheric thinning occurred.

1. Introduction

The North China Craton (NCC) (Fig. 1) is one of the world's oldest Archean blocks as manifested by crustal remnants as old as 3800 Ma (Liu et al., 1992; Song et al., 1996; Wu et al., 2008a; Zheng et al., 2004a). The existence of Ordovician diamondiferous kimberlites in the NCC indicates a thick (~200 km) lithosphere in the early Paleozoic. However, at present the lithosphere is <80 km thick as revealed by seismic studies and petrologic studies of mantle xenoliths in Mesozoic–Cenozoic "intra-plate" volcanism, suggesting that a significant part of the original lithospheric mantle beneath the eastern NCC was removed during the Phanerozoic (e.g. Fan and Menzies, 1992; Gao et al., 2002; Griffin et al., 1998; Menzies et al., 1993, 2007; Menzies and Xu, 1998; Xu, 2001; Zheng et al., 1998, 2007). The thick, old, cold and refractory subcontinental lithospheric mantle (SCLM) beneath the NCC was subsequently replaced by thin, young, hot and fertile mantle (e.g. Gao et al., 2002; Griffin et al., 1998; Huang et al., 2007; Menzies and Xu, 1998; Menzies et al., 2007; Wu et al., 2003, 2006a; Xu, 2001; Zhang et al., 2008; Zheng et al., 1998).

Although extensive investigations have been conducted on the lithospheric thinning process, there are still considerable debate on its mechanism, with lithospheric delamination (e.g. Deng et al., 2007; Gao et al., 2002, 2004, 2008; Wu et al., 2003, 2005a) and thermo-mechanical erosion (e.g.Griffin et al., 1998; Menzies and Xu, 1998; Xu, 2001; Zhang, 2005; Zhang et al., 2008) being commonly proposed. The delamination model, (a more rapid process), proposes that the thinning was triggered by foundering and sinking of heavy material, and predicts that the present SCLM is juvenile. In contrast, the erosion model emphasizes a slow chemical process of asthenospheric upwelling, forming a stratified SCLM with Archean relict overlying newly accreted material (Griffin et al., 1998; Menzies and Xu, 1998).

Understanding SCLM evolution is helpful in deciphering the lithospheric thinning mechanisms. For this reason, extensive studies have been conducted on mantle xenoliths and SCLM-derived mafic-alkaline rocks in the NCC (e.g., Chu et al., 2009; Gao et al., 2002; Wu et al., 2003, 2006a; Xu et al., 2008; Zhang et al., 2008; Zheng et al., 2009). However, our knowledge about the Paleozoic SCLM beneath the NCC is rather limited. Firstly, the age of the diamondiferous Mengyin (Shandong province) and Fuxian (Liaoning Province) kimberlites, erupted on opposite sides of the translithospheric Tanlu fault (Fig. 1), is not well determined. Available geochronological data yield a wide range from

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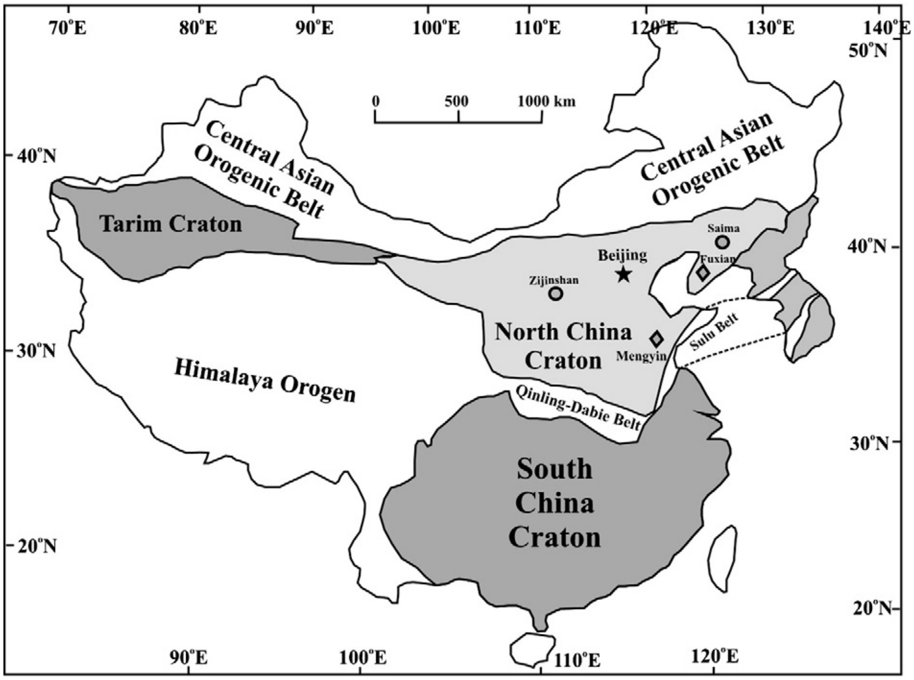

Fig. 1. Geological sketch map showing the Cratons in China and sample localities discussed in the text. Diamond: kimberlite. Circle: nepheline syenite.

456 Ma to 475 Ma based on phlogopite Rb–Sr and Ar–Ar, perovskite U–Pb by TIMS and LA-ICPMS methods (Dobbs et al., 1994; Li et al., 2005; Yang et al., 2009; Zhang and Yang, 2007). Secondly, although it has been proposed that the Paleozoic SCLM was Sr–Nd isotopically enriched, significantly different from that of depleted SCLM in the Cenozoic (Chi and Lu, 1996; Fan and Menzies, 1992; Griffin et al., 1998; Huang et al., 2007; Menzies and Xu, 1998; Zheng et al., 1998), this conclusion was based on the limited data from significantly altered peridotite samples. The Os isotope character of these altered samples is likely to be less disturbed and so an Archean melt-extraction age can be established (Chu et al., 2009; Gao et al., 2002; Wu et al., 2006a; Zhang et al., 2008; Rudnick et al., 2004), however other isotopic features like Sr–Nd–Hf systems of the SCLM are still in doubt or remain unknown (Wu et al., 2008b).

In this paper, we report a series of comprehensive dating results of phlogopite Rb–Sr, perovskite ^{238}U–^{206}Pb and ^{232}Th–^{208}Pb and baddeleyite ^{207}Pb–^{206}Pb analyses obtained from the Mengyin and Fuxian kimberlites. The baddeleyites, considered to be mantle xenocrysts, were used to trace the Hf isotope composition of the Paleozoic SCLM.

2. Geological settings and samples

The NCC is the oldest tectonic unit in China, with crustal components up to ca. 3.8 Ga exposed in the far north-east (e.g., Liu et al., 1992; Wu et al., 2008a). The Early Paleozoic Qilianshan Orogen and the Late Paleozoic Central Asian Orogenic Belt bound the craton to the west and the north, respectively, and in the south the Qinling-Dabie-Sulu ultrahigh-pressure metamorphic belt separates it from the South China Craton (Fig. 1). Based on age, lithological assemblage, tectonic evolution and P–T–t paths, the NCC has been divided into Eastern and Western blocks, which were amalgamated along the Paleoproterozoic Trans-North China Orogen (Zhao et al., 2005 and references therein). Based on today's seismology and geography, the NCC can be separated into two different tectonic domains by the N–S trending Daxinganling–Taihangshan gravity lineament (DTGL) (Ma, 1989; Menzies and Xu, 1998).

Similar to other Archean blocks around the world, the NCC contains both greenstone belts and high-grade metamorphic terrains, which were metamorphosed at 2.5 Ga and subsequently cratonized at 1.8 Ga by collision of the Eastern and Western blocks (e.g., Wu et al., 2005a; Zhao et al., 2005). After 1.8 Ga, the NCC has remained relatively stable and was covered by a thick sequence of Mesoproterozoic to Paleozoic sediments. In the Paleozoic, when the diamondiferous Mengyin and Fuxian kimberlites were emplaced in Shandong and Liaoning provinces, respectively (Zhang et al., 1989), and the NCC was characterized by thick carbonate sedimentation during the Cambrian to Early Ordovician. In the Mesozoic, extensive volcanic activity and granitoid emplacement occurred in the eastern NCC, possibly due to the interaction of the Eurasian and Pacific plates and resulting from the lithospheric thinning (Wu et al., 2003, 2005b). During the Cenozoic, numerous alkaline basalts containing mantle peridotite and minor lower-crustal granulites xenoliths were erupted throughout the central and eastern parts of the craton.

In this study, kimberlites from Mengyin and Fuxian were investigated. The Mengyin kimberlites are diamondiferous and erupted through the Archean Taishan Complex. About 100 kimberlitic dykes and pipes have been identified (Fig. 1, Chi and Lu, 1996; Wan, 1989). Among them, the pipe 1 (Shengli 1, N35°40′ and E117°47′) is the most important diamondiferous one in the area and was targeted for this study. Perovskite is relatively abundant in the Mengyin kimberlite groundmass, with concentrations up to 5% (rarely up to 20%, Yang et al., 2009). Most perovskite grains are dark orange to brown and euhedral shapes with grain sizes ranging from 30 to 200 μm. Phlogopite and perovskite were separated from sample MY12, the only one containing baddeleyite, for further investigation. The Fuxian diamondiferous kimberlites are emplaced in the Mesoproterozoic–Cambrian country rocks (Fig. 1). Samples here show more extensive alteration and weathering. Although a number of kimberlite samples were used to separate perovskite and baddeleyite, perovskite is extremely rare and baddeleyite was obtained from only one rock sample. In both localities, these kimberlites contain a variety of crustal fragments, including limestone, gneiss, amphibolite, mafic granulite xenoliths (Chi and Lu, 1996; Dong, 1994; Wan, 1989; Zheng et al., 2004a,b) and exotic zircons with ages of 2.5 Ga (Yin et al., 2005; Zheng et al., 2009).

3. Analytical procedures

The kimberlite samples were crushed using a jaw crusher and bico disk mill equipped with hardened steel plates. Minerals were concentrated using a wilfley Table, heavy liquids and a Frantz