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# Titanite evidence for Triassic thickened lower crust along southeastern margin of North China Craton

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ABSTRACT

Titanite U–Pb isotopic and major and trace element compositions of one mafic garnet granulite from a rare suite of lower crustal xenoliths (e.g., eclogite, garnet pyroxenite, and mafic garnet granulite) hosted in Early Cretaceous dioritic porphyries in the Xu–Huai area along the southeastern margin of the North China Craton (NCC) were analyzed by laser ablation ICP-MS. Titanite occurs as granular grains or coronary rims on rutile. The coronary titanite is clearly a secondary product of rutile decomposition. The granular titanite exhibits zonation in U–Pb age and chemical composition. Petrographic and geochemical evidence suggests that the zonation was formed by thermal diffusion and later fluid-assisted recrystallization. Occurrences of granular titanite between garnet grains point to a pressure of >10 kbar, while inclusions of rutile inside granular titanite rims imply that the pressure might have reached 15 kbar. Granular titanite cores give U–Pb ages of 237–241 Ma and Zr-temperatures of 794–831 °C at 10 kbar and 850–892 °C at 15 kbar, indicating high-pressure granulite-facies metamorphism. Together with previous P–T estimates of coeval eclogite-facies xenoliths, a geotherm of above 60 mW $m^{-2}$ is implied. The geotherm plots below the temperature field of amphibole dehydration melting, consistent with presence of abundant amphibole. This geotherm is similar to that of the Kohistan arc, which has preserved a 12-km-thick dense lower crust, but significantly cooler than the geotherm of the Talkeetna arc, where most of the dense lower crust has been foundered.

Our results provide new evidence for Triassic thickened dense lower crust along the southeastern margin of the NCC. By comparison with the Kohistan and Talkeetna arc crusts, we suggest that this dense lower crust was not hot enough to be foundered in the Triassic. Foundering must have occurred in the Jurassic–Cretaceous in order to explain the present-day seismic velocity structure characterized by a sharp Moho, overall slow velocities in the lower crust, and a thin crustal thickness in the Xu–Huai area and other parts of the eastern NCC. We suggest that the Jurassic–Cretaceous foundering was related to the Pacific subduction. On one hand, the Jurassic subduction may have further thickened the southeastern margin of the NCC prior to Cretaceous extension, leading to greater instability of the lower crust. On the other hand, the subduction-related magma provided heat and water that weakened the lower crust, resulting in the final foundering. The large contrast in mineralogy between the Xu–Huai eclogite-facies xenoliths and nearby Nüshan garnet-free granulite xenoliths entrained by Quaternary basalts indicates >20 km removal of the lower crust along the southeastern margin of the NCC.


## 1. Introduction

Titanite ($CaTiSiO_5$) is a common accessory mineral in high Ca/Al intrusive rocks and metamorphic rocks of diverse compositions and metamorphic grades (e.g., Frost et al., 2001; Gao et al., 2012; Spencer et al., 2013). Titanite usually has moderate amounts of U and Th (Frost et al., 2001). The closure temperature of its U–Pb system could be up to 700–800 °C (Cherniak, 1993; Gao et al., 2012; Spencer et al., 2013; Zhang and Schärer, 1996). In metamorphic rocks with complex thermal history, titanite may form multiple growth domains (e.g., Aleinikoff et al., 2002; Gao et al., 2012). These features make titanite an important U–Pb geochronometer. In addition, titanite serves as a geothermometer based on its Zr concentration (Hayden et al., 2008). Integration of its U–Pb age and Zr temperature provides marvelous insights into the temperature–time history of geological processes (e.g., Kohn and Corrie, 2011; Spencer et al., 2013).

In this paper, we report chemical and U–Pb isotopic compositions of large titanite grains and tiny zircon inclusions from one mafic garnet granulite from a rare suite of eclogite-associated lower crustal xenoliths

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hosted in Early Cretaceous high-Mg adakitic porphyries in the Xu–Huai area along the southeastern margin of the North China Craton (NCC). Our results provide new evidence for the Triassic thickened lower crust along the southeastern margin of the NCC, which is important for understanding the overall evolution of the eastern NCC and the mechanism of removal of its Archean lithospheric keel in the Mesozoic.

## 2. Geological background

### 2.1. North China Craton

The NCC is one of the oldest cratons in the world, preserving crustal remnants as old as 3.8 Ga (Liu et al., 1992, 2007; Song et al., 1996; Wan et al., 2012) with two major crustal growth peaks at ca. 2.5 and 2.7 Ga followed by intense metamorphic reworking at ca. 1.8–1.9 Ga (Zhai and Santosh, 2011, 2013; Zheng et al., 2013; Zhao and Zhai, 2013; Zhao et al., 2012) (Fig. 1). Its eastern block is perhaps the best example of removal of Archean lithospheric mantle and lower crust (Lee, 2014). In the eastern NCC, a thick, cold, and refractory Archean lithospheric mantle was manifested by garnet peridotite xenoliths with Os model ages of 2.5–2.9 Ga (Gao et al., 2002b; Wu et al., 2006; Zhang et al., 2008) from Ordovician diamondiferous kimberlites (Griffin et al., 1998; Menzies et al., 1993). In contrast, mantle xenoliths from Cenozoic alkaline basalts are characterized by fertile spinel peridotite xenoliths (Griffin et al., 1998; Menzies et al., 1993) with Os isotopic compositions similar to modern convecting mantle (Chu et al., 2009; Gao et al., 2002b; Liu et al., 2011, 2014; Wu et al., 2003, 2006; Zhang et al., 2008). The large contrast in mineralogical, chemical and isotopic compositions between the garnet and the spinel peridotite xenoliths documents a loss of >120-km-thick Archean lithospheric keel of the eastern NCC, which was replaced by young, fertile mantle after Ordovician (Chu et al., 2009; Gao et al., 2002b; Griffin et al., 1998; Menzies et al., 1993, 2007). However, the timing and mechanism of the destruction are still in hot debate. Several models have been proposed to explain the dramatic change in the lithospheric mantle, including (1) delamination of the lithospheric keel (e.g., Chu et al., 2009; Gao et al., 1998, 2002b, 2004, 2008; Windley et al., 2011; Wu et al., 2005; Xu et al., 2013), (2) thermal–chemical erosion (e.g., Griffin et al., 1998; Menzies et al., 2007; Xu, 2001; Xu et al., 2004; Zheng et al., 2007), (3) peridotite–melt reaction (e.g., Tang et al., 2014; Zhang, 2005; Zhang et al., 2002, 2007, 2009), (4) lithosphere extension and subduction dehydration (Niu, 2005), and (5) back-arc extension related to Pacific Plate subduction (Zhu et al., 2010, 2012). All the models emphasize the Jurassic–Cretaceous large volumes of magmatism with a significant peak at Early Cretaceous and formation of associated largest gold deposits in China (e.g., Goldfarb and Santosh, 2014; Guo et al., 2014b; Li et al., 2014; Windley et al., 2011; Wu et al., 2005; Yang and Santosh, 2014; Zhang, 2012; Zhang et al., 2013). This was followed by basin formation and eruption of asthenosphere-derived alkali basalts.

### 2.2. Xu–Huai lower crustal xenoliths

In the Triassic, the Yangtze Craton was subducted northward and westward beneath the NCC to ~50–60 km deep at ~246–244 Ma, to >200 km at ~235–225 Ma, then returned to <60 km after 215 Ma (Liu and Liou, 2011 and references therein). The final exhumation of the subducted Yangtze Craton formed the world's largest Dabie–Sulu ultra-high pressure metamorphic (UHPM) belt (Fig. 1).

The Xu–Huai area is located along the southeastern margin of the NCC, which is adjacent to the Sulu belt to the east and the Dabie belt to the south (Fig. 1). Several Early Cretaceous high-Mg ($Mg^{\#} = 48.8–61.3$) adakite-like dioritic porphyries intruded the Neoarchean crystalline basement and deformed Neoproterozoic–Paleozoic sedimentary cover (Xu et al., 2006b), and contain a rare suite of lower crustal xenoliths (e.g., eclogite, garnet pyroxenite and mafic garnet granulite) (Xu et al., 2002). The eclogitic xenoliths (including eclogite and garnet clinopyroxenite) have basaltic compositions with strong island-arc affinities, such as enriched large ionic lithophile elements, depleted

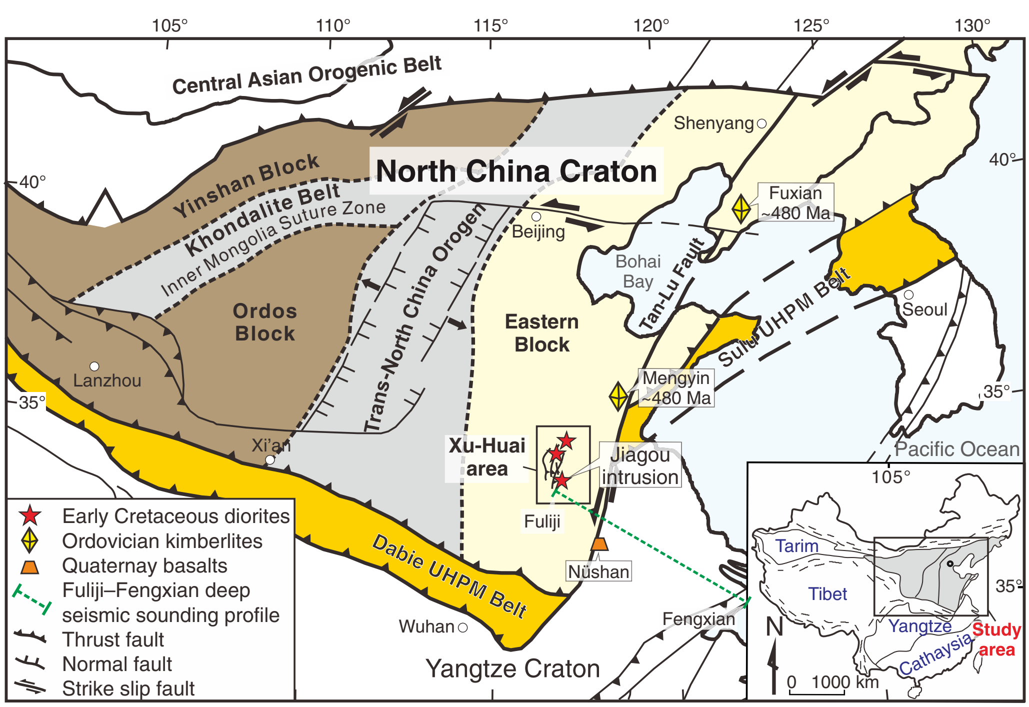


**Fig. 1.** Tectonic divisions of the North China Craton (modified from Zhao et al. (2001) and Santosh (2010)). Stars denote Early Cretaceous high-Mg adakitic dioritic porphyries in the Xu–Huai area. The mafic garnet granulite xenolith used in this study is from the 132-Ma Jiagou intrusion. Diamonds represent two Ordovician diamondiferous kimberlites (Li et al., 2011). The trapezoid denotes the Quaternary Nüshan basalts with garnet-free granulite xenoliths (Huang et al., 2004; Xu et al., 1998). The dashed line between Fuliji and Fengxian denotes a deep seismic sounding profile (Bai and Wang, 2006). UHPM = ultrahigh-pressure metamorphic.