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Discussion

Complex evolution of the lower crust beneath the southeastern North China Craton: The Junan xenoliths and xenocrysts: Reply

Huayun Tang[a,b,*], Jianping Zheng[a,b,*], William L. Griffin[b], Suzanne Y. O'Reilly[b], Chunmei Yu[a], Norman J. Pearson[b], Xianquan Ping[a], Bing Xia[a], Huaben Yang[a]

[a] State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China
[b] Australian Research Council Centre of Excellence for Core to Crust Fluid Systems and GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia

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ABSTRACT

In our paper, we suggested that the Junan granulite xenoliths and xenocrysts record evolution of the Precambrian lower crust beneath the southeastern North China Craton (NCC). Yuan and Xia (2015) disagree with us. However, they have not fully considered the evolutional histories of the NCC lithosphere, and geochemical and isotopic compositions of the Junan xenoliths. We also contend that they have misinterpreted the available geophysical data. Synthesizing the geochronological characteristics of the NCC lower crust, nature of the Junan granulite xenoliths, and reinterpretation of the resistivity profile, we again emphasize that the Junan granulite xenoliths are tectonically affiliated to the NCC lower crust, and the Junan zircon data could reflect the complex evolution of the lower crust beneath the southeastern NCC.

1. Introduction

There is an ongoing debate on the architecture and tectonic affiliation of the lithosphere beneath the Sulu terrane (Li, 1994; Liou et al., 2009; Zhang et al., 2006; Zheng et al., 2009), which is formed by the collision between the North China Craton (NCC) and the Yangtze Craton (YC) in the Late Triassic (Li et al., 1993). A crustal-detachment model suggests that the Sulu terrane was thrust as a rootless slice together with the upper crust of the YC over the NCC (Li, 1994); whereas the penetration model has proposed that the Sulu terrane was a part of the Yangtze crust, and together they subducted beneath the NCC (Zhang et al., 2006). We consider that this controversy centers on the subsurface boundary between the YC and NCC, and that the main reason for this debate is limited knowledge of the detailed geochronological, geochemical and isotopic characteristics of the deep lithosphere underneath the collisional zone.

In Tang et al. (2014), we concluded that the zircons in the Junan granulite xenoliths and xenocrysts record evolution the lower crust beneath the SE margin of the NCC. Yuan and Xia (2015) instead propose that our data reflect the characteristics of the Yangtze lower crust because they argue (1) the zircon data are compatible with those of basement rocks from the YC; (2) the Sulu terrane is coupled with the YC lower crust, which was thrust beneath the NCC as indicated by magnetotelluric surveys, hence “the Junan granulite xenoliths are most likely to be derived from the YC”. The discrepancy between Yuan and Xia (2015) and Tang et al. (2014) focuses on whether the Junan granulite xenoliths were ultimately derived from the lower crust of the YC or NCC. We welcome the comments from Yuan and Xia (2015), as it gives us an opportunity to further clarify our viewpoints, and to more carefully think about the nature and evolution of the Precambrian lower crust underneath the Junan region.

2. Are the Junan zircons best fitted with the YC lower crust?

Based on comparison of zircon data between our Junan samples and rocks from the YC, Yuan and Xia (2015) argue that (1) the Junan granulites have distinct overlap in U–Pb ages and Hf isotopes with the basement rocks of the YC; and (2) there is no isotopic evidence that the Junan granulites were derived from the NCC lower crust. However, Yuan and Xia (2015) did not make any comparison with the age of the NCC lower crust and so we are unclear how can they conclude “there is no isotopic evidence for the derivation of the Junan granulites from the NCC lower crust”?

Yuan and Xia (2015) consider that the Junan granulite xenoliths represent fragments of the YC lower crust based on the presence of ca 2.3 Ga and ca 2.0 Ga zircons, which are also found in the Precambrian Kongling and Kangdian massifs. However, the accretion and reworking

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* Corresponding authors at: State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China. Tel.: +86 27 67883001; fax: +86 27 67883002.
E-mail addresses: hytang2005@163.com (H. Tang), jpzheng@cug.edu.cn (J. Zheng).

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histories of the YC were highly heterogeneous both temporally and spatially, and the northeastern YC underwent rather different crustal evolution relative to the other parts of the craton (Tang et al., 2012). Therefore, both the Kongling and Kangdian massifs may well have different evolutionary histories, and cannot be considered to represent the entire YC. It is also unwise to use the ages of the surface basement rocks to represent the age of the lower crust. In addition, no direct evidence has been provided by Yuan and Xia (2015) to show that the YC preserves ca 2.3 Ga and ca 2.0 Ga lower crust. The NCC, in contrast, has widespread ca 2.3 Ga and ca 2.0–1.8 Ga outcropping basement rocks (e.g., Huang et al., 2012, 2013; Kröner et al., 2005; Tam et al., 2011; Zhao et al., 2012) and magmatic/metamorphic zircons in sediments (Diwu et al., 2014; J.H. Liu et al., 2013; Wan et al., 2006) from the Shandong Province and other areas of the NCC. Furthermore, lower crust with ages of 2.1–2.3 Ga is represented by the Nushan (2.2–2.3 Ga; Huang et al., 2004; Ying et al., 2010; Zheng et al., 2012) and Jiagou (ca 2.1 Ga; Y.C. Liu et al., 2013) granulite xenoliths in the southeastern NCC. Early Paleoproterozoic materials are also identified to be preserved in the deep crust of the southeastern NCC, as revealed by studies on the granitic plutons in the Bengbu area (Yang et al., 2007, 2009). All these highlight the existence of ca 2.3 Ga components and magmatism in the lower crust of the southeastern NCC.

Granulite xenoliths from broad areas of the NCC, such as Xinyang, Hannuoba, Yingxian and Qingdao, all contain ca 2.0–1.8 Ga zircons (Zhang, 2012; Zheng et al., 2008, 2012), indicating significant thermal events in the lower crust of the NCC during Paleoproterozoic. Therefore, the ca 2.3 Ga or ca 2.0 Ga overprints are intrinsic features of the NCC lower crust and outcropping basement, and so we would contend that it is reasonable to associate the Junan granulite xenoliths with the NCC lower crust (Tang et al., 2014; Ying et al., 2010).

Yuan and Xia (2015) argue that the Neoproterozoic tectonothermal events revealed by the Junan zircons are characteristics of the YC rather than of the NCC. This is solely based on the long-held interpretation that Neoproterozoic overprints are typical features of the YC, but almost absent in the NCC (Zhao and Cawood, 2012). However, more recent geochronological data (see Tang et al., 2014 for summary) have revealed that the Neoproterozoic tectonothermal events, although relatively scarce, are indeed preserved in the lithosphere of NCC, and probably reflect the assembly and evolution of the supercontinent Rodinia. Therefore, the possibility that the Junan Neoproterozoic zircons are from the NCC cannot be precluded. Considering the geochemical and isotopic data which have constrained that the Junan granulites are derived from the NCC (Ying et al., 2010), we believe that it is feasible to conclude that the Neoproterozoic zircons in the Junan samples are records of thermal modification in the NCC lower crust.

To our mind, Yuan and Xia (2015) have not provided convincing evidence to show that the lower crust beneath the northeastern YC underwent Early Paleozoic thermal modification, since the Early Paleozoic ages quoted by them from the Sulu-Dabie-Qinling Mountain are recorded in surface rocks, rather than from the lower-crustal domain of the YC. On the contrary, Early Paleozoic thermal events have been identified in the NCC lower crust (see Tang et al., 2014 for summary). A recent study also showed that an Early Paleozoic (ca 470 Ma) tectonothermal event has modified the lithospheric mantle beneath the southeastern NCC, inferred from peridotite bodies in the Sulu terrane (Zheng et al., 2014). The evidence for this tectonothermal event, combined with the presence of 414–461 Ma zircons in the Junan granulite xenoliths (Zhang et al., 2013), lead us to contend that it is best to interpret the Early Paleozoic zircons in Junan samples as reflecting thermal modification in the NCC lower crust.

The Triassic thermal events induced by collision between the NCC and YC have significantly modified the lithosphere of the NCC (Zhang et al., 2012). They are not only recorded in the lithospheric mantle beneath the southern NCC (Zheng et al., 2006), but also in the lower crust beneath the Liaodong Peninsula, Mengyin, Qingdao and Xinyang (Zhang et al., 2012; Zheng et al., 2008, 2012). The Jurassic thermal modification of the lower crust has been identified in Fuxin, the Liaodong Peninsula, and Nushan in southeastern NCC (H.F. Zhang et al., 2011; Huang et al., 2004; Zheng et al., 2012). The Early Cretaceous crust–mantle interactions were significant, resulting in considerable basaltic underplating in the Precambrian lower crust beneath wide areas of the NCC (Jiang et al., 2013; Wilde et al., 2003; Zhang et al., 2013; Zheng et al., 2012). Therefore, the Jurassic and Early Cretaceous zircons in the Junan samples can be better interpreted as recording anatexis and basaltic underplating in the lower crust beneath the southeastern NCC, respectively. This is consistent with the development of Late Jurassic (160–150 Ma) ancient lower crustal-derived granitic intrusions, and widespread Early Cretaceous (135–113 Ma) lithospheric mantle derived mafic–intermediate magmatic rocks in the Jiaodong Peninsula (Liu et al., 2008; Yang et al., 2005).

The Early Cretaceous zircons from the Junan granulite xenoliths show Hf-isotope signatures that are consistent with those in the nearby coeval magmatic rocks that derived from the enriched lithospheric mantle of the NCC (Fig. 9 of Tang et al., 2014). Yuan and Xia (2015) have argued that the Early Cretaceous ages are result of basaltic magmatism that brought the Junan granulite xenoliths onto the surface. However, this is untenable as the host magma of the xenoliths has been dated at 67 Ma (Ying et al., 2006). Hence, the Early Cretaceous thermal event was dominated by underplating of basaltic magma that originated from the NCC lithospheric mantle, rather than reworking of the YC Precambrian lower crust as proposed by Yuan and Xia (2015). Therefore, the Junan zircons are more consistent with derivation from the lower crust of the NCC, rather than that of the YC (Zhang et al., 2012).

3. Geophysical evidence

It was beyond the scope of our previous paper to discuss the kinematics of the collision between the YC and the NCC, and their subsurface relationships. There is still no consensus on these issues. Yuan and Xia (2015) propose that the seismic data and resistivity profile indicate that the YC was thrust beneath the NCC. However, the geophysical images only show the structure of the modern lithosphere, rather than direct evidence for ancient subduction processes. Moreover, the resistivity profiles are limited in their ability to indicate the tectonic affinity of the lithosphere, since anomalies and differences in resistivity could be caused by lithological variations. Hence, the resistivity profile quoted by Yuan and Xia (2015) only reflects a positive resistivity anomaly ($\log \rho > 2.4$) caused by the UHP metamorphic rocks (Yang, 2000).

Therefore, it is difficult for us to draw a conclusion that the YC was thrust beneath the NCC, based on a relatively small-scale resistivity profile. Line A-A′ can be best considered as a boundary of sudden change of electrical resistivity. The areas below line A-A′ with relatively low resistivity ($\log \rho < 2.4$) can not be uniquely regarded as the Yangtze crustal materials. In fact, a wider resistivity profile across the Sulu terrane also given by Yang (2002) showed that the materials with low resistivity clearly running from the most northwest to the southeast of Gaogou, leaving the UHP metamorphic rocks “floating” on them. We consider that these low-resistivity materials are more likely to be affiliated to the NCC crust. In this regard, the resistivity profile suggests that the lower crust beneath the Junan region is affiliated to the NCC. We would contend that the resistivity profile chosen by Yuan and Xia (2015) is too small-scale from which to make meaningful interpretations.

The main differences between the lower crust of the YC and NCC in terms of geophysics are their thickness, defined by seismic P-wave velocity (Vp). Several studies have shown that lower crust with Vp from 6.8 to 7.2 km/s beneath the NCC is less than 4 km thick, while that beneath the YC is 8–10 km thick (Deng et al., 2011; Gao et al., 1998; Z.J. Zhang et al., 2011). Available deep seismic sounding reflection/refraction profiles (DSS) around the Sulu area have revealed that the thickness of fast layer ($Vp = 6.8$ to 7.1 km/s) in the lower crust is only 3 km (Bai et al., 2007; Jia et al., 2014; Li et al., 2011),