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Neoproterozoic zircon inheritance in eastern North China craton (China) Mesozoic igneous rocks: derivation from the Yangtze craton and tectonic implications

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We propose that inherited Neoproterozoic zircons in Mesozoic igneous rocks from the eastern portion of the North China craton (NCC) were initially derived from the Yangtze/South China block, rather than from the NCC itself. The mechanism that introduced these zircons into the NCC was likely tectonic underplating during Triassic continental subduction/collision of the Yangtze block beneath the NCC. The addition of abundant crustal materials represented by the exotic zircons, probably along the Moho or weak interfaces within the NCC crust, led to the crustal thickening of the NCC. These silic materials contributed significantly to the Mesozoic igneous rocks, either as source rocks or as contaminants of magmas generated during an extensional environment following crustal thickening. Crustal thickening was spatially linked to lithospheric thinning, with both occurring mainly in the eastern segment of the NCC, suggestive of an intrinsic relationship between thickening and thinning events during Mesozoic evolution of the NCC.

Keywords: inherited zircons; felsic igneous rocks; underplating of the NCC; Mesozoic magmatism; North China craton

Introduction

The North China craton (NCC) is the oldest tectonic unit in China, with components of crustal materials as old as 3.85 Ga (Liu *et al.* 1992). In contrast to other ancient cratons elsewhere in the world, such as the North America (Hoffman 1988), South Africa (Kröner *et al.* 2000), and East European cratons (Bogdanova *et al.* 1994), the NCC however is characterized by intense geological activity during its Mesozoic–Cenozoic history, although it had remained relatively stable from its cratonization around the end of Palaeoproterozoic until the Mesozoic. The Mesozoic events in the NCC, which have long been known as ‘Platform Reactivation’ and were ascribed the local name of the ‘Yanshanian Movement’ by Chinese geologists (e.g. Wong 1927; Bao *et al.* 1983; Chen 1992), are indicated by many geological records, including large-scale extensional tectonism (Davis 2003; Liu *et al.* 2005; Wang *et al.* 2007), intense and extensive magmatism (Zhang *et al.* 2001, 2005, 2008; Yang *et al.* 2007, 2008; Zhai *et al.* 2007), and temporally related mineralization (Miao *et al.* 2002, 2005, 2008b; Mao *et al.* 2003; Zhou *et al.* 2003a), as

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well as sedimentary basin formation (Meng *et al.* 2003). Numerous studies during the last three decades have shown that the NCC's lithosphere has been thinned from a normal cratonic thickness of ~200 km during the early Palaeozoic to ~80 km at present, that is, ~120 km of the lithosphere was lost during the past 250 million years, and the concept of 'lithospheric thinning' has been formally proposed (Fan and Menzies 1992; Menzies *et al.* 1993). Subsequent research further confirmed that the lithospheric thinning mainly took place spatially in the eastern portion of the NCC during the late Mesozoic (Wu *et al.* 2005; Zhai *et al.* 2007; and references therein). Some authors proposed that the lithospheric thinning would be a fundamental geodynamic factor controlling the 'Yanshanian Movement' (Wu *et al.* 2000; Shao *et al.* 2005), although the mechanism of the thinning itself is as yet unclear. As a result, the lithospheric thinning of the NCC is presently still one of the hottest areas of both Chinese and international research.

Geophysical and geochemical data have demonstrated that the Mesozoic lithospheric thinning of the NCC is a concrete fact, but studies also suggest that the NCC lithosphere (at least the crust) had been thickened prior to the thinning (Zhang *et al.* 2001; Wu *et al.* 2006), which is supported by large-scale nappe structures identified in the periphery of the eastern NCC (Figure 1), including: (I) the Yanshan region (Davis 2003), (II) the Liaodong

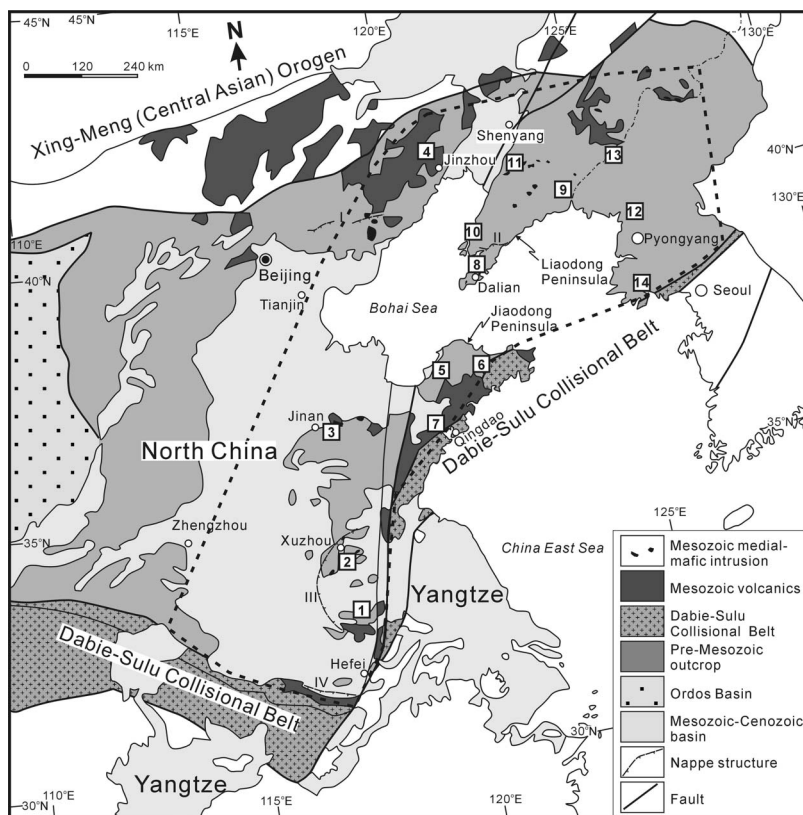


Figure 1. Sketch map showing distribution of Neoproterozoic inherited zircons in the eastern NCC. Numbered square symbols indicate the approximate positions where exotic zircons have been detected, and the numbers are those described in the text (see text for details). The polygon with a dashed line encloses the distribution extent of these zircons. Nappe structures: I, Yanshan region; II, Liaonan in Liaodong Peninsula; III, Xu-Huai region; IV, Northern Huaiyang district.

Peninsula (Xu *et al.* 1991), (III) the Xu-Huai region (Xu *et al.* 1993), and (IV) the North Huaiyang district (Jiang *et al.* 2003). Moreover, a plateau or highland was proposed to have existed in the eastern NCC during Mesozoic time (Dong *et al.* 2000; Zhang *et al.* 2001, 2008). This cognition was mainly based on the occurrence of Mesozoic adakite-like rocks in the eastern NCC, which are interpreted to form in a thickened crust setting (Zhang *et al.* 2008). Radiometric dates have revealed that transient crustal/lithospheric thickening of the NCC occurred prior to the lithospheric thinning (Zhai *et al.* 2007; Yang *et al.* 2008).

Presently, some key questions with respect to the lithospheric thickening and then thinning of the NCC remain to be answered. These include:

- (1) What are the detailed mechanisms of the lithospheric thinning? Many models have been proposed, for example, thermal-mechanic-chemical erosion (Menzies and Xu 1998; Xu 2001), lower crustal detachment (Gao *et al.* 2004; Zhang *et al.* 2006), mantle peridotite-melt/fluid interaction (Niu 2005), and asthenosphere intrusion (Lu *et al.* 2000; Shao *et al.* 2006) models.
- (2) What is the geodynamic nature of the lithospheric thinning? All the orogenic belts that bound the NCC, even mantle plume tectonics, have been considered for this (Davis *et al.* 2001; Wilde *et al.* 2003; Zheng *et al.* 2003; Wu *et al.* 2006), although in our opinion, concrete evidence for this is lacking.
- (3) Is there a spatially coupled relationship between the thickening and thinning? At present, there are no answers to this question because the thickening of the crust/lithosphere has not been emphasized by previous researches.

This article first summarizes the nature of zircon inheritance with, specifically, the Neoproterozoic inherited zircons recently detected in Mesozoic igneous rocks in the eastern NCC, and then introduces a tectonic model to interpret their derivation and the implications of them for Mesozoic crustal evolution of the NCC.

Zircon inheritance

Zircon (molecular formula: $ZrSiO_4$) is one of the most refractory minerals and is a powerful chronometer because it incorporates U but rejects Pb when it crystallizes. The high melting-point temperature ($\sim 2750^\circ\text{C}$) of zircon means that, if coexisting silicate melt ($\ll 1500^\circ\text{C}$) is zircon-saturated, then it can survive melting events in the crust and upper mantle. The low diffusion rates of U and Pb in zircon even at magmatic temperatures (Lee *et al.* 1997) mean that it can retain direct chronological information on the source materials or contaminants during magma genesis. This kind of zircon is commonly known as *inherited zircon*. Zircons captured by a magma from country rocks during its ascent can also remain undissolved in the magma, and this kind of zircons is normally referred to xenocrysts. However, it is rather hard to distinguish zircons with these two origins in an igneous rock from each other. Consequently, zircon inheritance generally refers to both zircons inherited from source rocks and xenocrysts.

Zircon inheritance is both a blessing and a curse for U–Pb geochronology. On the one hand, zircon inheritance is problematic in U–Pb dating by the dissolution and thermal ionization method because it results in ages that can be a mixture of magmatic and inherited zircons and thus are geologically meaningless (Wang *et al.* 1998). On the other hand, zircon inheritance can be used as a robust tool to probe petrogenesis and deep-level processes related to the zircon's host rock, because inherited zircons record plentiful information of these aspects. The latter application has been greatly reinforced since the development of

the *in situ* micro-analytical techniques (e.g. SHRIMP and LA-ICPMS), which are capable of separate analysis of inherited and magmatic zircons even if they coexist in one single crystal (Compston *et al.* 1984; Jackson *et al.* 2004).

Zircon inheritance is common in many igneous rocks. It was previously considered that zircon inheritance mainly occurs in crustally derived felsic magmatic rocks (e.g. Pidgeon and Compston 1992; Tikhomirova 2002), but more and more studies have revealed that mantle-derived mafic rocks, even those formed in non-continental settings (e.g. some ophiolites), also contain lots of inherited zircons (Pilot *et al.* 1998; Miao *et al.* 2008a), although the mechanism of these zircons entering the mantle-derived magmas in non-continental settings remains a matter of discussion. It is commonly known that the mantle of the Earth is unsaturated in Zr and Si, and thus the mantle itself cannot form zircons. Even if zircons are brought into the mantle by some recycling mechanism, it seems to be impossible to remain in their U–Pb isotopic systems for a long time, because the extremely high temperature of the mantle exceeds the blocking temperature of zircon's U–Pb isotopic system (~900°C; Lee *et al.* 1997). As a result, all inherited zircons in the mantle-derived igneous rocks should be from the crust, although some mantle-derived magmas themselves can crystallize zircons, late in crystallization from residual Si and Zr saturated liquid (Zheng *et al.* 2008).

Exotic zircons in the eastern NCC

In this article, we use the term 'exotic zircons' to refer to zircons in Mesozoic igneous rocks in the NCC, with ages that are evidently absent in the magmatic or/and metamorphic evolutionary history of the NCC itself. Correspondingly, the materials or geological bodies initially containing the exotic zircons are called 'exotic materials'.

Recent studies have detected many inherited zircons with Neoproterozoic, as well as early Phanerozoic, ages from Mesozoic igneous rocks in the eastern NCC. Information on these ages and the zircon's host rocks is summarized in Table 1, and the spatial distribution is shown in Figure 1.

These Neoproterozoic ages were detected mainly from inherited zircons in the Mesozoic igneous rocks, with minor amounts from actual intrusions of that age. These include as numbered in Figure 1: (1) the Jingshan granite in Bengpu area, which has an emplacement age of ca. 160 Ma and contains some inherited zircons with ages ranging from 433 to 704 Ma ($n = 8$; Xu *et al.* 2005); (2) eclogite and gneiss enclaves from adakites (emplacement age ca. 160 Ma) in the Xuzou district, which has a metamorphic age ca. 217 Ma and contains Neoproterozoic inherited zircons with ages varying from 678 to 816 Ma ($n = 6$; Xu *et al.* 2009); (3) the mafic dikes (ca. 210 Ma) in the Jinan area of the western Shandong Province containing abundant inherited zircons with ages of ca. 700–800 Ma (T.P. Peng, personal communication); (4) the volcanic rocks of the Xinglonggou Formation in western Liaoning Province that erupted at ca. 160 Ma and have Neoproterozoic inherited zircons with ages of ca. 825 Ma ($n = 5$; Gao *et al.* 2004); (5) the Linglong granite in Jiaodong Peninsula with emplacement age of 150–160 Ma containing inherited zircons with ages of 623–783 Ma ($n = 4$; Miao *et al.* 1997); (6) the Duogushan (emplacement age ca. 160 Ma), Wendeng (ca. 160 Ma), and Kunyushan (ca. 140 Ma) granites in the Wuling region of the Jiaodong Peninsula including inherited zircons with ages of 401–812 Ma ($n = 75$; Guo *et al.* 2005); (7) the Wulian gneissic granites in the Jiaodong Peninsula also having emplacement ages of 672–747 Ma (Zhou *et al.* 2003b); (8) diabase dikes (ca. 211 Ma) in Dalian region containing zircons with ages of 806–1125 Ma ($n = 9$; Yang *et al.* 2004); (9) the gneissic 'Liaoji Granites' (125 and 157 Ma) in Dandong district having

Table 1. Summary of inherited zircons and their host rocks in the eastern NCC.

Region	Lithology	Magmatic age		Pt ₃ inherited zircon age and number		Other inherited zircon age and number		Method	References
		Ma	Ma	Ma (n)	Ma (n)	Ma (n)	Ma (n)		
Bengpu (1) ^a	Migmatic granite	160 ± 2		433–704 (8)		204–248 (9)		SHRIMP	Xu et al. (2005)
Xuzhou (2)	Enclave of eclogite-gneiss from adakite	130 ± 2		678–816 (6)		1696–2574 (4)		LA-ICPMS	Xu et al. (2009)
		217 ± 9 ^b						Sm–Nd isochron	Xu et al. (2009)
Jinan (3)	Diabase dike	ca. 210		700–800		1800–2600		SHRIMP	Peng T. (personal communication)
Zhaoyuan (5)	Adamellite	154 ± 4		623 (1)		200–3446 (9)		SHRIMP	Miao et al. (1997)
Zhaoyuan (5)	Adamellite	160 ± 3		658–783 (2)		210 (1)		SHRIMP	Miao et al. (1997)
Wulian (7)	Gneissic adamellite	742 ± 9						TIMS	Zhou et al. (2003b)
Wulian (7)	Gneissic adamellite	747 ± 14						TIMS	Zhou et al. (2003b)
Wulian (7)	Gneissic granite	672 ± 4						TIMS	Zhou et al. (2003b)
Duogushan (6)	Granodiorite	161 ± 1		430–784 (15)		210–2530 (7)		SHRIMP	Guo et al. (2005)
Wendeng (6)	Adamellite	160 ± 3		433–812 (34)		207–352 (8)		SHRIMP	Guo et al. (2005)
Kunyushan (6)	Biotite adamellite	144 ± 3		620–720 (2)		221 (1)		SHRIMP	Guo et al. (2005)
Kunyushan (6)	Leucogranite	142 ± 3		401–756 (24)		205–342 (5)		SHRIMP	Guo et al. (2005)
Dalian (8)	Diabase	211 ± 2		835–912 (9)		1125 (1)		SHRIMP	Yang et al. (2004)
Dandong (9)	Adamellitic gneiss	157 ± 6		686 (1)		2110 (11)		SHRIMP	Li et al. (2004b)
Dandong (9)	Adamellitic gneiss	125 ± 2		467–638 (3)		170–2500 (4)		SHRIMP	Li et al. (2004b)
Fuxian (10)	Granulite enclave from kimberlite	?		629–752 (4)		1706–2593 (28)		SHRIMP	Zheng (2005)
Haicheng (11)	Gabbro	126 ± 4		747–969 (4)		1850–2450 (3)		SHRIMP	Miao et al. (2010)
Liaoxi (4)	High-Mg andesite	159 ± 4		~827 (5)		2480–2051 (22)		SHRIMP	Gao et al. (2004)
Jinchuan	Ultra mafic complex	827 ± 8		~880 (3)		1791–2415 (3)		SHRIMP	Li et al. (2004a)
North Korea (12)	Diabase	825 ± 6						SHRIMP	Peng et al. (2008)
North Korea (13)	Granite	1195 ± 5						SHRIMP	Zhao et al. (2006)
North Korea (14)	Gneissic granite	1198 ± 27						SHRIMP	Wu et al. (2007)

Note: ^aNumber shown in Figure 1; ^bMetamorphic age.

inherited zircon ages of 467–638 Ma ($n = 3$; Li *et al.* 2004b); (10) the mafic granulite enclaves in the Fuxian kimberlite containing zircons with ages of 629–752 Ma ($n = 4$; Zheng 2005); and (11) the Chaotiehe gabbro intrusion (ca. 125 Ma) in the Haicheng area with inherited zircon ages of 747–969 Ma ($n = 4$; Miao *et al.* 2010). Moreover, Neoproterozoic ages of intrusion have been occasionally reported for (12) mafic diabase dikes (ca. 825 Ma; Peng *et al.* 2008) in the Korean Peninsula on the eastern margin of the NCC and for the Jinchuan mafic–ultramafic complex (ca. 825 Ma; Li *et al.* 2004a) in the Longshoushan region of the southwestern margin of the NCC (not shown in Figure 1). Additionally, two gneissic granites (numbered as 13 and 14 in Figure 1) with emplacement ages of ca. 1.2 Ga were recently identified in the Korean Peninsula (Zhao *et al.* 2006; Wu *et al.* 2007). Besides Neoproterozoic inherited zircons, Archaean and Palaeoproterozoic inherited zircons are also common in nearly all of these Mesozoic igneous rocks, and Triassic ones were also found in some of them (Table 1).

According to the U–Pb data and cathodoluminescence imaging of zircons, provided by the above-mentioned references, these Neoproterozoic zircons mostly display well-developed oscillatory zonation characteristic of typical magmatic zircons and have essentially concordant ages, indicative of a magmatic origin for these zircons. Therefore, these zircon ages are an undoubted record of Neoproterozoic magmatic activity. However, as it is commonly known, the NCC itself displays little record of Neoproterozoic–Caledonian magmatic–thermal activities (Zhao *et al.* 2000). Consequently, these Neoproterozoic zircons are interpreted to be exotic in origin.

Discussion

Derivation of exotic zircons

The discovery in the eastern NCC of abundant exotic zircons in a broad region (Figure 1), not occasionally in just one locality, raises an important question – where did they come from? The answer to the question is presently not conclusive. Some authors still consider that Neoproterozoic magmatic activity may exist in the NCC itself and that the Neoproterozoic inherited zircon ages are an indicator of responses of the NCC to the assembly and breakup of the Rodinian supercontinent (Yang *et al.* 2004; Zhao *et al.* 2006), probably by ‘Grenvillian’ orogenesis at the end of the Mesoproterozoic and breakup initiated at ca. 820 Ma (Li *et al.* 2002). This viewpoint is mainly based on the identification of two granites with Grenvillian-like ages (ca. 1.2 Ga; Zhao *et al.* 2006; Wu *et al.* 2007) in the Korean Peninsula and two mafic and/or ultramafic intrusions with Neoproterozoic ages (ca. 825 Ma; Li *et al.* 2004a; Peng *et al.* 2008) in the Korean Peninsula and the Alashan block, with both situated in the margins of the NCC. Other authors suggested that some intrusions with Neoproterozoic ages in the southeastern margins are representative of materials from the Yangtze craton that were tectonically accreted to the margin of the NCC during Triassic collision between the North China and Yangtze cratons (Zhou *et al.* 2003b), or of materials from the Yangtze craton that were previously subducted underneath the NCC (Guo *et al.* 2005; Miao *et al.* 2010). With the present level of information, we contend that the exotic zircons in the Mesozoic igneous rocks in the eastern NCC were likely derived from outside of the NCC itself. The reasons are as follows:

First, the two previously reported Neoproterozoic mafic or ultramafic intrusions are both located on the margins of the NCC, with one in the eastern margin and the other in the southwestern one. On the other hand, no Neoproterozoic magmatic activity and/or high-grade metamorphism have been recognized in the principal part of the NCC,

especially in the regions where the Neoproterozoic inherited zircons were found. If the igneous Neoproterozoic zircons were from NCC itself, then all the igneous bodies from which the zircons were crystallized do not outcrop at present surface, but are located in the deep crust. This scenario seems to be impossible, because Early Precambrian basement rocks are presently well exposed at the surface of the NCC, but Neoproterozoic igneous rocks are absent. As a result, this absence implies an exotic derivation of these zircons, rather from the NCC itself.

Secondly, if in fact the NCC participated in the Rodinian Supercontinent, as some authors have suggested, then there was just a very small amount of Neoproterozoic magmatic activity (Yang *et al.* 2004). This would be difficult to reconcile with Neoproterozoic zircons appearing as inheritance in Triassic to Cretaceous igneous rocks at widely scattered localities.

Thirdly, if during the Neoproterozoic, the NCC was located in the vicinity of an orogenic belt that is coeval with the Grenvillian one and received deposits from this belt (Yang *et al.* 2004), where are these sedimentary rocks in the NCC? At the very least, even if there were this kind of sedimentary deposition in the NCC, the strata might have been located underneath the basement of the eastern NCC because only in this case can the zircons be captured by magmas intruding the basement. This would require that the crust of the NCC was structurally duplicated or overturned, but so far, there is no evidence to support this.

Finally, regarding the Grenvillian-aged (ca. 1.2 Ga) granites in the Korean Peninsula (Zhao *et al.* 2006; Wu *et al.* 2007), which were considered to be indicative of the existence of Grenvillian magmatic activity in the NCC itself, another alternative is that these Mesoproterozoic granites with gneissic texture may be representative of exotic crustal materials that had been tectonically thrust under the NCC and were then exhumed to the present surface by subsequent geological processes (e.g. development of metamorphic-core-complex structures). However, further work is needed to verify this.

The Precambrian evolutionary histories of the North China and Yangtze cratons are distinctly different. The NCC possesses a basement older than that of the latter and has widespread Early Precambrian age records concentrated at ca. 2.5, ca. 2.0, and ca. 1.85 Ga (Zhao *et al.* 2000; Lu *et al.* 2004; Zhai 2004) and sparse Mesoproterozoic magmatic records of 1.2–1.4 Ga (Zhao *et al.* 2006; Gao *et al.* 2007; Wu *et al.* 2007), but lacks records for the Neoproterozoic and the early Palaeozoic. In contrast, the Yangtze or South China craton is characterized by intense Neoproterozoic and early Palaeozoic magmatism and abundant Grenvillian- and Caledonian-aged records, although Early Precambrian ages also exist (Li *et al.* 2002; Zheng 2003; Zheng and Zhang 2007). Considering these differences, we contend that the exotic inherited zircons in Mesozoic igneous rocks in the eastern NCC have an affinity with the Yangtze/South China block, and thus it is likely that they were derived from it. It is worth pointing out that some inherited zircons with Early Precambrian ages in the NCC Mesozoic igneous rocks may also be derived from the Yangtze/South China block, but it is presently difficult to distinguish them from those from the NCC itself.

Tectonic implications

As a common accessory mineral of igneous rocks or a detrital mineral of sedimentary rocks, zircon itself cannot be captured or inherited in isolation, but only together with other components of its host rock. Abundant exotic zircons detected from igneous rocks at many localities in an extensive tract of the eastern NCC strongly suggest that a large

amount of exotic materials with the Yangtze affinity had been placed beneath the eastern NCC before the production of these Mesozoic igneous rocks. Because most exotic zircons were detected in crustally derived granitic intrusions, these exotic materials were likely located in the lower crust. An important question is, what was the mechanism that introduced these exotic materials beneath the NCC? According to the available data, the amalgamation of the North China and the Yangtze cratons along the Su-Lu ultra-high-pressure (UHP) metamorphic belt took place during the early Triassic (Ames *et al.* 1993, 1996) and involved deep subduction of the Yangtze block continental crust (Ye *et al.* 2000). Consequently, it can be deduced that the addition of the exotic materials beneath the NCC should be coeval with, or later than, the collision or continental subduction. Preliminarily, we propose that the collision/subduction tectonism is likely responsible for the addition. The spatial distribution of the igneous rocks containing the exotic zircons supports this; these igneous rocks are distributed on the northern flank of the collisional belt (Figure 1). For example, granites in the Jiaodong and adakites in the Xuzhou (western side of the Tan-Lu fault) regions are immediately adjacent to the belt, the 'Liaoji Granites' and diabase dikes in the southern part of the Liaodong Peninsula are relatively far north from the belt, and the Chaotiehe gabbro in Haicheng and volcanics in Liaoxi regions are much farther north from the belt. Moreover, the temporal relation of the igneous rocks and the collision also supports this conclusion. The emplacement or eruption of these igneous rocks mainly occurred during the Late Triassic to Cretaceous, which is immediately after the collision time (240–210 Ma; Ames *et al.* 1993, 1996; Li *et al.* 1999). Additionally, the Triassic metamorphic ages of the eclogite enclaves in the adakites and Triassic inherited zircons from some granites (Table 1) in the eastern NCC are indicative of a relation to the collision/subduction belt.

Regarding the Triassic collision between the North China and Yangtze cratons, several models have been proposed. These mainly include indentation (Yin and Nie 1993), crustal detachment (Li 1994; Li *et al.* 2001), and continental deep subduction (Ye *et al.* 2000). The indentation model emphasized that the Yangtze block indented the mid-deep crustal levels of the NCC as a wedge with the shape of the Yangtze similar to the present. On the other hand, the crustal detachment model proposed that the Yangtze's crust was detached, with the upper crust thrust upon the NCC and the lower crust, possibly together with the lithospheric mantle, subducted. The continental deep-subduction model believed that some materials of the Yangtze block was subducted to a depth >200 km and then partially returned to the surface or crust level somewhere, resulting in the Su-Lu UHP belt. Here, we do not intend to commend the validities of these models, but note that the newly discovered exotic zircons in the eastern NCC should be taken into consideration when constructing a model.

No matter which model is correct, it seems that there are two possible mechanisms to realize the addition of the exotic materials to the NCC. One possibility is that crustal materials of the Yangtze block were directly indented into, or tectonically underplated beneath, the NCC's crust during the continental collision. Alternatively, another scenario is that materials of the Yangtze block were deeply subducted and then were tectonically attached to the deep NCC crust. In the latter case, it is required that the tectonically attached materials must pass through the thick lithospheric mantle of the NCC. Therefore, this latter model is more difficult to realize. Consequently, we prefer the former case and further suggest a model for the collision/subduction to explain the derivation of the exotic zircons (Figure 2). This model emphasizes that the crustal materials primarily containing the exotic zircons from the Yangtze/South China block were tectonically underplated in the Early Triassic beneath the NCC's crust during continental collision or

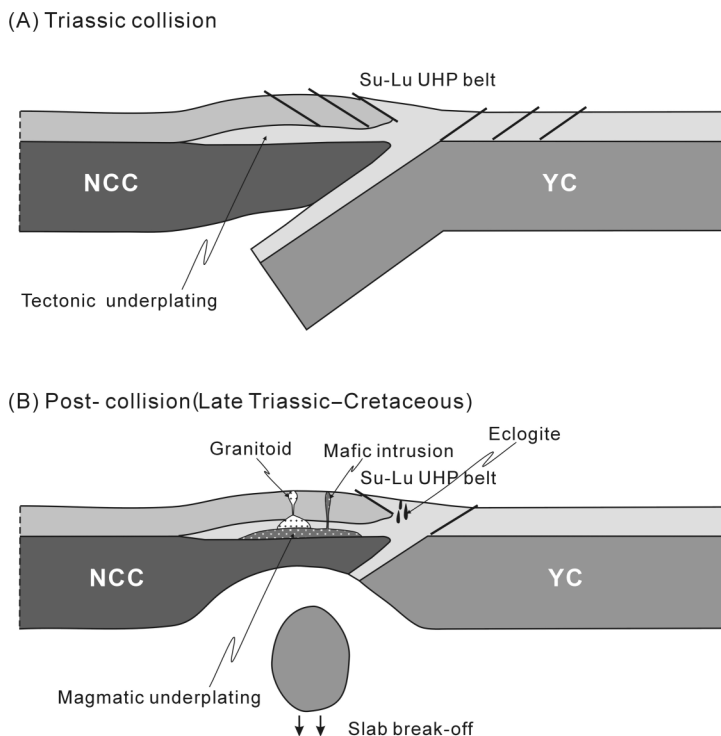


Figure 2. A possible tectonic model for the collision between the NCC and the Yangtze craton (YC), which is used to explain the derivation of Neoproterozoic zircons detected in eastern NCC Mesozoic igneous rocks (see text for details). (A) Crustal thickening by tectonic underplating during the collision and subduction of the Yangtze; (B) lithospheric thinning in the post-collisional/thickening setting.

subduction of the Yangtze block (Figure 2A). These materials were then reworked within a post-collisional environment, either as contributing source rocks for granitic magmas or as contaminants of mantle-derived mafic melts (Figure 2B). The tectonic underplating of the Yangtze's crustal materials beneath the eastern NCC likely occurred mainly along the Moho or major discontinuities within the deep-middle NCC crust. In summary, the exotic zircons in Mesozoic igneous rocks in the eastern NCC were not derived from the NCC itself, but likely from the Yangtze/South China block, probably by tectonic underplating during the Triassic collision between the NCC and the Yangtze/South China block.

Constraints on Mesozoic crustal evolution of the NCC

The exotic zircons discovered in the eastern NCC will place important constraints on the Mesozoic crustal evolution of the craton. The (tectonic) addition of a large amount of exotic material into the deep crust of the NCC will undoubtedly cause considerable crustal thickening and at the same time would have modified the composition and thermal structure, to the extent that it was destabilized. As demonstrated in many typical orogenic belts, post-thickening, there is an extensional environment characterized by large-scale magmatism (Zeck *et al.* 1998; Vanderhaeghe and Teyssier 2001). The eastern NCC Mesozoic igneous rocks containing exotic zircons have been considered as formed in an extension setting related to the lithospheric thinning (Yang *et al.* 2004; Guo *et al.* 2005; Zhai *et al.* 2007).

The somewhat younger ages of these extension-related igneous rocks (Late Triassic to Cretaceous) than those of the thickening event (Early Triassic) indicate that there is a relation between the crustal thickening and the thinning.

The extent of the exotic zircon distribution in the NCC is indicative of the scale of crustal thickening that resulted from tectonic underplating during the Triassic collision. The extent of the exotic zircons presently identified is generally consistent with that for the Mesozoic lithospheric thinning identified by other means (Menzies *et al.* 1993; Zhang *et al.* 2005), with both taking place mainly only east of the (Taihangshan) gravitational gradient zone (Zheng *et al.* 2009). Hereby, the tectonic underplating of exotic Yangtze materials is likely an important mechanism that leads to the crustal thickening and is probably one of factors that triggered the lithospheric thinning of the NCC.

Summary

The large number of inherited Neoproterozoic zircons detected from Mesozoic igneous rocks in the eastern NCC are interpreted as exotic in their initial derivation – that is, they were not derived from the NCC itself, because the NCC lacks evident magmatic activity of that age (Zhao *et al.* 2000).

Considering the fact that Neoproterozoic magmatic activity is common in the Yangtze/South China block, and the coincident spatial distribution relationship of exotic zircons with the North China-Yangtze collisional belt, we propose that these exotic zircons were primarily derived from crustal materials of the Yangtze craton. The mechanism that introduced these heterogeneous zircons/materials into the NCC was likely via tectonic underplating along the NCC Moho, or discontinuities in the deep-middle NCC crust, during the Triassic collision between the two cratons. These tectonically underplated Yangtze-derived exotic materials contributed significantly to the petrogenesis of the Mesozoic igneous rocks, either as source rocks or as contaminants of the subsequent melts.

Tectonic addition of a large amount of exotic materials to the NCC crust probably was an important mechanism leading to crustal thickening of the NCC. The Mesozoic igneous rocks containing the exotic zircons are younger than the crustal thickening event, but coeval with lithospheric thinning, suggesting that they were generated in a post-collisional thickening setting. Spatially, distribution of the heterogeneous zircons generally coincides with that of the NCC lithospheric thinning, which maybe indicative of a direct causal relationship of extension following the thickening.

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