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Lithos 96 (2007) 281 – 298
LITHOS
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Diachronous lithospheric thinning of the North China Craton and formation of the Daxin'anling–Taihangshan gravity lineament

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Received 14 October 2005; accepted 5 September 2006
Available online 18 December 2006

Abstract

The Daxin'anling–Taihangshan or North–South Gravity Lineament (NSGL) is an important geologic zone within the North China Craton (NCC). Crustal elevation, morphology, crustal and lithospheric thickness and gravity anomalies all change considerably across the NSGL. However, the timing of formation and the mechanism are poorly understood. Comparison of on-craton Cenozoic basalts and their included xenoliths reveals that the NSGL is not only a physical boundary but also a chemical "discontinuity" that separates two different mantle domains. Mantle xenoliths from the western NCC have a wider range in isotopes than those from eastern China. In particular, they show the lowest ε_{Nd} and $^{187}Os/^{188}Os$ ratios. Such a lateral heterogeneity may have resulted from lithospheric extension within the NCC, that was diachronously taking place in the east in the Mesozoic and that in the west in the Cenozoic. Such processes could have produced differences in lithospheric thickness underneath the western and eastern NCC during the Cretaceous, eventually giving birth to the NSGL. Formation of the NSGL by diachronous lithospheric thinning is supported by paleogeographic data, which indicates the presence of the NSGL in the early Cretaceous, a period of peak magmatism within the NCC. It is proposed that the NSGL might represent the interaction front between two tectonic regimes, with back-arc extension related to Pacific subduction in the east and Indo-Eurasian collisional extension in the west. The location of the NSGL could be controlled by the western boundary of the vigorous convection induced by stagnant oceanic slabs in the mantle transition zone and old major lithospheric weak zones in the region.

Keywords: Daxin'anling–Taihangshan gravity lineament; Lithospheric thinning; North China Craton

1. Introduction

One of the most pertinent geologic features of eastern China is the NEE-trending Daxin'anling–Taihangshan or North South Gravity Lineament (NSGL), which runs over 3500 km from south China to northeast China (Fig. 1). This lineament, roughly parallel to the Tanlu fault, is a zone *ca.* 100 km wide, in which the Bouguer anomaly decreases rapidly from −100 mGal in the west to −40 mGal in the east (Ma, 1989; Fig. 1a). This steep gravity gradient, roughly overlapping the Trans-North China Orogen, in the North China Craton (NCC), cuts across major tectonic units in eastern China including craton margins, the Dabie and Yanshan orogenic belt. More importantly, the NSGL separates two topographically, tectonically and seismically different regions (Ye et al., 1987; Ma, 1989; Griffin et al., 1998; Menzies and

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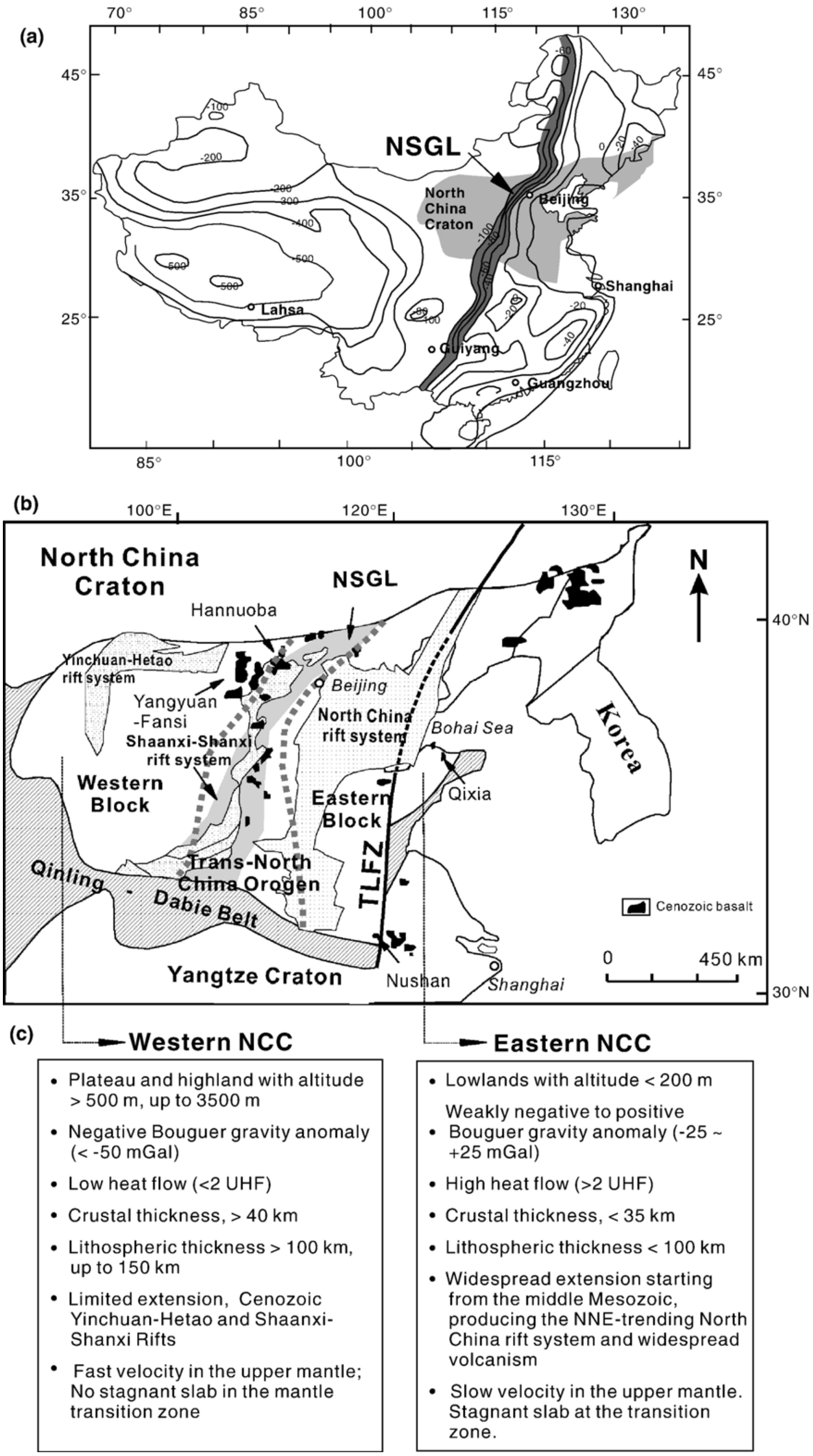
doi:10.1016/j.lithos.2006.09.013



Western NCC

- Plateau and highland with altitude > 500 m, up to 3500 m
- Negative Bouguer gravity anomaly (< -50 mGal)
- Low heat flow (<2 UHF)
- Crustal thickness, > 40 km
- Lithospheric thickness > 100 km, up to 150 km
- Limited extension, Cenozoic Yinchuan-Hetao and Shaanxi-Shanxi Rifts
- Fast velocity in the upper mantle; No stagnant slab in the mantle transition zone

Eastern NCC

- Lowlands with altitude < 200 m
- Weakly negative to positive Bouguer gravity anomaly (-25 ~ +25 mGal)
- High heat flow (>2 UHF)
- Crustal thickness, < 35 km
- Lithospheric thickness < 100 km
- Widespread extension starting from the middle Mesozoic, producing the NNE-trending North China rift system and widespread volcanism
- Slow velocity in the upper mantle. Stagnant slab at the transition zone.

Fig. 1. (a) Bouguer gravity map of China showing Daxin'anling–Taihangshan gravity lineament (NSGL). Modified after Ma (1989). (b) Simplified geologic map showing distribution of Cenozoic rifting systems and tectonic division in the North China Craton (NCC). Modified after Xu (2002). Two shaded and dashed lines outline the Trans-North China Orogen, which separates the western and eastern Blocks of the NCC according to the new tectonic division of Zhao et al. (2001). Note the overlap of the NSGL with the Trans-North China Orogen. For the purpose of this study, the NCC is separated by the NSGL into the western and eastern NCC, which have contrasting geologic and geophysical characteristics (c).

Xu, 1998; Niu, 2005; Fig. 1c). In the NCC, east of the NSGL is dominated by lowlands with an altitude generally less than 200 m. This region includes the Huabei Plain, the Bohai Sea, the highlands of Shandong and the Liaodong Peninsula. Widespread lithospheric extension during the late Mesozoic and Cenozoic resulted in a NNE-trending rift system (i.e., North China rift system) and widespread volcanism (Fig. 1b). The crust beneath this region is thin (<35 km) with a minimum crustal thickness of ~28 km beneath the Bohai Sea (Ma, 1989; Li and Mooney, 1998). The regional Bouguer gravity anomaly is weakly negative to positive (Tang, 1996) and heat flow is high (~2 UHF, Wang et al., 1996) so that the lithosphere is inferred to be thin (<80–100 km) (Ma, 1989; Chen et al., 1991). In contrast, the western NCC includes the Yan and Taihang Mountains and the Loess Plateau and is characterized by high crustal elevation (>500 m, up to 3500 m), thicker crust (>40 km, Ma, 1989; Li and Mooney, 1998), negative Bouguer gravity anomalies (Ma, 1989; Tang, 1996) and lower heat flow that reflects thick (>100 km) lithosphere (Chen et al., 1991). Widespread extension was absent in the western NCC, with only two isolated late Cenozoic rift systems, namely, the Yinchuan–Hetao Rift and the Shaanxi–Shanxi Rift (Fig. 1b). In addition, seismic tomography shows a flat high velocity body in the transition zone (*ca.* 660 km) under eastern China, interpreted as subducted Pacific oceanic lithosphere (Fukao et al., 1992; Zhao, 2004). Interestingly, the western end of the subducted slabs coincides with the NNE-trending Taihang Shan Range (Pei et al., 2004). So far subducted slabs have not been detected using seismic tomographic models, in the region to the west of the NSGL (Fig. 1c).

The fundamental importance of the NSGL has been recognized for decades (e.g., Ye et al., 1987; Ma, 1989), but how and when this lineament formed remains largely unanswered. The coincidence of a number of parameters/anomalies over the depth of 0–660 km along and across the NSGL is the key to understanding its temporal and spatial evolution. Since the NSGL likely marks a major change in the nature of the subcontinental lithosphere (Griffin et al., 1998; Menzies and Xu, 1998), understanding mantle processes in this region is pivotal to uravelling the NSGL. Recent research has focused on the dramatic change in lithospheric structure amounting to the loss of >100 km of lithospheric keel underneath the NCC (Fan and Menzies, 1992; Menzies et al., 1993; Griffin et al., 1998; Menzies and Xu, 1998; Fan et al., 2000; Xu, 2001; Gao et al., 2002). However, several important questions are unanswered. Does lithospheric destruction apply to the whole craton, or did it proceed in a diachronous/heterogeneous manner? Were lithospheric thinning processes and the formation of the NSGL related? The answers to these questions may exist, in part, in a comparison of Mesozoic–Cenozoic tectonic evolution, the geochronology, petrology and geochemistry of magmas and their included xenoliths from either side of the NSGL in the NCC. On the other hand, as the NSGL also defines a topographic difference in the western and eastern NCC, a paleogeographic examination may yield information about the timing at which the current topographic feature of the NCC was developed. The objectives of this paper are:

(1) to provide an overview on Mesozoic and Cenozoic tectonic evolution in the NCC by highlighting diachronous and variable lithospheric extension in the western and eastern NCC;
(2) to compare the data available on mantle-derived rocks on either side of the NSGL in order to define the spatial variation in lithospheric structure/composition in the NCC;
(3) to constrain the timing of the NSGL formation using paleogeographic data; and
(4) to propose a model that relates the formation of the NSGL to diachronous lithospheric thinning processes in the NCC.

2. Geologic background and previous studies

The NCC is one of the oldest continental nuclei in the world (Jahn et al., 1987; Liu et al., 1992a; Zheng et al., 2004). Its basement is divided into three blocks, namely the eastern and western Blocks and the intervening Trans-North China Orogen (Zhao et al., 2001; Fig. 1b). The Eastern Block consists predominantly of Early to late Archean tonalitic–trondhjemitic–granodiotitic batholiths. The late Archean lithologies, structural style and metamorphic history of the Western Block are similar to those of the Eastern Block. The Trans-North China Orogen is composed of late Archean to Paleoproterozoic TTG gneisses and granitoids, interleaved with abundant sedimentary and volcanic rocks. These rocks underwent compressional deformation and peak high-pressure metamorphism during the late Paleoproterozoic (2.0–1.8 Ga), the result of collision between the Western and Eastern Blocks (Zhao et al., 2001). The NSGL roughly coincides with the Trans-North China Orogen (Fig. 1b). For the purpose of this study and also because the NSGL is most likely a relatively young feature, we use the NSGL to divide the NCC into the western and eastern NCC.

Recent studies reveal a contrasting geotherm, thickness and composition of the lithospheric mantle beneath the eastern NCC between the Paleozoic and the present time (Menzies et al., 1993; Griffin et al., 1998; Zheng, 1999; Xu, 2001). While diamond inclusions, xenoliths and mineral concentrates in kimberlites indicate a thick (>180 km), cold (<40 mW/m^2) and refractory lithospheric keel beneath the NCC during the Paleozoic, basalt-borne xenoliths reveal a thin (<80 km), hot (~65 mW/m^2) and fertile lithosphere in the Cenozoic. This led to the suggestion of a dramatic change to the lithospheric architecture in the Phanerozoic (Fan and Menzies, 1992; Menzies et al., 1993; Griffin et al., 1998). The issue as to why this happened in the NCC is of great significance in understanding the Earth's dynamics (Niu, 2005), and in exploration of mineral resources as well (e.g. Yang et al., 2003).

The replacement of the thick, old, cold and refractory lithospheric keel (preserved at least until the Palaeozoic) by a thin, young, hot and fertile mantle may be related to the widespread lithospheric extension in the eastern NCC during the late Mesozoic and Cenozoic, but the mechanisms and dynamic trigger of this process still remain controversial. Delamination has been suggested as a viable mechanism to thin the lithospheric keel beneath eastern NCC (Gao et al., 2002; Wu et al., 2003a; Yang et al., 2003). Gao et al. (2004) recently found that late Jurassic andesites, dacites and adakites from Xinglonggou (northern NCC) have chemical signatures consistent with their derivation as partial melts of eclogite that interacted with mantle peridotite. They proposed that lithospheric thinning had reached such a stage by the late Jurassic that lower crustal rocks could be delaminated, converted to eclogite, incorporated into the convecting mantle and melted. Whether this delamination model is applicable to the whole NCC, however, requires further studies because both Mesozoic mafic and felsic magmatism peaked in the early Cretaceous (Yang et al., 2003; Xu et al., 2004a; Wu et al., 2005), rather than the Jurassic as predicted by the delamination model. On the other hand, rapid delamination is apparently at odds with the protracted magmatism (~100 Ma) in the NCC (Xu et al., 2004a). Alternatively, the protracted lithospheric transformation may be due to thermal–mechanical erosion (Griffin et al., 1998; Xu, 2001). Within this scheme, lithospheric thinning proceeded by heat transport into the lithosphere and small-scale asthenospheric convection induced by extension. Once lithospheric mantle is thermally converted to asthenosphere, it can convectively mix with, and eventually be replaced by, asthenosphere (Davis, 1994). A similar thermal conversion model is favored by Niu (2005), although he emphasized the role of water rich fluids derived from the transition zone (*ca.* 660 km).

So far, several tectonic factors including Pacific subduction, enhanced mantle temperature associated with plumes, the India–Eurasia collision and North China–South China collision have been proposed as the cause of the destabilization of the cratonic lithosphere (Menzies et al., 1993; Yin and Nie, 1996; Deng et al., 2005; Griffin et al., 1998). The mantle plume model seems implausible (Niu, 2005) because of the lack of surface volcanism associated with plume activity and the lack of a thermal anomaly in the deep mantle under this region (Pei et al., 2004; Zhang and Tanimoto, 1993). Menzies et al. (1993) speculated that the collision of India and Eurasia had a role to play in lithospheric destruction. Whilst this may have an effect in the Cenozoic it is likely that lithospheric thinning occurred in the late Mesozoic (Xu, 2001; Yang et al., 2003; Wu et al., 2005), significantly before the Indo-Asia collision (<65 Ma). Yin and Nie (1996) proposed that the North China plateau was created during the late Triassic during the collision of the North China and South China Blocks along the Qiling–Dabie orogenic belt (Li et al., 1993). The plateau later collapsed due to a combination of subduction of the Pacific plate from the east and the Mongolo–Okhotsk ocean from the north. This idea is rooted in the fact that the Mesozoic of the NCC is characterized by the E–W trending Yanshannian fold and thrust belt on the northern margin superimposed onto thermally weakened crust caused by roughly synchronous, westward Pacific subduction and associated magmatism (Davis et al., 1996; Yin and Nie, 1996; Ratschbacher et al., 2000). The Triassic North China–South China collision has also been considered by Menzies and Xu (1998) and Gao et al. (2002) as a dynamic trigger of lithospheric thinning in the eastern NCC. However, most of the Mesozoic structures in eastern China are NEE-orientated and therefore cannot be the consequence of northward penetration of the Yangtze block underneath the NCC. The considerable temporal gap between these two events (Triassic *versus* late Mesozoic) also argues against a direct relationship between them. It is possible that Triassic collision between the NCC and the Yangtze Block initiated the loss of the physical integrity of the craton which facilitated lithospheric thinning during the Cretaceous (Xu, 2001). At this stage, subduction of the Pacific plate underneath the eastern Asian continent seems the most plausible model (Griffin et al., 1998; Wu et al., 2003a) given the coherent timing between the two events. Structural geology and tectonic reconstruction also indicate that the Mesozoic evolution of the NCC is predominantly controlled by the combination of the Pacific subduction from the east and the Mongolo–Okhotsk collision from the north (Yin and Nie, 1996; Ratschbacher et al., 2000). This is evident as widespread extensional basins in the eastern NCC (Ren et al., 2002) and metamorphic core complexes (Davis et al., 1996; Liu et al., 1994). Pacific subduction as a dynamic trigger was not favored by Menzies et al. (1993) largely based on the lack of any evidence for a subduction influence in the geochemistry of early Tertiary to recent volcanic rocks. However, as will be discussed later, it is perhaps the physical aspect of the subduction (i.e., enhanced vigorous mantle convection) that played a pivotal role in the destruction of the lithospheric keel in the NCC.

Cenozoic volcanism is widespread in the eastern NCC and is largely associated with the North China rift system and the Tanlu fault. These basalts and entrained xenoliths provide direct samples of lithospheric mantle processes, and have been the focus of many studies on the age of the lithosphere mantle, the characteristics of the Palaeozoic keel, the timing and the mechanism of lithospheric thinning in the NCC (E and Zhao, 1987; Zheng et al., 2001; Gao et al., 2002; Zhang et al., 2002; Wu et al., 2003a,b; Zhang et al., 2003a,b; Gao et al., 2004; Rudnick et al., 2004; Chen et al., 2004; Xu et al., 2004a,b; Deng et al., 2005; Menzies et al., this volume). Comparatively, the western NCC is poorly understood.

3. Diachronous lithospheric extension in the NCC

Continental rift systems and extensional basins that are widespread in the eastern NCC mainly formed during the Cretaceous–Paleogene (Ren et al., 2002). A series of NNE-trending faults run parallel to the continental margin of which the Tanlu strike-slip fault is the largest (Xu et al., 1987; Fig. 1). This fault experienced a complex evolution, for which four stages have been recognized during Cretaceous deformation (Zhang et al., 2003a,b). The earliest Cretaceous was dominated by N–S extension responsible for the formation of the Jiaolai basin. The middle early Cretaceous, was rift-dominated and characterized by widespread silicic to intermediate volcanism, normal faulting and basin subsidence. It was at this stage that the Tanlu-parallel Yi-Shu Rift was initiated by E–W to WNW–ESE extension (Zhang et al., 2003a,b). Early Cretaceous extension in eastern NCC is also marked by late Jurassic–early Cretaceous clastic sedimentation in several NE trending basins (Watson et al., 1987; Ren et al., 2002) and by scattered development of metamorphic core complexes such as in southern Liaoning (Liu et al., 1994). This rifting episode was followed by a period of late Cretaceous compression. The North China rift system was reactivated in the Eocene along a series of major Mesozoic NNE and/or NE faults, and widespread post-Miocene subsidence developed over the area (Ye et al., 1987; Gilder et al., 1991; Ren et al., 2002). These basins entered a post-rift phase during Neogene times, forming a regional downwarp. Thermal subsidence is also revealed by thermal modeling in the Bohai area which shows a decrease in heat flow from 75–90 mW/m^2 in the early Miocene to 55–65 mW/m^2 at the present time (Hu et al., 2001).

Mesozoic extensional core complexes with Jurassic and Cretaceous ages are also present in the region west of the NSGL such as those in the Daqiang Shan and along the China–Mongolia border (Davis et al., 1996; Ratschbacher et al., 2000). All these core complexes are located within the Yanshannian Orogenic belt, probably due to collapse subsequent to crustal thickening. Therefore, Mesozoic extension in the western NCC is only on a local scale, and is confined to the northern NCC. In contrast to widespread Mesozoic–Cenozoic rifting/basins in the eastern NCC, only two late Tertiary rift systems, the Yinchuan–Hetao rift system and Shanxi graben system, developed around the Ordos block within the western NCC (Ye et al., 1987; Xu and Ma, 1992; Ren et al., 2002). Crustal deformation along these graben systems involved normal slip on NE–SW striking graben-bounding faults, normal right lateral and normal left-lateral slip on NEE–SSW striking faults. This fault pattern is consistent with NW–SE trending extension (Zhang et al., 1998). Although rifting started to develop in the Yinchuan–Hetao graben system and the southern part of the Shanxi graben in the early Oligocene or late Eocene, major extension and rapid subsidence occurred in the Neogene and Quaternary (Ye et al., 1987). Structural geology and stratigraphic records show that the sedimentary infilling in the Shanxi graben is older and thicker in the south than in the north. This is accompanied by a northward deepening of Moho topography suggesting a northward decreasing amount of the crustal extension (Tapponnier and Molnar, 1977). Collectively, available data suggest a later, and less active extension in the western NCC than in the eastern NCC.

The orientation of extensional basin systems in the western NCC is different from the dominant NEE-trending basins in the eastern NCC. For instance, the Yinchuan–Hetao graben system (Fig. 1b) consists of two individual grabens: the NNE-trending Yinchuan graben and the E–W trending Hetao graben. The Shaanxi–Shanxi Rift (Fig. 1b) consists of a series of an echelon grabens, extending from the southern margin of the Loess Plateau north–northeastward across the plateau, delineating a rough S-shape form.

The causes of the diachronous extension and contrasting magnitude of extension in western and eastern NCC are controversial. Cenozoic rifting and volcanism in eastern China were traditionally related to the rollback of the subducting Pacific plate during northwestward Pacific subduction beneath the eastern margin of the Asian continent (Ye et al., 1987). The most convincing evidence for this argument is the correlation between the timing of extension and the change of converging rate between the Eurasia and Pacific plates (Northrup et al., 1995). This is further supported by the E–W to WNW–ESE extension associated with the Tanlu fault during the middle early Cretaceous (Zhang et al., 2003a, b), which is nearly orthogonal to the west Pacific margin. Yin (2000) suggested that Cenozoic rifting in the interior of Asian continent [including the Shanxi graben (in western NCC), Baikel rift and N–S trending rifts in southern Tibet] was also related to mantle upwelling induced by subduction of the Pacific plate. In contrast, studies of seismic anisotropy and numerical modeling led Liu et al. (2004) to suggest that the Indo-Asian collision may have driven significant eastward, lateral mantle flow under the Asian continent, leading to diffuse asthenospheric upwelling, rifting, and widespread Cenozoic volcanism in eastern China.

Both the Pacific subduction and the Indo-Asian collision must have exerted significant influence on the Mesozoic–Cenozoic evolution of the NCC, but neither of these models can fully account for the contrasting extensional history in the western and eastern NCC. For example, Cretaceous–early Tertiary extension in the eastern NCC cannot result from the Indo-Asia collision as they significantly predate the collisional event (Ye et al., 1987). Moreover, extensional basins in eastern China are not restricted to those associated with east-trending strike-slip faults predicted by Tapponnier et al. (1982), but occurred all along the eastern Asian margin. All these make it unlikely that the Indo-Asia collision is the dynamic trigger of extension in eastern China. Equally, the proposal that the far field effect of the Pacific subduction reached to the western NCC (Yin, 2000) is problematic. Specifically, the high-K post-collisional magmas associated with the NS-trending rifts in southern Tibet and asthenosphere-derived melts in the Shanxi graben reflect different tectonic settings and therefore cannot be compared directly. Also, there is little evidence of Eocene faulting and the Oligocene graben-type sediments are generally thin (Ye et al., 1987), suggesting that the influence of the Pacific subduction in the western NCC must have been very limited. Progressive migration from south to north associated with the development of the Shanxi graben is consistent with transmitted stress issued from the Indo-Asia collision (Zhang et al., 1998). It is likely that the late Cenozoic extension in western NCC is the consequence of the Indo-Asia collision as already emphasized by the pioneering work of Molnar and Tapponnier (1975) and Tapponnier and Molnar (1977). In fact, the different orientation of extensional basin systems in the western and eastern NCC suggests fundamentally different tectonic regimes under which Cenozoic lithospheric deformation in the western and eastern NCC took place. It is suggested here that the contrasting extension in western and eastern NCC may have resulted from the interaction of two tectonic regimes, namely Pacific subduction in the east and Indo-Asia collision in the west.

4. Comparison of basalts and xenoliths from western and eastern NCC

4.1. Cenozoic basalts: trends in petrochemistry and Sr–Nd isotopes

Xu et al. (2004c) compared the petrogenetic trends of Cenozoic basalts from the eastern and western NCC. They demonstrated that in the western NCC, magmas evolved from late Eocene–Oligocene alkali basalts to late Miocene–Quaternary alkali and tholeiitic basalts. This change in basalt type was accompanied by progressive lithospheric thinning in the western NCC during the Cenozoic (Xu et al., 2004c) evident as a decrease in La/Yb and an increase in Yb content. This model assumes a “lithospheric lid effect” (e.g., McKenzie and Bickle, 1988; Langmuir et al., 1992; Fram and Lesher, 1993) and was confirmed by a detailed comparison of the Quaternary Datong alkali basalts and the Miocene Hannuoba counterparts (Xu et al., 2005). The Datong basalts have conspicuously lower Al_2O_3 and CaO, higher SiO_2 and HREE contents and Na/Ti ratios, compared to Hannuoba lavas at comparable MgO. Such differences are attributed to different lithospheric thickness when Quaternary Datong basalts (thin lithosphere, ~70 km)) and Miocene Hannuoba basalts (thick lithosphere, 100–120 km) were erupted. This suggests that thinning of the lithosphere in the western NCC was post-Miocene.

In contrast to the western NCC, Cenozoic basalts in the eastern NCC display a temporal variation in petrochemistry generally opposite to that observed in the western NCC (Fig. 1c). The early Tertiary basalts, which occur voluminously in the extensional basins, are mainly quartz- and olivine-normative tholeiites, with subordinate sub-alkali basalts (olivine basalts) and minor alkali basalts (Liu et al., 1992b; Fan and Hooper, 1991). Sub-alkaline rocks continued to occur but diminished in quantity in the late Tertiary and the Quaternary, while alkali and strongly alkali basalts (basanite and nephelinite) progressively became the dominant rock types. This trend may reflect lithospheric thickening in the eastern NCC during the Cenozoic (Xu, 2001; Xu et al., 2004c), probably related to regional thermal decay following peak magmatism in the late Cretaceous–early Tertiary (Menzies and Xu, 1998; Hu et al., 2001).

The contrasting lithospheric processes (lithospheric thinning in the western NCC *versus* thickening in the eastern NCC) during the Cenozoic yield implications for the lithospheric architecture beneath the NCC if the thermomechanical erosion is assumed as mechanism of lithospheric thinning; the lithospheric mantle beneath the eastern NCC is stratified with old lithosphere overlying newly accreted lithosphere, whereas the lithospheric mantle beneath the western NCC may consist mainly of old lithospheric relicts after thermomechanical erosion (Xu et al., 2004c). So far the test of the stratified lithosphere hypothesis is hampered by the absence of reliable thermobarometric methodology for spinel–facies peridotites. However the contrasting lithospheric architecture in western and eastern China is reflected in the Os isotopic compositions of peridotite xenoliths from Cenozoic basalts (see next section) and in the composition of basalts (Fig. 2). Lavas from the western NCC display a larger range in Nd isotope and tend to have lower ε_{Nd} than those from the eastern NCC. This may be related to lithosphere–asthenosphere interaction in the genesis of magmas (e.g., Perry et al., 1987; Arndt and Christensen, 1992). To assess the cause of this isotopic difference requires a careful petrogenetic study, which is beyond the scope of this paper. However, given the general absence of crustal contamination in the Cenozoic basalts (Zhou and Armstrong, 1982; Peng et al., 1986; Zhi et al., 2001) and the fact that some samples with low ε_{Nd} are xenolith-bearing, it has been argued elsewhere (Xu et al., 2004c) that the larger ε_{Nd} range in the basalts from the western NCC might reflect greater involvement of ancient lithospheric mantle in magma generation compared to those from the eastern NCC. If this interpretation is correct, it implies that old lithospheric mantle is present to a larger extent underneath the western NCC than under the eastern NCC.

4.2. Mantle and lower crust xenoliths

4.2.1. Peridotite xenoliths

Mantle xenoliths, entrained by alkaline basalts during their ascent to the surface, are direct samples of the lower lithosphere. Sr–Nd–Os isotopic compositions of these deep-seated samples provide pivotal information about the lithospheric mantle below a specific region (Menzies, 1990; Pearson et al., 2003). Fig. 3a is a compilation of Nd isotopic data for peridotite xenoliths from Cenozoic basalts from the NCC. Although both the samples from the western and eastern NCC are predominantly depleted in Nd isotopic composition, they show a different range in ε_{Nd}. With a few exceptions, the ε_{Nd} value of the peridotite xenoliths from the eastern NCC clusters between 0–12, which resembles the isotopic composition of oceanic basalts (Fig. 3a). This contrasts with those from the western NCC that encompass both extremely depleted and enriched mantle fields ($\varepsilon_{Nd}=-16$–$+26$). Most of the enriched samples from Yangyuan (Ma and Xu, 2006) are characterized by low ε_{Nd} and low $^{87}Sr/^{86}Sr$ ratios. This EM1 like signature, reminiscent of those found in south African xenoliths which could be as old as >3.0 Ga (e.g., Richardson et al., 1984), is typical of old lithospheric mantle (Menzies, 1990; Pearson et al., 2003).

Different stabilization ages for the lithospheric mantle beneath the eastern and western NCC is revealed by recent Re–Os isotopic analyses on peridotite

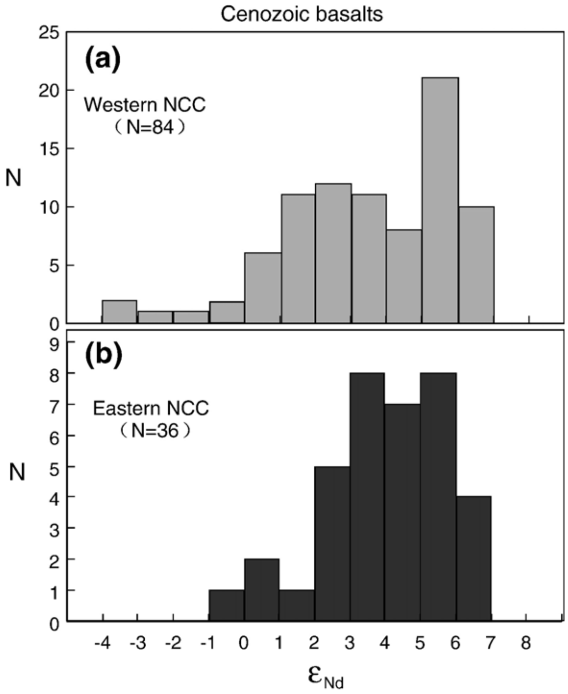


Fig. 2. Histogram of ε_{Nd} of Cenozoic basalts from (a) western and (b) eastern NCC. Data source: Zhou and Armstrong (1982), Peng et al. (1986), Chen et al. (1990), Song et al. (1990), Basu et al. (1991), Liu et al. (1995) and Xu et al. (2004c, 2005; unpublished data).

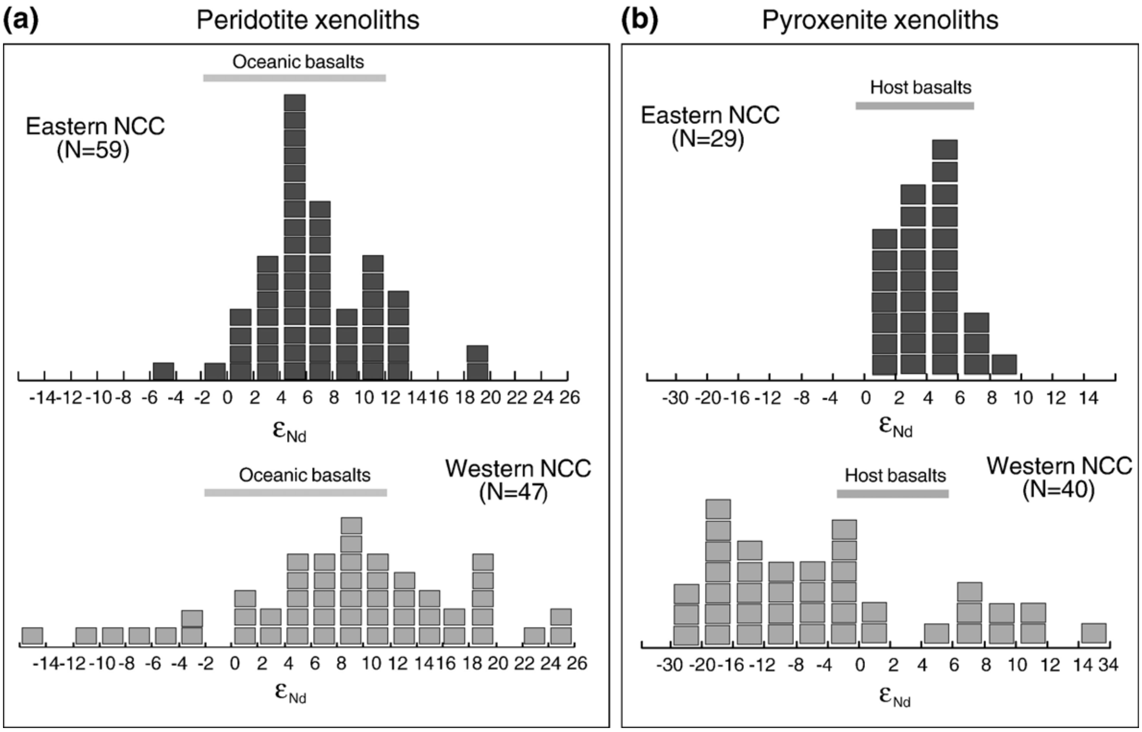


Fig. 3. Histogram of $\varepsilon_{\mathrm{Nd}}$ of basalt-borne xenoliths from the western and eastern NCC. (a) Peridotite and (b) pyroxenite. Data source: Song and Frey (1989), Tatsumoto et al. (1992), Fan et al. (2000), Xu (2002), Rudnick et al. (2004); Xu et al. (2003), Liu and Xu (2005), Ma and Xu (2006). The range for oceanic basalts is after Hofmann (2003).

xenoliths. For instance, while the peridotite xenoliths from Hannuoba (western NCC) define a Paleoproterozoic Re–Os isochron age of 1.9 Ga, the Qixia peridotites from the eastern NCC have modern T_{RD} and T_{MA} ages (Gao et al., 2002). In recognizing that this interpretation could be somehow model-dependent, we adopt the practical approach used by Pearson et al. (2003) to directly compare the Os isotopic ratios of xenoliths with those of typical cratonic peridotites. Yet, this approach is complicated by the compositional dependence of Os isotopic ratios of mantle xenoliths. Xenoliths from the same source but experiencing varying degrees of partial melting will show different time-integrated Os isotopic compositions, with the depleted samples having unradiogenic Os isotopes (Reisberg and Lorand, 1995; Gao et al., 2002). Accordingly, the lowest ^{187}Os/^{188}Os at a given locality will be emphasized in the discussion of the lithospheric age. Fig. 4 shows a difference in Os isotopic ratio for peridotite xenoliths from the eastern and western NCC. The eastern NCC samples display a relatively narrow ^{187}Os/^{188}Os range (0.118–0.128; Fig. 4a), with most samples within the Os isotopic range of abyssal peridotites (Snow and Reisberg, 1995). In contrast, a larger range (0.110–0.130) is observed for the peridotites from the western NCC (Fig. 4b). Specifically, the western NCC samples tend to be lower in ^{187}Os/^{188}Os, with more than half of the sample analyzed having ^{187}Os/^{188}Os <0.12 and the lowest ^{187}Os/^{188}Os of 0.110. Similar low ^{187}Os/^{188}Os ratios have only been reported in peridotite xenoliths collected from cratons like Kaapvaal, south Africa, Siberian and Wyoming, USA (Pearson et al., 1995a,b; Carlson et al., 2004). The contrast in Os isotopic ratio of peridotites from the western and eastern NCC is compatible with the view that the lithospheric mantle beneath the western NCC is old and perhaps was stabilized in the late Archean and Early Proterozoic (Xu et al., in prep) and may partly have been remobilized during the Paleoproterozoic (Gao et al., 2002). In contrast, the majority of the lithospheric mantle under the eastern NCC is “young” although the local presence of old components in this region cannot be ruled out (e.g., Wu et al., 2003a,b; Reisberg et al., 2005).

4.2.2. Pyroxenite xenoliths

A contrast in Nd isotopic composition is also apparent for pyroxenite xenoliths from both sides of the NSGL (Fig. 3b). Pyroxenite xenoliths collected from the western NCC show a considerable range in Nd isotopic

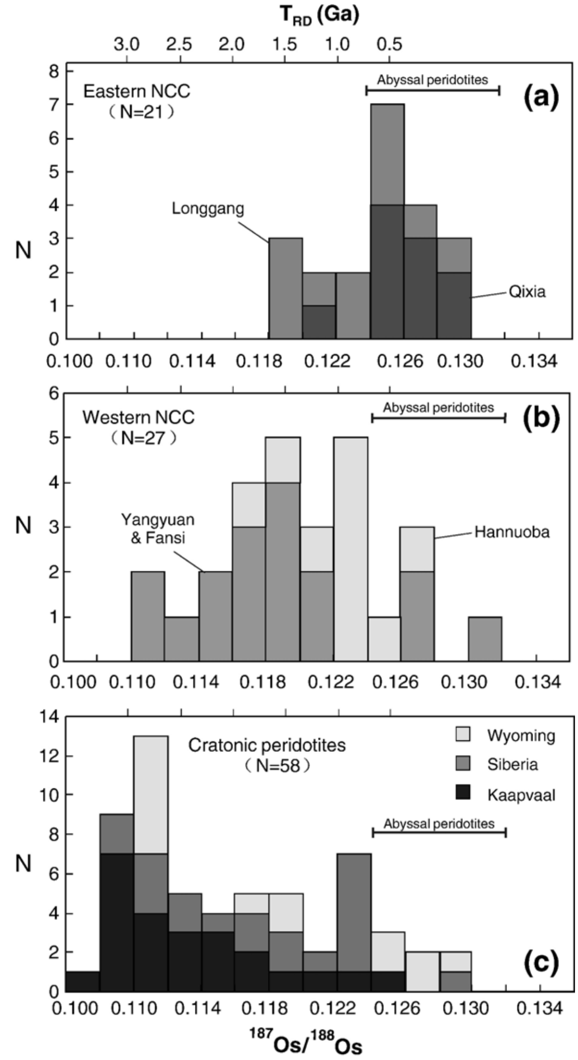


Fig. 4. Comparison of $^{187}Os/^{188}Os$ of basalt-borne xenoliths from (a) western and (b) eastern NCC with (c) those of typical cratonic peridotites. T_{RD} ages corresponding to Os isotopic compositions are given on the top horizontal axis. Data source: NCC — Gao et al. (2002); Wu et al. (2003a); Xu et al. (unpublished). Cratons — Pearson et al. (1995a,b); Carlson et al. (2004). Abyssal peridotites — Snow and Reisberg (1995).

composition with ε_{Nd} ranging from −30 to +34. This range exceeds that of the host basalts in this region (Fig. 3b), ruling out any genetic relationship between them. In contrast, pyroxenite xenoliths from the eastern NCC show a rather restricted range in ε_{Nd} (0–8) which is the same as that of the host basalts (Fig. 3b). This observation indicates a genetic link between the pyroxenites and their host basalts in the eastern NCC or that pyroxenites are high-pressure cumulates from a melt with the isotopic signature similar to that of host basalts. The contrasting composition of pyroxenites from the western and eastern NCC does not necessarily correspond to the different ages for the lithosphere, because it could be related to complex crust–mantle processes (Xu, 2002; Wilde et al., 2003; Liu et al., 2005a,b). Nevertheless, the spatial variation in the isotopic composition of pyroxenites supports the suggestion that the NSGL separates two different lithospheric domains, where processes are very different. Because pre-Cenozoic mafic magmas in the NCC are compositionally distinct from Cenozoic basalts (Xu, 2001; Zhang et al., 2002), a relatively young age can be reasonably inferred for these pyroxenites.

4.3. Crust–mantle transition zone

Cenozoic basalts in two localities, Nushan in the eastern NCC and Hannuoba in the western NCC (see Fig. 1b) contain garnet pyroxenites and/or peridotites and lower crust xenoliths. This lithological diversity allows for the reconstruction of the thermal gradient and examination of the nature of the crust–mantle transition zone in this region (Xu et al., 1998a; Chen et al., 2001; Liu et al., 2001; Zhou et al., 2002; Huang et al., 2004). Fig. 5 summarizes the seismic velocity profile, the thermal gradients and reconstructed lithological profiles at the two localities. Although the geotherms (constructed on the basis of P–T estimates of mantle xenoliths) are very similar at two localities, the Vp structure of the lower crust and the nature of the crust–mantle transition are quite distinct:

(a) A high velocity layer of 3–5 km thick occurs in the lowermost crust at Hannuoba (Liu et al., 2001). It consists of granulites with variable proportions of pyroxenites and peridotites (Chen et al., 2001). In contrast, this high velocity layer is not observed in the case of Nushan;

(b) The depth to the crust–mantle boundary (CMB) (i.e., “petrologic Moho”, Griffin and O'Reilly, 1987) at Nushan is *ca.* 30 km, consistent with the depth to Moho as revealed by seismic refraction data (Fig. 5b; Huang et al., 2004). In contrast, the depth to the CMB at Hannuoba (32 km) is significantly shallower than the seismic Moho (~42 km), implying a thick (~10 km) crust–mantle transition zone.

(c) The lower crust at Hannuoba (24–42 km) is significantly thicker than that beneath Nushan (20–31 km). Thermobarometric data suggest a shallower derivation for the Nushan granulites (6–9.5 kbar) than the Hannuoba granulites (>10 kbar) (Huang et al., 2004).

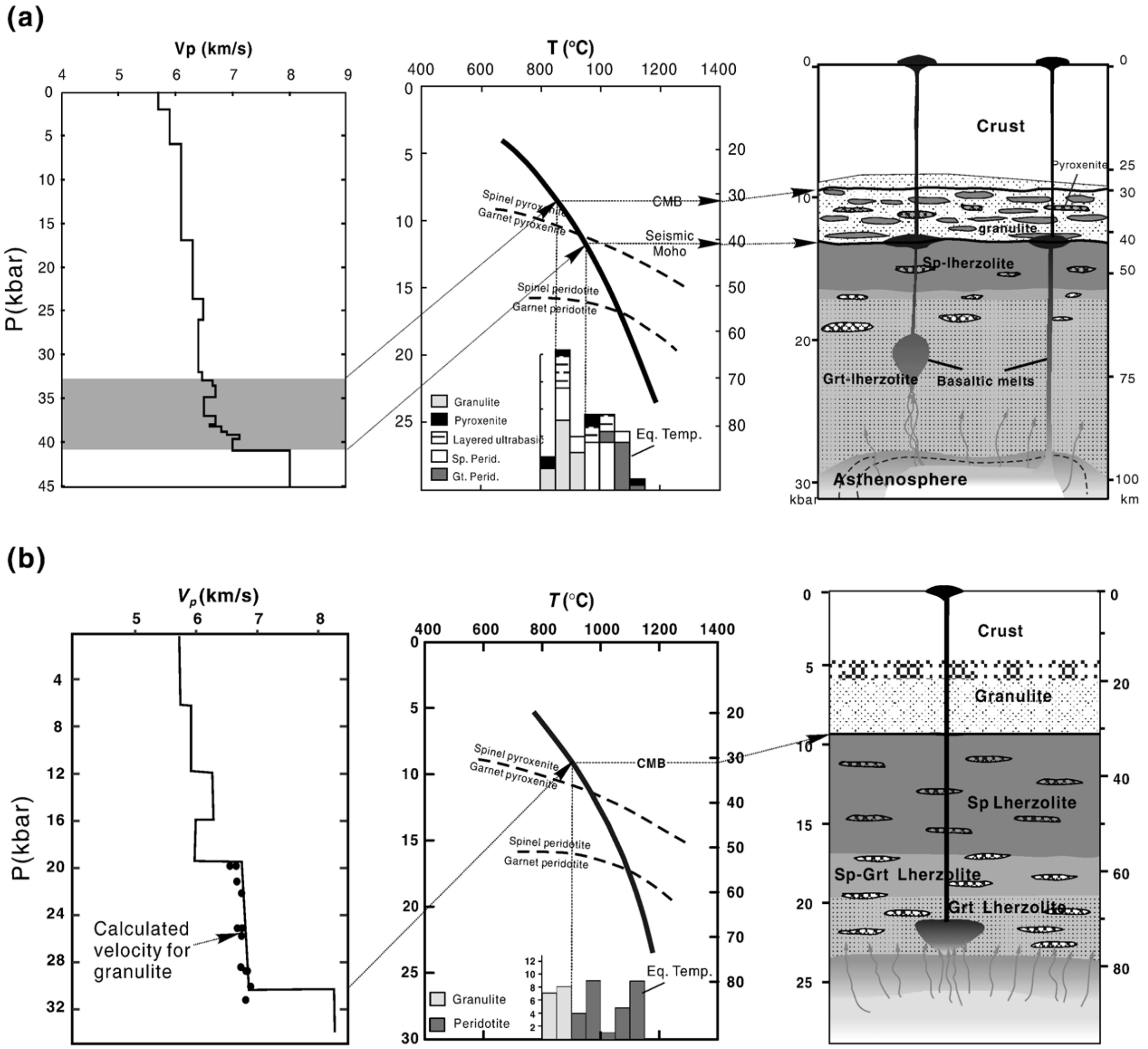


Fig. 5. Comparison of seismic velocity structure, xenolith-derived geotherm and lithologic profile of the lower crust and upper mantle at (a) Hannuoba (western NCC) and (b) Nushan (eastern NCC). Data are compiled from Xu et al. (1998a), Chen et al. (2001), Liu et al. (2001) and Huang et al. (2004).

The different crust–mantle structure in the NCC may have resulted from different degrees of magma underplating in the western and eastern NCC (Huang et al., 2004). Magmatic underplating must have been important at Hannuoba, because geochronologic studies (Fan et al., 1998; Wilde et al., 2003) reveal that magma underplating occurred during the late Mesozoic, coeval with the initiation of widespread thermo-tectonic reactivation of the NCC (Griffin et al., 1998; Xu, 2001). In contrast, underplating was minor at Nushan given the predominant "Proterozoic age" of the granulite xenoliths and the coincidence of the "petrologic" and "seismic" Mohos (Huang et al., 2004). The different extent of Mesozoic underplating at Nushan and Hannuoba correlates with heterogeneous lithospheric extension in these regions. Nushan lies close to the southern part of the translithospheric Tanlu fault zone (Fig. 1b), where the lithosphere is significantly thinner than that beneath rift basins (Ma, 1989). In this mechanically weakened zone, mantle-derived magmas could traverse the crust–mantle boundary and intrude the middle–upper crust. This is consistent with abundant Mesozoic volcanic rocks and plutonic rocks (Xu et al., 1993; Guo et al., 2001; Zhang et al., 2002; Xu et al., 2004a,b; Wu et al., 2005) in the eastern NCC. In contrast, Hannuoba is located west of the NSGL, where lithospheric extension

Table 1
Comparison of geochemical characteristics of mantle-derived rocks and lithospheric structure in the western and eastern North China Craton

Category	Western NCC	Eastern NCC
1. Basalt evolution	Early Tertiary alkali basalts to late Tertiary alkali basalts and tholeiites	Early tholeiites to late Tertiary alkali basalts and to Quaternary highly alkali basalts
2. Basalt composition	^{86}Sr/^{87}Sr=0.7035–0.7053 ε_{Nd}=−4.0–+6.6	^{86}Sr/^{87}Sr=0.7031–0.7048 ε_{Nd}=−0.3–+6.9
3. Xenolith occurrence	Mantle xenoliths in early Tertiary basalts	No mantle xenoliths in early Tertiary basalts
4. Peridotite composition	^{86}Sr/^{87}Sr=0.7006–0.7061 ε_{Nd}=−14.2–+23.3 ^{187}Os/^{188}Os=0.1106–0.1311	^{86}Sr/^{87}Sr=0.7021–0.7048 ε_{Nd}=−5.9–+19.1 ^{87}Os/^{188}Os=0.1186–0.1299
5. Pyroxenite composition	ε_{Nd}=−30–+34	ε_{Nd}=0–+10
6. Mantle components	Depleted and enriched mantle	Dominantly depleted mantle
7. Mantle model ages	Late Archean–Mesoproterozoic	Predominantly modern age, with subordinate Proterozoic age
8. Crust–mantle transition	Thick	Thin
9. Crust–mantle coupling	Yes — western Block No — Trans-North China Orogen	No
10. Interpretation	Old lithospheric relicts	Old relicts+newly accreted lithosphere

was less intense and the lithosphere was generally thicker than that beneath the eastern NCC. Consequently, mantle-derived magmas were trapped at the CMB due to their density contrast. Repeated underplating of basalts may have accounted for vertical crustal growth, giving rise to the formation of a thick crust–mantle transition zone at Hannuoba (Fig. 5).

5. Formation of the NSGL in the North China Craton

The NSGL is not only a physical zone across which the altitude/topography, gravity anomaly and crustal/lithospheric thickness change considerably (Fig. 1c), but also is a chemical boundary which separates two different mantle domains with different formational histories (see summary in Table 1). It has been proposed that the contrasting lithospheric composition and structure in the western and eastern NCC may have resulted from diachronous lithospheric thinning processes (Xu et al., 2004c). This process may also explain the formation of the NSGL, which separates the western and eastern NCC. This is supported by paleogeographic data which support a temporal link between the formation of the NSGL and the destruction of the lithospheric keel.

5.1. Timing of the NSGL formation

The NSGL cuts across all the tectonic units of eastern China. Its formation therefore postdated amalgamation of the different tectonic blocks. It is well established that the Yangzte block collided with the North China block during the Triassic (Li et al., 1993). The amalgamation of the Mongol–Okhotsk plate with the NCC took place at roughly the same time (Yin and Nie, 1996). Taken together, this constrains the formation of the NSGL as post middle Triassic.

More precise information about timing can be deduced from the plaeogeographic record. Fig. 6 illustrates the change in paleogeographic facies in the NCC during the early Cretaceous (Wang, 1985). During the early

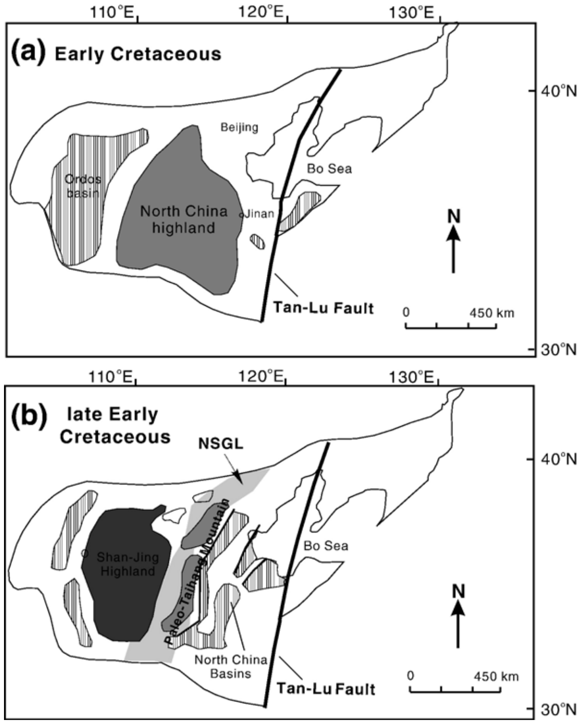


Fig. 6. Paleogeography during (a) early Cretaceous and (b) late early Cretaceous in the NCC. Modified after Wang (1985). Light shaded area shows the present location of the NSGL. Note the coincidence of the NSGL with the paleo-Taihang Mountain.

Cretaceous, the center of the NCC was characterized by the North China Highland. To the west was the post-Jurassic Ordos Basin (Fig. 6a). This paleogeographic configuration suddenly changed in the early Cretaceous, during which time most of the eastern NCC was covered by the North China basins. This continental rift system was bounded to the west by the paleo-Taihang mountain belt (Fig. 6b), and further west the Ordos basin inverted and was replaced by the Shan-Jing Highlands. Essentially, the paleo-topography of the NCC during the early Cretaceous (high crustal elevation in the west, lowlands in the east) reflected the present-day morphology of this region. This highlights the fundamental role of early Cretaceous (deep) lithospheric processes in the evolution of the NCC. Because the paleo-Taihang mountain coincides with the present-day NSGL (Fig. 6b), the first occurrence of the NSGL can be inferred to be during the early Cretaceous. More importantly, the early Cretaceous was the period of intensive Mesozoic mafic (132–126 Ma; Xu et al., 2004a) and silicic magmatism (132–120 Ma; Wu et al., 2005). Although debate continues on the time-scale of destruction of the lithospheric keel underneath the NCC, it is widely agreed that the early Cretaceous marked a key period (Yang et al., 2003; Xu et al., 2004a; Wu et al., 2005). The synchroneity therefore provides additional evidence for a temporal link between the formation of the NSGL and lithospheric thinning processes in the NCC. It is possible that the process responsible for lithospheric destruction also produced the NSGL.

5.2. Formation of the NSGL by diachronous lithospheric thinning

The previous review provides a basis for the suggestion that diachronous lithospheric thinning occurred in the NCC and took place in the eastern NCC earlier than in the western NCC. This was responsible for generation of the NSGL. Lithospheric thinning was dominant in the evolution of the eastern NCC during the late Mesozoic, resulting in loss of the Archean lithospheric keel (>100 km) (Fan and Menzies, 1992; Menzies et al., 1993; Griffin et al., 1998). Most likely, this process proceeded throughout the Cretaceous period (Xu, 2001; Xu et al., 2004c). Such large scale lithospheric thinning and concomitant upwelling of the asthenosphere caused significant lithospheric stretching and subsidence. In contrast, major lithospheric thinning in the western NCC did not occur until the Cenozoic (Zhang et al., 2003a,b; Xu et al., 2004c), given the general absence of Mesozoic extensional basins in the western NCC (Ren et al., 2002). As a consequence, a huge contrast in topography and lithospheric thickness was created during the Cretaceous, with the eastern NCC having thinner crust and lithosphere than the western NCC (Fig. 7). The transition zone between these two regions is the NSGL. A rapid change in gravity anomaly and crustal thickness is expected to occur across this zone.

It is clear that the NSGL is not the reason for, but rather the consequence of, diachronous lithospheric thinning in the NCC. But why did the NSGL occur in its present location, and not elsewhere? A preliminary model is proposed by integrating geological and geophysical data and available modeling results.

Diachronous lithospheric extension in the NCC may be the consequence of interaction between different tectonic regimes. The formation of the NNE-trending basins in the eastern NCC may have been induced by subduction of the Pacific plate underneath the Asian continent, which began in the late Mesozoic (Ye et al., 1987; Griffin et al., 1998). Global tomography studies show that the subducted Pacific oceanic slabs have become stagnant within the mantle transition zone and extended subhorizontally westward beneath the East Asian continent (Fukao et al., 1992; Zhao et al., 2004). The improved resolution of this regional tomography further reveals that the western end of the stagnant oceanic slabs above the 660-km discontinuity correlates well with the NNE-trending NSGL (Pei et al., 2004). Before the tomographic data are used to constrain the tectonic issue, it is necessary to assess whether the present seismic image reflects that of Cretaceous time. The calculation made by Niu (2005) suggested that the maximum speed of western motion of the within-transition zone slabs is 40 km/Ma. This yields a maximum time interval of ~75 Ma for the western end of the slab reaching 100°E. Because subduction of the Pacific Plate beneath the Asian continent started in the Jurassic (Engebretson et al., 1985), slabs may well have existed beneath eastern China during the Cretaceous day do today. It is thus possible that the presence of horizontal stagnant slabs induced vigorous convection in the upper mantle above the slab (Fig. 7b). This convection could have been enhanced by western Pacific subduction suction which requires asthenospheric replenishment from the west (Niu, 2005). This vigorous convection may have been responsible for the removal of the cratonic lithospheric keel beneath the NCC, which probably proceeded via thermomechanical erosion (Buck, 1986; Davies, 1994). The precise mechanism responsible for conversion of cratonic lithospheric to asthenosphere is not well defined but must involve a viscosity change triggered by water, heat or

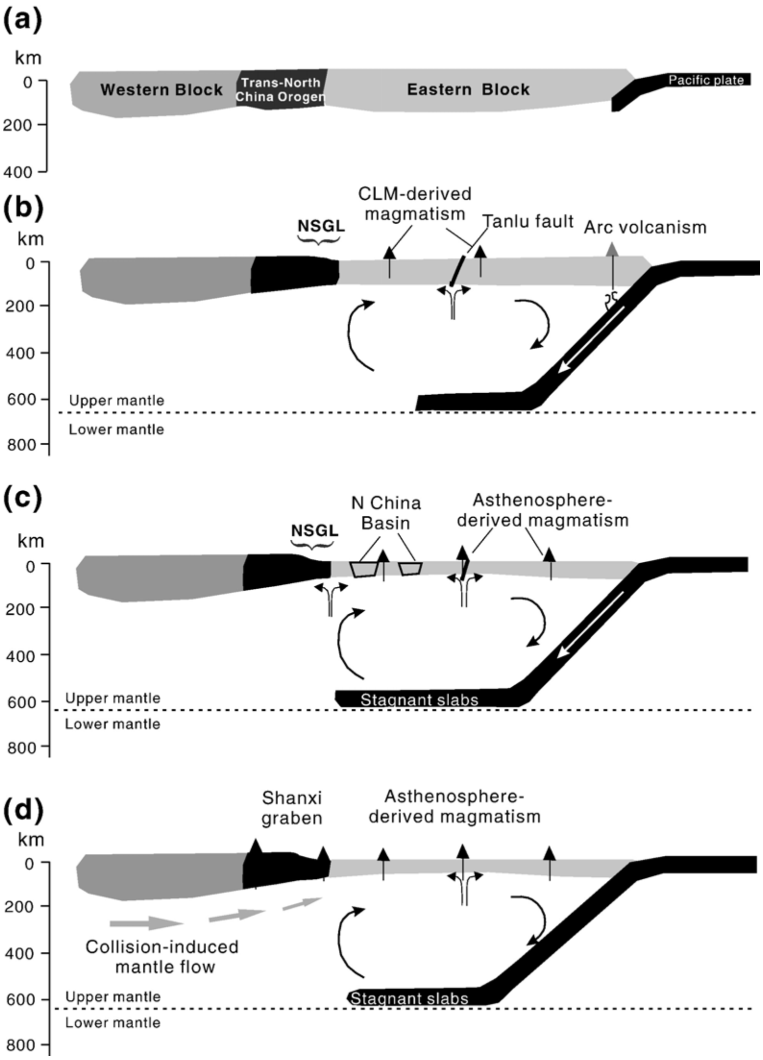


Fig. 7. Schematic illustration of the NSGL formation by diachronous lithospheric thinning in the NCC. (a) Jurassic — the thick lithospheric keel remained largely unaffected. But the local occurrence of intraplate magmas (180–160 Ma) probably marked the initial transformation of the lithospheric root (Xu et al., 2004a); and (b) early Cretaceous — subduction of Pacific plate underneath the Asian continent induced upper mantle convection and back-arc extension. Mantle flows were focused along lithospheric weak zones (i.e., Tanlu fault and boundaries between eastern Block and Central Block), resulting in convective removal of the lithospheric keel under eastern NCC, surface subsidence (i.e., formation of the North China basins) and continental lithospheric mantle (CLM)-derived magmatism. The lithosphere under central and western Blocks was less affected due to its location beyond the convection system. This differential lithospheric thinning created topographic contrast between central and eastern Blocks, giving birth to the NSGL. (c) Late Cretaceous — further development of the NSGL as a result of enhanced vigorous convection due to the stagnant oceanic slabs in the mantle transition zone. The lithosphere was thin enough to ensure melting of the asthenosphere. (d) Early Tertiary — initiation of extension in western NCC as a result of arrival of horizontal mantle flow due to a combined effect of Indo-Eurasian collision and corner suction of the Pacific subduction.

melt ingress. Aspects of thermal and chemical erosion as they affect post-Archaean (i.e. non-cratonic) lithosphere have been considered by Bedini et al. (1997) and Xu et al. (1998b). Due to the configuration of the slab graveyard at 660 km depth, the region most affected by the large scale upper mantle convection was confined to the eastern NCC (Fig. 7b). As discussion in Section 3, the influence of the Pacific subduction in the western NCC must have been very limited. This is consistent with the fact that the western NCC sits beyond the region affected by the stagnant slabs. Lithospheric thinning in the western NCC is most likely related to mantle flow and convection along the lithospheric weakness (i.e., peripheries of the Ordos block) induced by the

Indo-Eurasian collision (Molnar and Tapponnier, 1977; Liu et al., 2004; Fig. 7c). The northeastward propagation of rifting and the stress patterns in the Shanxi graben can be accounted for by the east–northwestward movement of the Tibetan Plateau (Ye et al., 1987; Zhang et al., 1998).

Ancient lithospheric structure may also have exerted its influence on the development of the NSGL, judging from the overlap between the NSGL and the Trans-North China Orogen that separates the Eastern and Western Blocks of the NCC (Zhao et al., 2001; Fig. 1b). The boundaries between these major blocks represent weak zones in the lithosphere. Another major lithospheric weak zone within the NCC is the NEE-trending translithospheric Tanlu fault. It is noted that the North China rift system is bounded to the east by the Tanlu fault and to the west by the boundary between the Trans-North China Orogen and the Eastern Block of the NCC (Fig. 1b). The Shanxi graben roughly coincides with the boundary between the Trans-North China Orogen and the Western Block (Fig. 1b). It is possible that lithospheric extension and thinning likely initiated along these major structural/tectonic boundaries and propagated towards the interior of the rigid lithosphere, because along these boundaries the lithosphere is weakest and mantle flows became focused (Tommasi and Vauchez, 2001). Mantle flow could be further enhanced by thermal anomalies resulting from secondary convection induced by topographic contrasts between different blocks and lithospheric extension along lines of weakness (King and Anderson, 1995). All these account for the proximity of the NSGL to major lithospheric boundaries.

The proposed model for the generation of the NSGL, which involves the interplay between the Indo-Asia collision and Pacific subduction, is somehow reminiscent of the models proposed for Cenozoic tectonic in Asia many years ago (Molnar and Tapponnier, 1975; Yin and Nie, 1996). The new ingredients of the present model include: (a) deep mantle convection induced by the flat slabs in the transition zone rather than shallow mantle convection associated with the conventional subduction model. This explains the scarcity of andesite in eastern China and also explains why the Mesozoic and Cenozoic magmatism reached so far into the continental interior; (b) eastward lateral mantle flow driven by the Indo-Asia collision (Liu et al., 2004) in addition to previously focused stress transmission through the lithosphere (e.g., Tapponnier et al., 1982); and (c) ultimate controls of deep processes on deformation patterns and geophysical anomalies on the surface.

5.3. Does the diachronous lithospheric thinning model apply for the entire eastern China?

The above model is essentially proposed for the Taihangshan gravity lineament in the NCC. However, the NSGL is not confined to the Taihang range but extends to South China and to Northeast China (Fig. 1). This raises a question as to whether the diachronous lithospheric thinning model applies to the entire eastern China. In other words, did the lithospheric thinning process also happen in NE China and south China?

Lithospheric thinning or removal of the lithospheric keel was initially proposed for North China on the basis of contrasting lithospheric thickness and composition in the Paleozoic and Cenozoic. Whether such a process exists in south China is not well defined due to the lack of evidence for equivalent Paleozoic keel(s) in this region. Cretaceous magmatism, which was presumably related to the lithospheric thinning in the NCC (Xu, 2001; Zhang et al., 2002; Chen et al., 2004), is equally distributed in the Dabie orogenic belt, South China and NE China (Faure et al., 1996; Ratschbacher et al., 2000; Wu et al., 2005). This can be taken as evidence for a common lithospheric thinning in the entire eastern China. Additional supporting arguments can be found in mantle xenolith studies. Xu et al. (2000) argued that the majority of the upper mantle beneath southeastern China is newly accreted subsequent to lithospheric thinning. The polybaric melting mechanism recorded in mantle xenoliths from Qilin is also consistent with the asthenospheric upwelling and lithospheric thinning (Xu and Bodinier, 2004). These authors also argued that the upper mantle beneath South China is stratified with a Proterozoic mantle overlying an oceanic mantle. Wu et al. (2003a) and Zhang et al. (2006) reached a similar conclusion for NE China on the basis of Os isotopic analyses on mantle xenoliths and Mesozoic–Cenozoic magmatic evolution, respectively.

To sum up, lithospheric thinning seems to be an integral process throughout eastern China and could be a first order model to explain the formation of NSGL. It is true that the present lithospheric thickness in both sides of the NSGL in South China is less contrasted than in North China. This may be due to different post-formational processes. Specifically, while North China experienced subsidence forming great North China plain, South China has been uplifted during the Cenozoic making Mesozoic granite exposed. The mechanism for this difference remains poorly constrained, but the distinct responses of South China and North China to the Indo-Asian collision (Liu et al., 2004) could be a subject of future studies.

6. Summary and conclusions

An integration of tectonic and geophysical data, temporal changes in plaeogeographic configuration and in the isotopic composition of Cenozoic lavas and mantle xenoliths allows constraints to be placed on the NSGL, one of the most prominent geologic features in eastern China. The essence of the preliminary model presented herein is that the formation of the NSGL is most likely driven by deep upper mantle processes and the west–east contrast across the NCC is the surface manifestation of these deep processes (*ca.* 660 km). Below we list some of the major characteristics about the NSGL and its formation:

(1) A fundamental geological feature that separates the NCC into two parts. Crustal elevation, geomorphology, crustal and lithospheric thickness and gravity anomalies change dramatically across the NSGL.
(2) The western end of a zone of high velocity anomalies at 660 km coincides with the NSGL. These anomalies are interpreted as stagnant, recycled oceanic slabs in the mantle transition zone.
(3) Cenozoic mafic rocks reveal contrasting lithospheric processes and mantle compositions in either side of the NSGL within the NCC. Temporal variations in the isotope geochemistry of Cenozoic basalts reflect lithospheric thickening/accretion in the eastern craton and progressive lithospheric thinning in the western craton.
(4) Sr–Nd–Os isotopic data for mantle xenoliths further emphasize that the lithospheric mantle in the western NCC is relatively old (late Archean–early Proterozoic) compared to that beneath the eastern NCC which is "young" and similar to oceanic or abyssal mantle. Indeed the eastern craton may be comprised of hybrid mantle — a mixture of old lithospheric relics and newly accreted mantle. The NSGL is therefore not merely a physical zone, but also a chemical boundary separating two different mantle domains.
(5) Paleogeographic reconstructions suggests the first appearance of the NSGL during the early Cretaceous, a time of peak Mesozoic magmatism in the NCC. Since Mesozoic magmatism was related to lithospheric thinning, it can be argued that diachronous lithospheric thinning was the mechanism responsible for the NSGL. Lithospheric thinning in the eastern NCC took place in the late Mesozoic, significantly earlier than the Cenozoic thinning in the western NCC. This diachronous process resulted in different lithospheric thicknesses underneath the western and eastern NCC during the Cretaceous, which eventually gave birth to the NSGL.
(6) The NSGL might mark off the boundary between two tectonic regimes in the NCC, with back-arc extension related to Pacific subduction in the east and Indo-Eurasian collisional extension in the west. The location of the NSGL is not random but is controlled by the western boundary of the vigorous convection induced by stagnant oceanic slabs in the transition zone and the old major lithospheric weak zones in the region.

Acknowledgements

We thank Shan Gao, Yaoling Niu and an anonymous referee for constructive comments that help improve the quality of the paper. Comments from colleagues at the SECE-IUGS Beijing meeting in 2005 are appreciated. The author gratefully acknowledges the financial support from the Chinese Academy of Sciences (the Baren Project) and the National Natural Science Foundation of China (49925308, 40421303). This paper was written during a research visit to the Geology Department, Royal Holloway University of London in 2005. Martin Menzies is thanked for his support during that visit, and his comments on an early and final version of this paper.

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