SCIENCE CHINA
Earth Sciences

• REVIEW •

December 2014 Vol.57 No.12: 2878–2890
doi: 10.1007/s11430-014-4995-0

Thinning and destruction of the cratonic lithosphere: A global perspective

WU FuYuan[1*], XU YiGang[2], ZHU RiXiang[1] & ZHANG GuoWei[3]

[1] *State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China;*
[2] *State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China;*
[3] *State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an 710069, China*

Received July 3, 2014; accepted October 8, 2014; published online November 6, 2014

It has been proposed that the North China Craton (NCC) was thinned up to a thickness of >100 km during the Phanerozoic, and underwent an associated craton destruction. Evidently, it is an important topic worthy of future study to understanding the mechanism of cratonic destruction and its role played in the continental evolution. After synthesized the global cratons of India, Brazil, South Africa, Siberia, East Europe (Baltic) and North America, we found that lithospheric thinning is common in the cratonic evolution, but it is not always associated with craton destruction. Most cratons was thinned by thermal erosion of mantle plume or mantle upwelling, which, however, may not cause craton destruction. Based on the studies of the North American and North China Cratons, we suggest that oceanic subduction plays an important role in caton destruction. Fluids or melts released by dehydration of the subducted slabs metasomatize the mantle wedge above and trigger extensive partial melting. More importantly, the metasomatized mantle lost its original rigidity and make craton easier to be deformed and then to be destoyed. Therefore, we suggest that the widespread crust-derived granite and large-scale ductile deformation within the continental crust can be regarded as the petrological and structural indicators of craton destruction, respectively.

lithospheric thinning, destruction, mantle plume, subduction, craton

Citation: Wu F Y, Xu Y G, Zhu R X, et al. 2014. Thinning and destruction of the cratonic lithosphere: A global perspective. Science China: Earth Sciences, 57: 2878−2890, doi: 10.1007/s11430-014-4995-0

The surface of Earth's continents is mostly covered by two geological units, the orogenic belts and the cratons. Unlike the orogenic belts, the cratons can remain stable for a long time. In past decades, abundant studies have attributed the stability of cratons to their thick lithospheric keels, which commonly have low densities and water contents. These characteristics make the floating of cratons above the convective asthenosphere. Moreover, the cratons are immune to destruction caused by later geologic resetting, due to the high rigidity of their thick and dry lithospheric keels (Sleep, 2005; Peslier et al., 2009; Lee et al., 2011). Therefore, the common wisdom is that cratons remain stable in the Earth's history and are commonly not subjected to the intra-lithospheric or intra-crustal deformation. Except the weak deep-seated magmatism, both extensive magmatism and mineralization are basically absent within the cratons. However, the eastern portion of the North Craton Craton (NCC) has experienced lithospheric thinning and craton destruction during the Phanerozoic, which completely ruined its original rigidity. The scientific issue is why the stable craton can be destroyed. With the main aim of studying the mechanism of craton destruction, the project, Destruction of the North China Craton, has been implemented by Natural Science Foundation of China in 2007. Progresses in

*Corresponding author (email: wufuyuan@mail.igcas.ac.cn)

several perspectives, such as the tempo-spatial scale and the mechanism of crtaon destruction, have been already achieved in recent years (Zhu et al., 2012). In this paper, we first discussed whether lithospheric thinning and caton destruction are common phenomena or not based on the comparison of several cratons in the world (Figure 1). Then, effects of deep thermal events, as represented by mantle plumes, on thinning and modification of cratonic mantle are illustrated. Finally, we disclosed the mechanism that led to the destruction of the NCC through the comparison between the NCC and other cratons that have also been subjected to destruction.

1 Definition: Lithospheric thinning and craton destruction

The relationship between lithospheric thinning and craton destruction is of key importance in the study of craton destruction. However, no consensus on this relationship has been obtained in previous studies on the NCC. Therefore, it is necessary to clarify the concepts of lithospheric thinning and craton destruction.

Lithospheric thinning describes only the change in the lithosphere thickness of a geological unit, which does not imply any mechanism involved. Studies have shown that lithospheric thinning occurred in most areas of the Earth in the geological history, and, in particular, is more common in orogenic belts (Krystopowicz and Currie, 2013). Based on studies on mantle xenoliths or mineral inclusions in diamond trapped by the Paleozoic kimberlite (~480 Ma), it has been estimated that the lithosphere of the NCC had a thickness of ca. 200 km at that time. Constraints from mantle xenoliths entrained in the Cenozoic basalts, however, reveal that the Cenozoic lithosphere of the NCC has a thickness less than 80 km, which is also consistent with the geophysical data (Lu et al., 1991; Menzies et al., 1993; Griffin et al., 1998). Therefore, the lithosphere of the NCC has thinned for more than 100 km since 480 Ma. Although the mechanism for this process is still controversial, it becomes a consensus that the NCC has experienced lithospheric thinning.

However, some recent studies questioned whether the whole lithosphere of the NCC has been thinned or not (e.g., Zhang, 2011). It is argued that the distribution of the Paleozoic kimberlites (e.g., Mengyin in Shandong Province and Fuxian in Liaoning Province) in the NCC is too limited, and thus, the lithosphere thickness inferred by the kimberlite-borne mantle xenoliths or minerals cannot represent the thickness of the whole NCC. They suggested that lithosphere thinning has not occurred in the NCC but these two locations. A full discussion on such opinions is beyond the scope of this paper, and here we only list several lines of facts. Firstly, the NCC evolved as a whole unit after its cratonization in 1.8 Ga. The lithosphere beneath the western NCC, where the lithosphere has not been or weakly thinned, still has a thickness of ca. 200 km (Chen et al., 2008), which is as thick as the Paleozoic lithosphere beneath both Mengyin and Fuxian. This suggests that the NCC overall had a thick lithosphere during the Paleozoic. Secondly, the thickness of global lithosphere has also been constrained by data from limited regions. Occurrence of kimberlites everywhere on a craton in a specific geological period cannot not expected. Even if kimberlites are widely distributed, it is

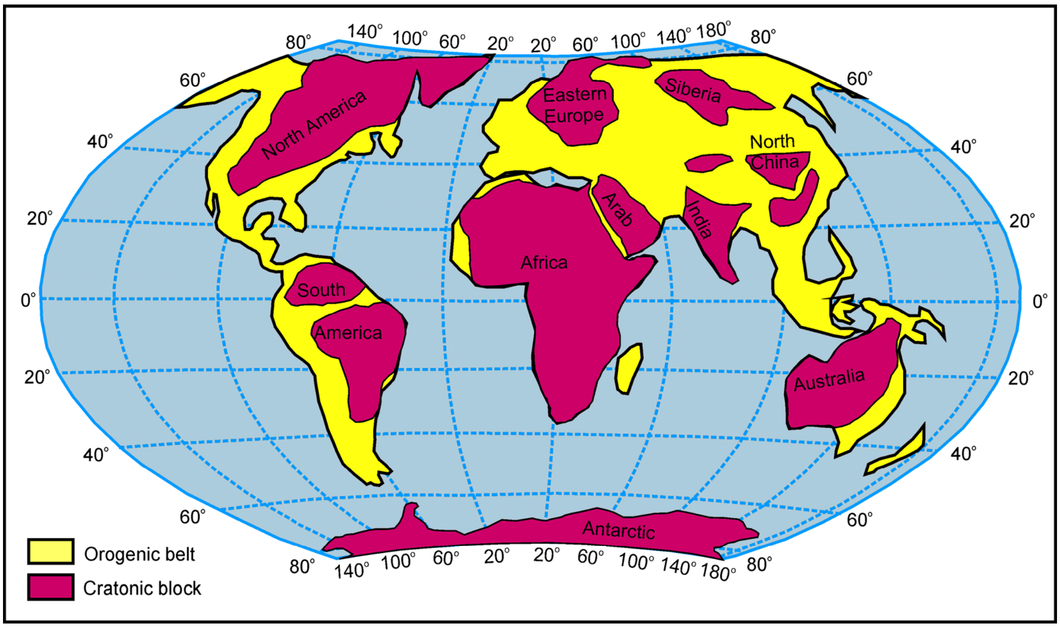

Figure 1 Distribution of the global Precambrian cratons.

unwarrantable to obtain mantle xenoliths or xenocrysts that are suitable for estimating the lithosphere thickness everywhere. Thirdly, the lithosphere widely discussed in the literature refers to the thermal lithosphere, of which the thickness is constrained by both the conductive geotherm of the lithosphere and the adiabatic gradient of the asthenosphere (McKenzie and Bickle, 1988). The temperature of the asthenosphere is basically known and adiabatic upwelling of the asthenosphere suggests that the temperature of lithosphere-asthenosphere boundary (LAB) beneath most areas should be similar. Nevertheless, the conductive geotherm of cratons reversely correlates with its thickness; that is, the thicker the craton is, the colder geotherm it has. It is hard to imagine that the thickness of the lithosphere beneath an area, particularly beneath the craton, is highly variable in a limited space. Such a scenario is only expected for the lithosphere of orogenic belts.

The definition of craton destruction has not been strictly clarified yet. We generally refer it as the geological phenomenon that a craton loses its stability (Wu et al., 2008). Craton destruction has also been termed as decratonization or destabilization (Yang et al., 2009). As implied by its definition, a destroyed or destructed craton does not share any characteristics of stable cratons, unless it has been recratonized later. The geologic indicator of craton stabilization is that its sedimentary cover preserves its original horizontal status. The main characteristic of shields without sedimentary cover is that their basement rocks have not experienced remarkably metamorphism and deformation. During the Mesozoic, the eastern NCC has been subjected to extensive magmatism and strong deformation, hence lost its stability. From this perspective, craton destruction is similar to platform reactivation. However, platform reactivation is a descriptive term, meaning that the craton reactivates and becomes unstable. Similarly, both mantle replacement (Zheng, 1999) and lithospheric transformation (Zhou, 2009) have been coined to emphasize the changes in compositions and thermal state of the deep mantle during lithosphere thinning. As can be seen from these definitions, craton destruction is not equal to lithosphere thinning and there is no certain relationship between each other. Specifically, craton destruction can be accompanied by lithospheric thinning, whereas the occurrence of lithosphere thinning does not certainly cause craton destruction.

Lithosphere modification is another important geological process related to craton destruction. Modification is ubiquitous in the global lithosphere. Every craton can be disturbed by various geological processes, such as subduction and upwelling of the anomalously hot magmas from the deep. In terms of magmatism, deep-seated magmas, which are represented by kimberlites but also include alkaline magmas, lamprophyres and carbonatites, are widely distributed in all cratons after their formation. These magmas are commonly the expression of mantle plumes or mantle upwelling on cratons. Lithosphere modification can accelerate or act as the prerequisite condition of craton destruction. As discussed in the following, however, it cannot destabilize the cratons and trigger craton destruction in most cases. In the extreme case, craton destruction can be regarded as one way for continental reformation.

Whether continental break-up can be called as craton destruction or not is another question worth discussing. Continental break-up refers to the process that a continent is split into several small blocks. If cratons still preserve their stability during breakup, then this process cannot be called as craton destruction. Several supercontinents existed in the Earth's history, and the distribution of present cratons resulted from the breakup of the Pangea supercontinent during the Paleozoic. Opening of the Atlantic Ocean separates the African, South American, North American and European continents. However, ancient blocks within these continents still preserve their stability similar to cratons.

2 Is lithospheric thinning certainly accompanied by craton destruction?

The NCC is distinguished from other cratons in the world by its significant lithosphere thinning (Carlson et al., 2005), which was also accompanied by craton destruction. It is unclear whether there is a certain relationship between lithospheric thinning and craton destruction or lithospheric thinning is certainly accompanied by craton destruction. To answer this question, here we give a brief review of several classic cratons in the world.

The first example is the Indian Craton (Figure 2), which consists of two parts, the Aravalli and Bundekhand Cratons in the north, and the Dhawar, Bastar and Singhbhum Cratons in the south. These two parts were connected by the central tectonic belt (Zhao et al., 2002). The Indian Craton preserves geologic records of 3.6 Ga (Rajesh et al., 2009), of which the early geological evolution history is similar to the NCC (Zhao et al., 2003). Assembly of the northern and southern blocks along the central orogenic belt at ca. 1.8 Ga led to the final cratonization. The Purana sedimentary series were deposited over the craton during the Proterozoic, which have not been subjected to strong metamorphism and deformation. The Cudppah basin developed above the Dhawar craton is composed of this sedimentary series. In 65 Ma, about million square kilometers of the Indian Craton is covered by the Deccan basalts that erupted at ca. 65 Ma (Courtillot et al., 1986; Duncan and Pyle, 1988).

As one of the classic cratons in the world, the Indian Craton preserves different types of anorogenic magmatic rocks, of which the most famous are the kimberlites and lamprophyres. In particular, both the Wajrakur kimberlite in the eastern Dhawar craton and the Majhgawan lamprophyre in the Bundelkhand craton are rich in diamonds. These areas are also regions with the earliest (ca. 4000 years ago) discovery and utilization of diamonds in the world. Although ages of these kimberlites were controversial, recent studies indicated that they were emplaced at ca. 1.1 Ga, representing an important global thermal event in the deep mantle (Kumar et al., 2007a; Chalapathi Rao et al., 2013). More importantly, these kimberlites also contain abundant mantle xenoliths, such as garnet peridotite and eclogite. According to the mineral assemblage of the mantle xenoliths and the occurrence of diamonds, it has been inferred that the lithosphere of the Indian Craton when the kimberlites were emplaced had a thickness of ca. 200 km (Figure 2) and a typical cratonic geotherm of 40–45 mW/m^2 (Nehru and Reddy, 1989; Rao et al., 2001; Griffin et al., 2009; Karmalkar et al., 2009).

Coeval with the eruption of the Deccan basalts, both basalts and lamprophyres also erupted at the western part of the Indian Craton, which also contain mantle xenoliths. Different from the kimberlite-borne xenoliths, these mantle xenoliths are spinel-facies peridotites, suggesting they were derived from depths less than 80 km (Mukherjee and Biswas, 1988; Karmalkar et al., 2000). In combination with the pressure and temperature data of granulite xenoliths, the lithosphere beneath the Dharwar craton had a thickness of ca. 80 km during ~65 Ma (Dessai et al., 2004; Karmalkar et al., 2009; Figure 1(b)), which is consistent with the results of modern geophysical observation (Roy and Rao, 2000; Sarkar et al., 2001; Gokarn et al., 2004; Sarkar and Saha, 2006; Kumar et al., 2007b; Kiselev et al., 2008; Shalivahan et al., 2014).

In summary, more 100 km lithosphere had been thinned beneath the Indian Carton from 1.1 Ga to 65 Ma. The thickness of thinning is similar to the NCC. Unlike the NCC, however, the Indian Craton remains stable after its formation. Both the Proterozoic sedimentary rocks and the Deccan basalts on the top of this craton, covered like a layer of quilt, have not been subjected to strong metamorphism and deformation. Moreover, the seismic activity is also weak in the Indian Craton. The lithospheric thinning resulted in the quick drift of the India continent northward, like a cheetah, which finally collided with the Eurasian Block (Kumar et al., 2007b).

The Siberian Craton, which has been regarded as the representatives of typical cratons in the world together with the South African Craton, is the second example of lithospheric thinning. Basement rocks are rarely outcropped in the Siberian Craton, which are only exposed in the Aldan Shield to the south and in the Anabar Shield to the north (Figure 3(a)). Previous studies on these two shields suggested that the cratonization of the Siberian Craton was taken place at ca. 1.85 Ga (Rosen et al., 2005). The whole Siberian Craton has been covered by platform sedimentary rocks (Riphean and Vendian) since the Proterozoic. However, multiple stages of anorogenic magmatism have been developed in the stable Siberian Craton. Our recent study (Sun et al., 2014) has revealed that kimberlite magmas formed repeatedly during at least four episodes (Figure 3(b)), i.e., 420, 360, 220 and 160 Ma, of which the kimberlites erupted at ca. 360 Ma are diamondiferous. Moreover, both the Udachnaya pipe (360 Ma) in the Daldyn field and the Obnajonnaya pipe (160 Ma) in the Kuoika field contain abundant peridotites, eclogites and different kinds of crustal xenoliths, which provide an opportunity to study the compositions and the thermal state of the deep mantle (Pearson et al., 2003; Howarth et al., 2014). Studies on mantle xenoliths from these two kimberlite pipes indicate that the Paleozoic (360 Ma) lithosphere beneath the Siberian Craton had a thickness more than 200–220 km and a cold thermal gradient that is typical of cratons during the Paleozoic

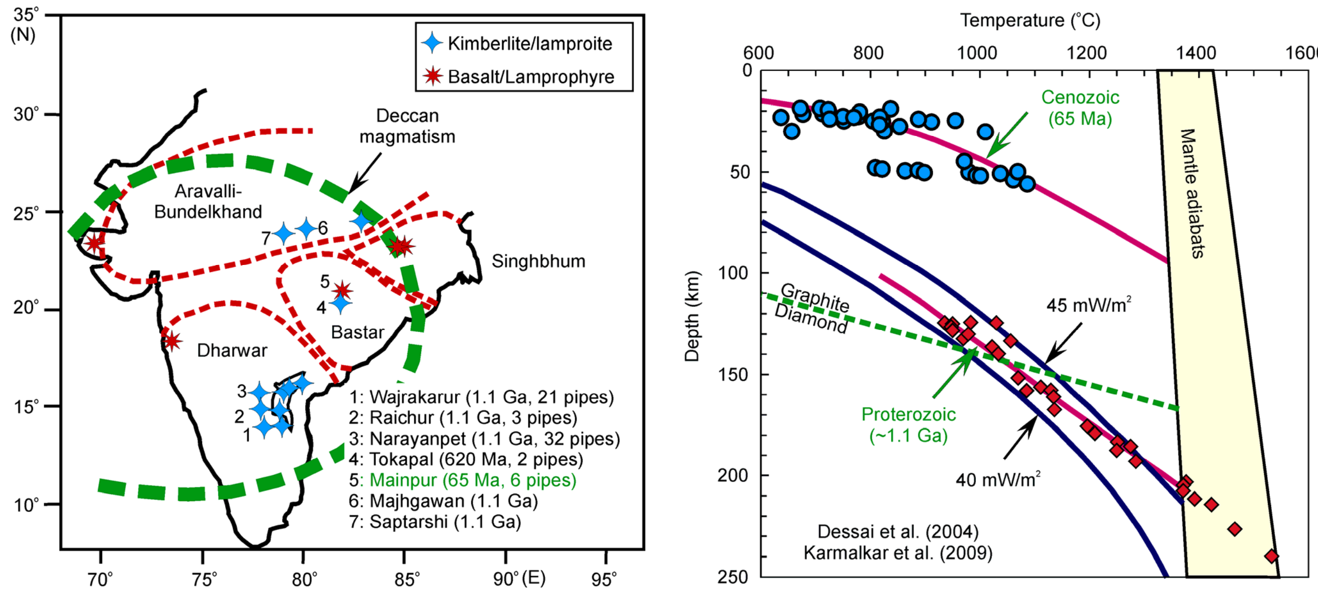

Figure 2 Geological units of the Indian Craton (a) and its inferred lithospheric thickness at different ages (b).

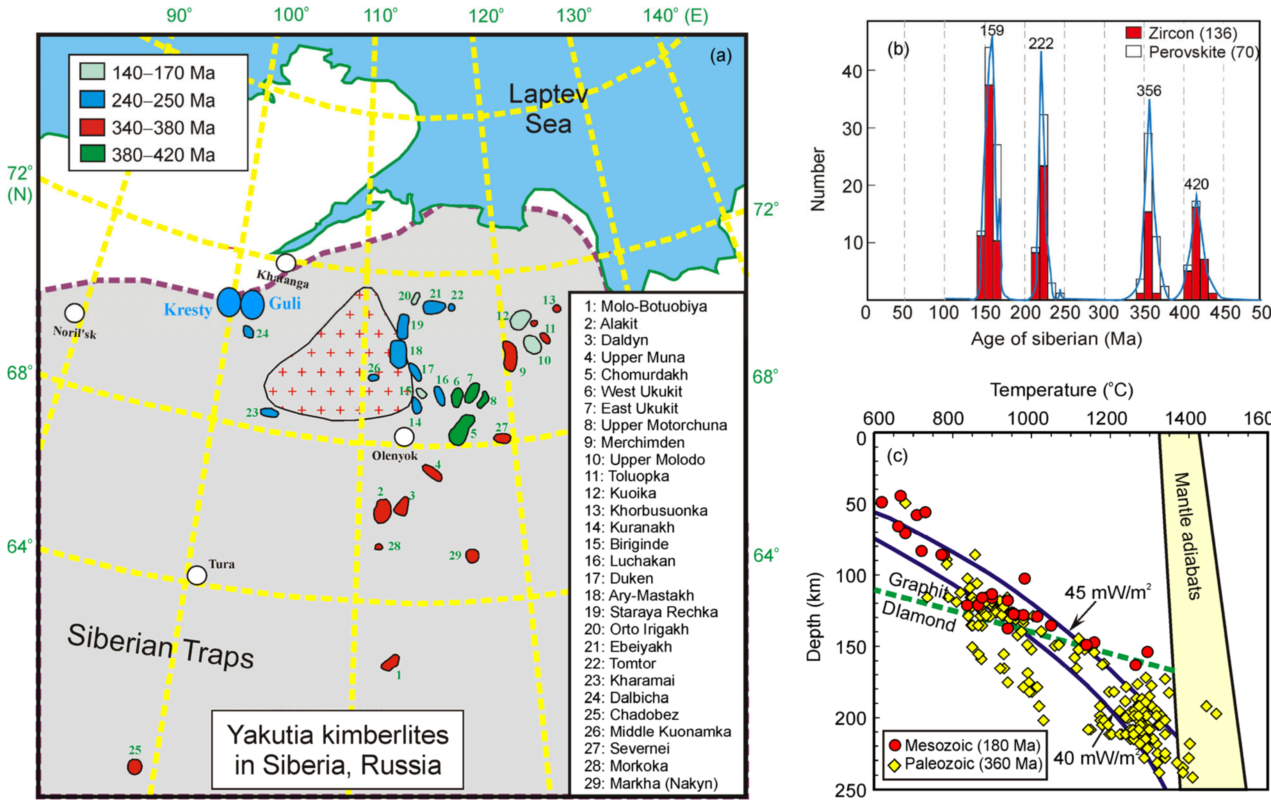

Figure 3 Distribution of kimberlites in the Siberian Craton (a), the emplacement ages of kimberlites (b) and the thickness of lithosphere beneath the Siberian Craton during the Paleozoic and the Mesozoic. Data of the Paleozoic Udachnaya mantle xenoliths are from Boyd (1984), Boyd et al. (1997), Ionov et al. (2010), Doucet et al. (2013), Agashev et al. (2013) and Howarth et al. (2014). Data of the Mesozoic Obnajonnaya mantle xenoliths are from Taylor et al. (2003) and Howarth et al. (2014).

(Figure 3(c)). In comparison, a hotter thermal gradient is inferred for the Mesozoic (160 Ma) lithosphere by the mantle xenoliths entrained in the Obnajonnaya kimberlite pipe. This, together with the fact that the Mesozoic kimberlites are diamond-barren, implies a thinner (150 km) lithosphere beneath the Siberian Craton at during the Mesozoic (Taylor et al., 2003; Howarth et al., 2014). Such a thickness is consistent with the results obtained by garnet xenocrysts from the Kharamai kimberlite that erupted at ca. 220 Ma (Griffin et al., 2005). Therefore, we can deduce that the Siberian Craton has lost ~50 km lithosphere during 360–220 Ma (Griffin et al., 1999; Howarth et al., 2014).

Griffin et al. (1999) suggested that the Siberian Craton has been subjected to a small scale of lithosphere thinning, which is also supported by later studies (Tychkov et al., 2008). However, Ashchepkov et al. (2010) argued that the Siberian Craton has not experienced lithosphere thinning or has been subjected to a small extent of thinning. They attributed the variation in the lithosphere thickness estimated by mantle xenoliths to the difference in the spatial positions of both Udachnaya and Obnajonnaya (Obnazhennaya) kimberlites. That is, the Obnajonnaya pipe erupted at the northern margin of the Siberian Craton, where the lithosphere has a thinner thickness than the craton center. There are four kimberlite fields in the neighboring area of the Obnajonnaya pipe, i.e., Mechimden (360 Ma), Kuoika (160 Ma), Upper Malodo (160 Ma) and Toluopka (360 Ma). The geotherm constructed by garnets supports that the lithosphere beneath the Toluopka area at the time of kimberlite eruption (360 Ma) had a thickness of ca. 180 km (Griffin et al., 1999), which is similar to the thickness of lithosphere in other areas of the craton during the Paleozoic. This suggests that the Siberian Craton has been indeed subjected to lithosphere thinning, although the extent was probably small.

Another example of lithosphere thinning comes from the South American Craton, which is bounded by the Atlantic Ocean to the east and by the active continental margin to the west that was formed as response to the subduction of the Pacific Ocean. This craton is also called as the Brazilian craton, because its main part locates within Brazil. Before the opening of the south Atlantic Ocean, the Brazilian Craton was assembled together with the South Afirican and the Antarctican cratons. The actual area of the Brazilian craton is very big, but most of which is covered by the Phanerozoic sedimentary rocks. This craton is composed of two subcratons, i.e., the Amazonas Craton in the west and the Sao Francisco Craton in the east (Figure 4). The Brazilian Craton has a complicated history of geological evolution during the Archean, and the cratonization finished after three orogenic events during the Paleoproterozoic, the

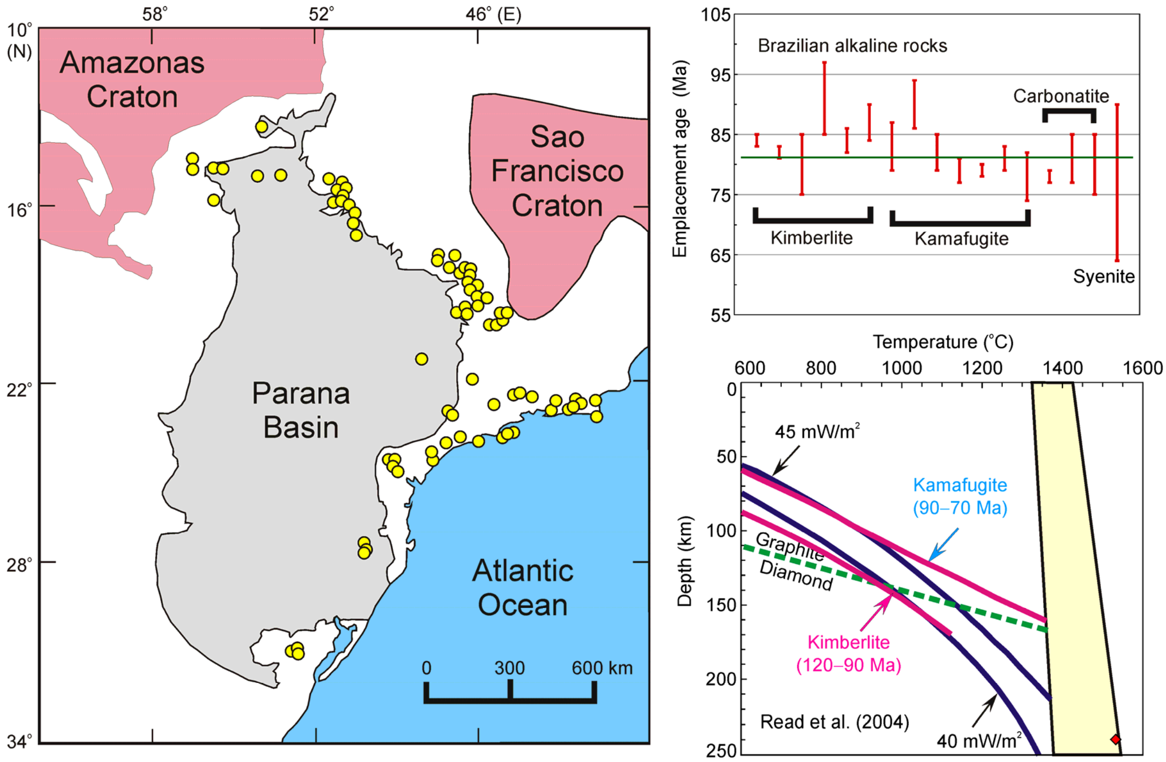

Figure 4 Distribution and emplacement time of Cretaceous kimberlite and alkaline rock, comparison of lithospheric thickness of different episodes in the Brazilian craton.

Mesoproterozoic and the Pan-African (De Almeida et al., 2000). Typical anorogenic magmas, including kimberlites, kamafugites, carbonatites and alkaline rocks, are developed in the Brazilian Craton during the Cretaceous (Ulbrich and Gomes, 1981; Morbidelli et al., 1995), of which the carbonatites are the main resources of Nb and Ta in the world (Cordeiro et al., 2011). Geochronological data have shown that the early stage of diamondiferous kimberlites emplaced at ca. 90 Ma (Guarino et al., 2013), whereas other igneous rocks without diamonds were developed during 70–90 Ma. Studies on pyroxene xenocrysts have suggested that the lithosphere beneath the Brazilian Craton was thinned from 200 to 125 km, i.e., with a thinning of ca. 75 km (Read et al., 2004).

In summary, examples of three cratons (i.e., India, Siberia and Brazil) indicate that lithospheric thinning is very common during the evolution of craton rather than occurred uniquely in the NCC. Unlike the NCC, lithosphere thinning in these cratons was not accompanied by craton destruction, i.e., they remained stable after thinning.

3 Can thermal erosion by mantle plume certainly result in lithospheric thinning?

In the above discussions on the Indian, Siberian and Brazilian cratons, the reason resulting in the thinning of cratonic lithosphere has not been fully elaborated. Xenoliths entrained in the Deccan basalts and other related rocks have demonstrated that lithosphere beneath the Indian Craton has been thinned before the eruption of these magmas (Karmalkar et al., 2009). Moreover, these magmatic activities were developed earlier than the late extension. This excludes the mechanical stretching as the reason for the lithosphere thinning of the Indian Craton (Hooper et al., 2009). It has been suggested that the lithosphere thinning of the Indian Craton was taken place coeval with the breakup of the Gondwana supercontinent during the Mesozoic (Griffin et al., 2009; Shalivahan et al., 2014). However, we prefer to invoke magmatism triggered by the Deccan mantle plume as the main mechanism for lithosphere thinning, because little geological record is preserved in the Indian Craton during breakup of the Gondwana supercontinent.

As discussed above, lithospheric thinning occurred in the Siberian Craton during 360–160 Ma. Kimberlites erupted at ca. 360 Ma was probably coeval with the Yakutsk mantle plume (Courtillot et al., 2010). After that, the most important event that occurred in this craton was the Siberian mantle plume, which erupted at ca. 250 Ma (Basu et al., 1995; Renne, 1995; Reichow et al., 2009). Although basalts of this age in this area have been explained by edge-driven convection or delamination (King and Anderson, 1998; Elkins-Tanton, 2005), it is commonly accepted that formation of large volumes of basalts in the Siberian Craton is related to the mantle plume (Saunders et al., 2005). Similarly, the lithospheric thinning in the Brazilian Craton was coeval with the Trindade mantle plume, which formed the Parana-Etendaka large igneous provinces (LIPs) and Minas-Goias (or Alto Paranaiba) alkaline igneous province in South America (Gibson et al., 1995, 2006).

It has been proposed that mantle plumes are stemmed from the core-mantle boundary and have relatively high temperatures (Campbell, 2007). As a mantle plume impinges on the base of the lithosphere, the bottom of the lithosphere will be heated and weakened, and may be removed by the horizontal flow of the asthenosphere, i.e., thermal-mechanical erosion (Davies, 1994). Results of thermal simulation suggested that it takes 10 Ma to thin a cratonic lithosphere from 200 to 100 km by a mantle plume with a temperature 1600°C, and 34 Ma from to 200 to 50 km (Yuen and Fleitout, 1985). Higher temperature of the mantle plume would fasten the lithospheric thinning or increase the extent of the thinning at a certain time. In contrast, a small mantle plume or an upwelling mantle with low temperature would result in a limited scale of lithosphere thinning or even no thinning of the craton (Qiao et al., 2013). Summary of the Sr-Nd isotopic compositions of the Deccan and Siberian basalts (Figure 5) suggests that most basalts in both areas display relatively higher Sr but lower Nd isotopic ratios than basalts from other LIPs. This implies that the lithosphere made important contributions to the genesis of these basalts. Hence, we suggest that the lithosphere beneath these two cratons was thinned through partial melting of the sub-continental lithospheric mantle, which is also supported by a resent study on the Tarim mantle plume (Xu et al., 2014).

Nevertheless, is lithospheric thinning of all cratons in the world caused by the mantle plume or upwelling mantle? Here we take the South African Craton (Figure 6), a typical craton in the world, as an example to illustrate this issue. The South Afirican Craton has a very ancient history. It consists of the Zimbabwe Craton in the north and the Kaapvaal Craton in the south, which are connected by the Limpopo orogenic belt in the middle. The oldest geological records in the Kaapvaal Craton are preserved in the early Archean greenstones in Barberton and the gneisses in Swaziland. It has been subjected to multiple stages of cratonization at 3.1, 2.6 and 1.8 Ga, and then became a stable craton (de Wit et al., 1992; Schoene et al., 2008). Similar to other cratons, the South African Craton, after its formation, has also been affected by several episodes of anorogenic magmatism (Torsvik et al., 2010), such as the Bushveld layered intrusion in 2.1 Ga, the Umkondo and Karoo mafic magmtism at 1.1 and 180 Ma, respectively (Jourdan et al., 2005; Kinnaird, 2005; Hanson et al., 2006; Svensen et al., 2012). Five episodes of kimberlites emplaced in the South African Craton (Wu et al., 2011, 2013a), Kuruman (1.6 Ga), Premier (1.2 Ga), Venetia (500 Ma), Jwaneng (250 Ma) and Kimberley (140–90 Ma). However, the South African Craton has not been destroyed, and is exemplified as the representative of stable craton in the world. The lithoporbe studies suggested that lithospheric thickness of this craton remains more than 200 km (Bell et al., 2003; Pearson et al., 2003), which is consistent with the geophysical data (Fouch et al., 2004; Begg et al., 2009). It is also worth noting that the Juina kimberlite emplaced at 94 Ma in the Amazonas Craton has been suggested to stem from the core-mantle boundary, as diamonds in this kimberlite pipe contain mineral inclusions deriving from core-mantle boundary (Harte, 2010; Walter et al., 2011). In fact, the Amazonas craton has not been destroyed.

Cratons that were affected by mantle plumes or upwelling mantle but have not been thinned or destroyed are not uncommon. Even in China, the western part of the Yangtze Craton was affected by the Emeishan mantle plume during the Permian. Although evidence for lithosphere thinning are still scarce, the Yangtze Craton was not destroyed; in contrast, the lithosphere beneath the Yangtze Craton might have been thickened through magma underplating (Xu et al., 2004). In North China, formation of the Paleozoic kimberlites might be related to mantle plume, which resulted in the uplift of the most 200 million km^2 of the whole craton during the Early Ordovician and Carbonaceous (Yang et al., 2009). However, there is no evidence support-

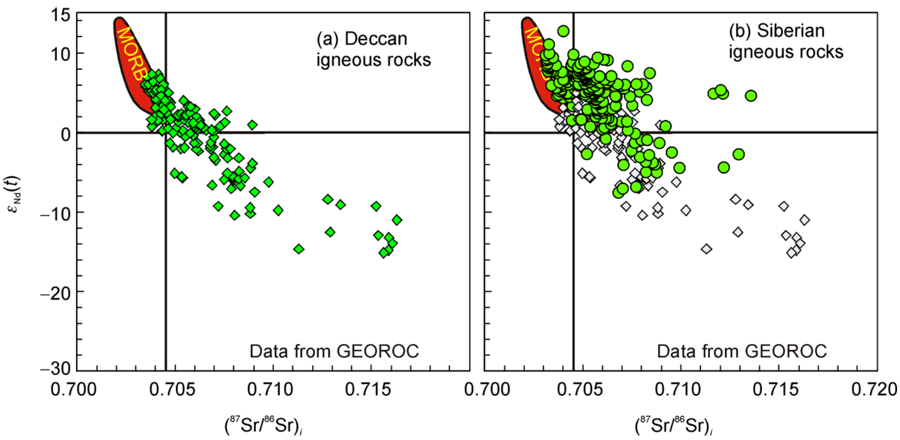

Figure 5 Sr-Nd isotopic compositions of basalt from Deccan and Siberian large igneous provinces.

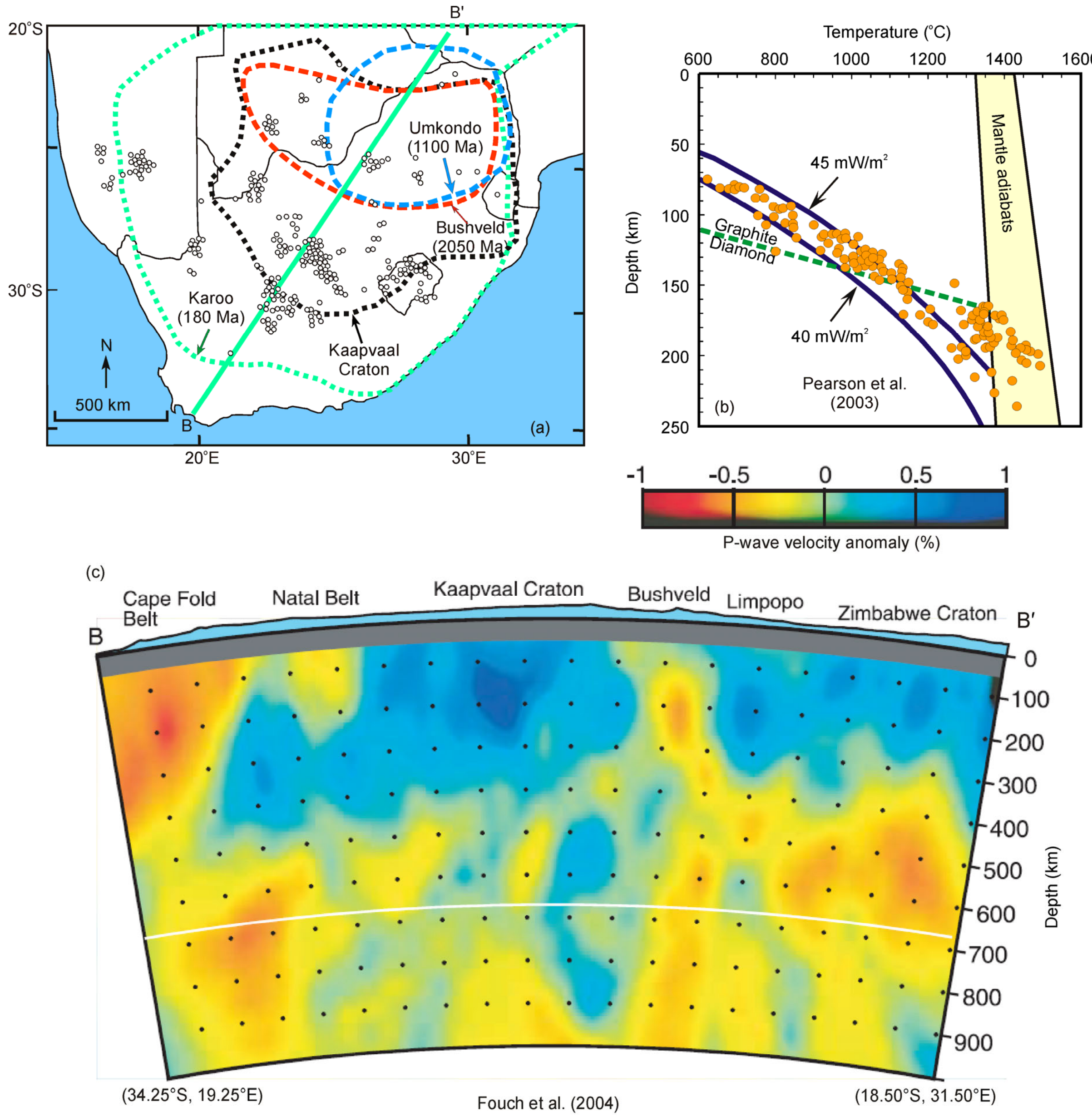

Figure 6 (a) Simplified map for different episodes of thermal events distributed in South Africa. Open circle is the kimberlites and B-B′ is the location of figure (c). (b) Lithospheric thickness and geotherms obtained by xenoliths from kimberlites. (c) Structure of lithosphere beneath South Africa obtained by P-wave.

ing the lithospheric thinning or destruction at that time. If thermal erosion of mantle plume can result in lithosphere thinning, how could the lithosphere beneath cratons like the South African Craton still keep their original thickness after being affected by several mantle plumes? Discussion on this question is beyond the scope of this paper. Here we provide the example of the East European Craton (Baltica). This craton has been subdivided into the North Kola and Karelia Cratons in the Kola Peninsula (Figure 7). These two cratons was collided along the Kola-Karelia orogenic belt at 1.9 Ga, resulting in the final cratonization (Zhao et al., 2002). Distinctive anorogenic magmatic rocks, including kimberlites, alkaline rocks and carbonatites, have been developed in this craton during the Paleozoic, among which both Khibiny and Lovozero are the two biggest alkaline plutons in the world. Recent studies have shown that these two alkaline plutons were formed in a short period of time at ca. 380 Ma (Wu et al., 2013b) and have a close genetic relationship with mantle plume (Arzamastsev et al., 2001; Downes et al., 2005). Constraints from both lithoprobe (Artemieva, 2003) and geophysical data suggest that this craton has a crust with a thickness of 40 km and a lithospheric mantle of 180 km. Moreover, the lithospheric mantle consists of two portions, the upper ancient mantle and the lower juvenile mantle. This implies that the lower juvenile mantle was probably accreted from the upwelling mantle plume during the

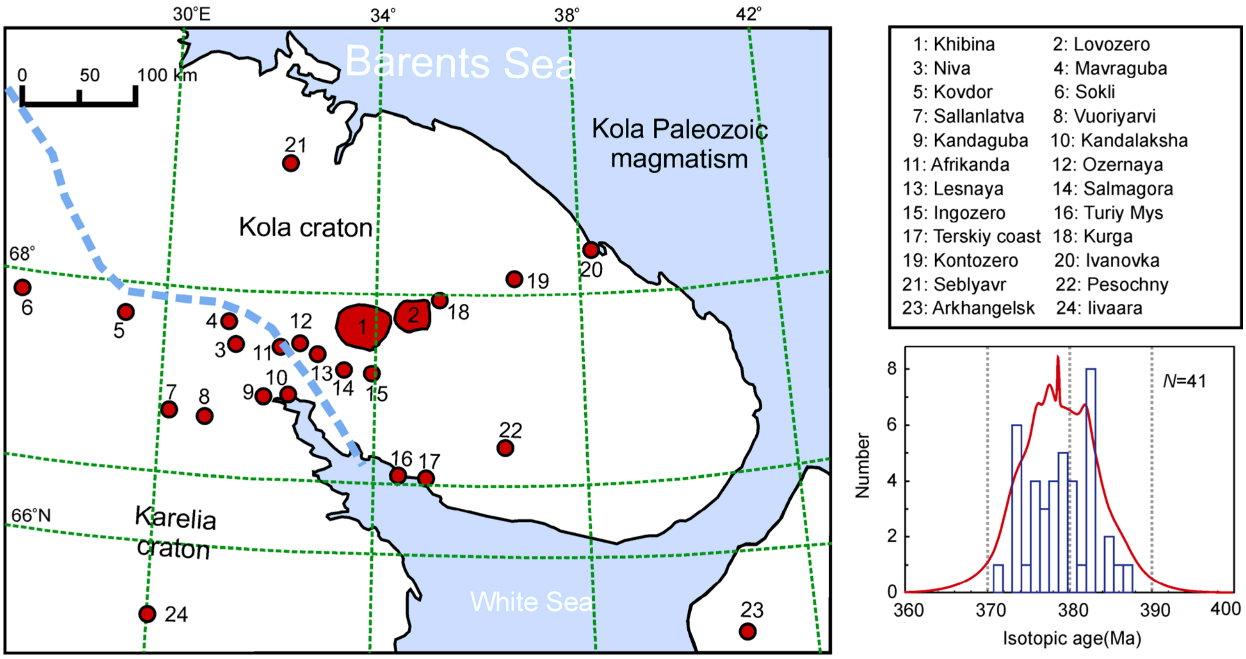

Figure 7 Distribution of the Paleozoic alkaline rocks in the Kola Peninsula and their ages.

Phanerozoic. The East European Craton might have been thinned by the mantle plume or the upwelling mantle, as occurrence of basalts in large areas of this craton requires a <125 km lithosphere (Ellam, 1992). However, large volumes of low-density residual mantle can be produced after large degrees of melting of the mantle plume, which could form juvenile lithospheric mantle via cooling. Upwelling of a mantle plume with a higher temperature or a bigger scale would result in higher degrees of partial melting of the asthenosphere, which could produce more mantle residues. In this case, the lithosphere beneath the craton should not be subjected to obvious thinning, and could preserve its original thickness. Therefore, whether the mantle plume can trigger lithospheric thinning depends on several factors, such as the size and thickness of the craton, the scale and intensity of the plume, and the size of juvenile mantle formed beneath the lithosphere (Petitjean et al., 2006).

4 Geological features of global destroyed cratons

Besides the NCC, the North American Craton is another craton that has been destroyed (Bleeker, 2003). The North American Craton is composed of several cratons (Figure 8), including the Superior Craton in the south, the Rae and Hearne Cratons in the middle, the Slave Craton in the north and the Wyoming Craton in the west. Collage of the Superior Craton in the south with the Rae-Slave-Wyoming Cratons along the Trans-Hundson orogenic belt during 1.8–1.9 G formed a stable continent. After its formation, the North American Craton has been subjected to multiple giant thermal events, as represented by the MacKenzie dike during 1267–1268 Ma (Heaman and LeCheminant, 1993), the Franklin dike in 723 Ma (Heaman et al., 1992), the mid-continental rifting in 1109 Ma (Heaman and Machado, 1992), and several episodes of kimberlites widespread within the craton (Heaman, 2003, 2004). However, this craton remained stable before the Paleozoic. However, subduction of the Pacific Ocean led to the formation of the Cordillera orogenic belt in the west of North America, which also resulted in the destruction of both the Wyoming Craton, and the Yavapai-Mazatzal and Wopmay Paleoproterozoic orogenic belts (Dickinson, 2004).

After the formation of the Wyoming Craton during 1.8–1.9 Ga (Duebendorfer and Houston, 1987; Frost et al., 1998), anorogenic magmatic rocks, including both Chicken Park (615 Ma) and Iron Mountain (410 Ma) kimberlites, were developed in its eastern margin, which lasted until the Cenozoic. High alkaline rocks and lamprophyres were also formed in different areas, like Bearpaw and Highwood Mountains (Carlson and Irving, 1994; O'Brien et al., 1995; Downes et al., 2004). Genesis of such lithologies supports that the Wyoming Craton is stable. During the subduction of the Pacific Ocean, the whole North America continent was subjected to strong magmatism and deformation, which extended to 1500 km within the hinterland. The Pacific subduction resulted in the magmatism along the Cordillera active continental margin, and the formation of both the Colorado plateau and the Basin and Range Province. Remarkable volcanic and intrusive complexes, including the Rocky Mountains, the Idaho Batholith, the Sierra Nevada Batholith and the Peninsula Batholith, were developed during the Pacific subduction. In particular, the Idaho Batholith, which locates at the western margin of the Wyoming Craton (Figure 8), was formed via partial melting of old crustal materials. Such a case is very similar to the NCC. Tectonically, the Cordillera orogenic belt is mainly expressed as multi-stage compressional and extensional deformation, which is exemplified by the extensional structures and the metamorphic core complex in the Basin and Range Province (Sonder and Jones, 1999). Clearly, the western part of the North American Craton has been significantly destroyed and lost its stability during the Mesozoic and Cenozoic.

Previous studies suggested that the lithosphere of the Wyoming Craton and its adjacent areas have been considerably thinned since the Mesozoic. However, it is still controversial over the mechanism for lithosphere thinning, and different mechanisms have been proposed, including thermal erosion, stretching and so on. However, it is commonly accepted that delamination of the thickened crust triggered the lithospheric thinning in this area (Bird, 1979; Ducea and Saleeby, 1998; Lee et al., 2000; Zandt et al., 2004; Boyd et al., 2006).

Discussion on the reason why granites and metamorphic core complex are formed in the Cordillera area could provide invaluable information of evolution for other destroyed cratons. Although different mechanisms have been proposed to explain the formation of these granites and metamorphic core complexes, it is generally suggested that their formation is related to the oceanic subduction. The subducted slab influences the above mantle wedge in two ways. Firstly, fluids or melts released through dehydration of the subducted slab metasomatize the above mantle wedge, which decreases the solidus of mantle peridotites and triggers partial melting to produce magmas. This is the reason for development of extensive magmatism in active continental margins. Secondly, slab-derived fluids or melts tend to decrease the viscosity of mantle lithosphere and result in a rheologically instability, which is conducive to different types of structural deformation in the lithosphere (Lenardic et al., 2003; Lee et al., 2011). From the perspective of crust, hence, the destroyed Wyoming Craton is characterized by development of large volumes of granites and extensional deformation within the crust.

Similarly, except local influences from the Paleo-Asian and Paleo-Tethyan oceans (Chen et al., 2013; Ma et al., 2013), destruction of the NCC has been generally ascribed

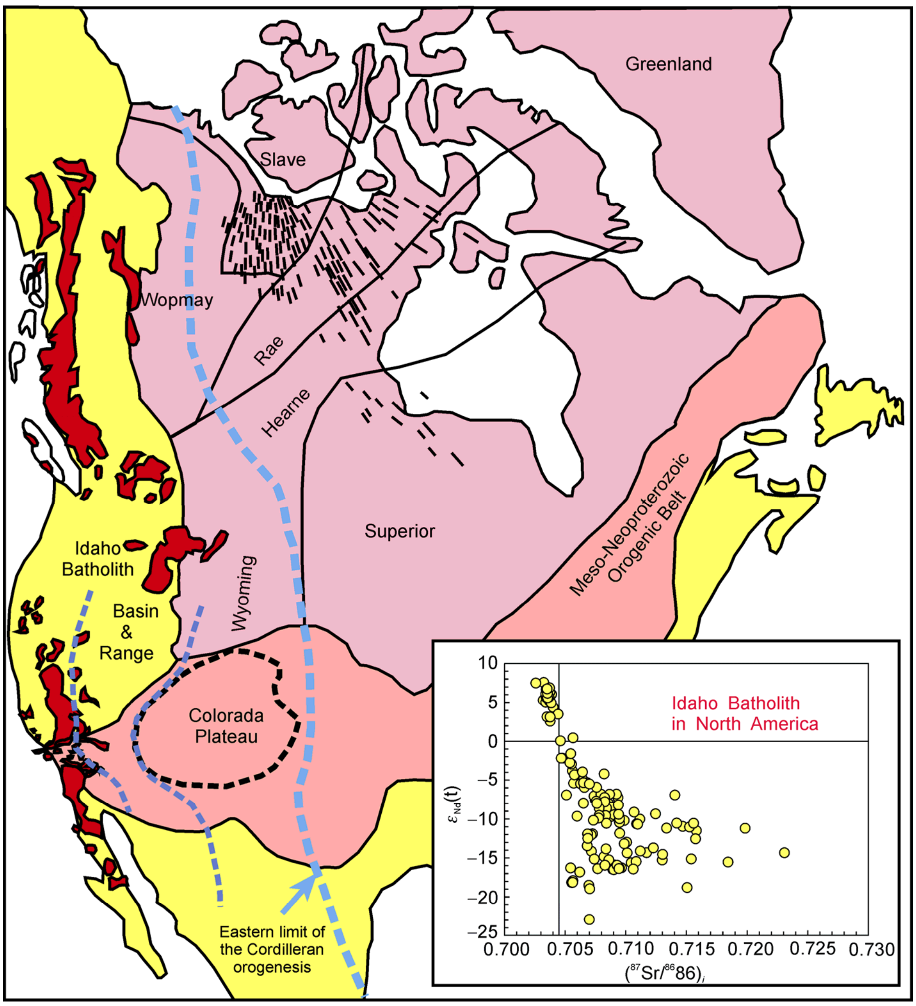

Figure 8 Sketch map of the North American Craton and the distribution of the Mesozoic granites in its western margin.

to the westward subdction of the Pacific Ocean during the Mesozoic (Zhang et al., 2009; Zheng and Wu, 2009; Zhu et al., 2012; Li, 2013). This issue has been discussed previously in details (Wu et al., 2007), and new evidences come from water contents of mantle xenoliths of different ages (Xia et al., 2010, 2013). It is worth noting that large volumes of crustal magmas represented by granites (Wu et al., 2005) and extensional deformation represented by metamorphic core complexes (Wang et al., 2012) were widely developed during the destruction of the NCC, which is very similar to the western margin of North America. Therefore, if both the NCC and the North America Craton are taken as stereotypes of craton destruction, then the extensive granitic magmatism and metamorphic core complexes could be regarded as petrological and structural indicators of craton destruction.

5 Conclusions

Based on the summarization of the global cratons, we can draw the following conclusions: (1) Lithospheric thinning is common in the evolution of cratons, which is not certainly accompanied by craton destruction. That is, lithosphere thinning is not equal to craton destruction. (2) Mantle plume or upwelling mantle can lead to lithospheric thinning. However, example of craton destruction caused by mantle plume has not yet been documented. (3) Craton destruction is more likely related to the subduction of oceanic crust. (4) Extensive granitic magmatism and metamorphic core complexes can be treated as the petrological and structural indicators of craton destruction.

Constructive comments and suggestions from three anonymous reviewers and the chief editor, Yong-Fei Zheng, greatly improve the quality of the manuscript. This study was supported by National Natural Science Foundation of China (Grant Nos. 41130313 and 91014007).

Agashev A M, Ionov D A, Pokhilenko N P, et al. 2013. Metasomatism in lithospheric mantle roots: Constraints from whole-rock and mineral chemical composition of deformed peridotite xenoliths from kimberlite pipe Udachnaya. Lithos, 160-161: 201–215

Artemieva I M. 2003. Lithospheric structure, composition, and thermal regime of the East European Craton: Implications for the subsidence of the Russian platform. Earth Planet Sci Lett, 213: 431–446

Arzamastsev A A, Bea F, Glaznev V N, et al. 2001. Kola alkaline province in the Palaeozoic: Evaluation of primary mantle magma composition and magma generation conditions. Russ J Earth Sci, 3: 1–32

Ashchepkov I V, Pokhilenko N P, Vladykin N V, et al. 2010. Structure and evolution of the lithospheric mantle beneath Siberian Craton, thermobarometric study. Tectonophysics, 485: 17–41

Basu A R, Poreda R J, Renne P R, et al. 1995. High-^{3}He plume origin and temporal-spatial evolution of the Siberian flood basalts. Science, 269: 822–825

Begg G C, Griffin W L, Natapov L M, et al. 2009. The lithospheric architecture of Africa: Seismic tomography, mantle petrology, and tectonic evolution. Geosphere, 5: 23–50

Bell D R, Schmitz M D, Janney P E. 2003. Mesozoic thermal evolution of the southern African lithosphere. Lithos, 71: 273–287

Bird P. 1979. Continental delamination and the Colorado Plateau. J Geophys Res, 84: 7561–7571

Bleeker W. 2003. The Late Archean record: A puzzle in ca. 35 pieces. Lithos, 71: 99–134

Boyd F R. 1984. Siberian geotherm based on lherzolite xenoliths from the Udachnaya kimberlite, USSR. Geology, 12: 528–530

Boyd F R, Pokhilenko N P, Pearson D G, et al. 1997. Composition of the Siberian cratonic mantle: Evidence from Udachnaya peridotite xenoliths. Contrib Mineral Petrol, 128: 228–246

Boyd O S, Jones C H, Sheehan A F. 2006. Foundering lithosphere imaged beneath the southern Sierra Nevada, California, USA. Science, 305: 660–662

Campbell I H. 2007. Testing the plume theory. Chem Geol, 241: 153–176

Carlson R W, Pearson D G, James D E. 2005. Physical, chemical, and chronological characteristics of continental mantle. Rev Geophys, 43, doi: 10.1029/2004RG000156

Carlson R W, Irving A J. 1994. Depletion and enrichment history of subcontinental lithospheric mantle: An Os, Sr, Nd and Pb isotopic study of ultramafic xenoliths from the northwestern Wyoming craton. Earth Planet Sci Lett, 126: 457–472

Chalapathi Rao N V, Wu F Y, Mitchell R H, et al. 2013. New Mesoproterozoic U-Pb ages, chemical and Sr-Nd isotopic composition of perovskite from kimberlites of the Eastern Dharwar craton, Southern India: Distinct mantle sources and a widespread 1.1 Ga tectonothermal event. Chem Geol, 353: 48–64

Chen B, Niu X L, Wang Z Q, et al. 2013. Geochronology, petrology, and geochemistry of the Yaojiazhuang ultramafic-syenitic complex from the North China Craton. Sci China Earth Sci, 56: 1294–1307

Chen L, Wang T, Zhao L, et al. 2008. Distinct lateral variation of lithospheric thickness in the northeastern North China Craton. Earth Planet Sci Lett, 267: 56–68

Cordeiro P F D, Brod J A, Palmieri M, et al. 2011. The Catalao I niobium deposit, central Brazil: Resources, geology and pyrochlore chemistry. Ore Geol Rev, 41: 112–121

Courtillot V, Besse J, Vandamme D, et al. 1986. Deccan flood basalts at the Cretaceous/Tertiary boundary? Earth Planet Sci Lett, 80: 361–374

Courtillot V, Kravchinsky V A, Quidelleur X, et al. 2010. Preliminary dating of the Viluy traps (Eastern Siberia): Eruption at the time of Late Devonian extinction events? Earth Planet Sci Lett, 300: 239–245

Davies G F. 1994. Thermomechanical erosion of the lithosphere by mantle plumes. J Geophys Res, 99: 15709–15722

De Almeida F F M, Neves B B D, Carneiro C D. 2000. The origin and evolution of the South American Platform. Earth-Sci Rev, 50: 77–111

Dessai A G, Markwick A, Vaselli O, et al. 2004. Granulite and pyroxenite xenoliths from the Deccan Trap: Insight into the nature and composition of the lower lithosphere beneath cratonic India. Lithos, 78: 263–290

De Wit M J, Roering C, Hart R J, et al. 1992. Formation of an Archaean continent. Nature, 357: 553–562

Dickinson W R. 2004. Evolution of the north American cordillera. Annu Rev Earth Planet Sci, 32: 13–45

Doucet L S, Ionov D A, Golovin A V. 2013. The origin of coarse garnet peridotites in cratonic lithosphere: New data on xenoliths from the Udachnaya kimberlite, central Siberia. Contrib Mineral Petrol, 165: 1225–1242

Downes H, Balaganskaya E, Beard A, et al. 2005. Petrogenetic processes in the ultramafic, alkaline and carbonatitic magmatism in the Kola alkaline province: A review. Lithos, 85: 48–75

Downes H, MacDonald R, Upton B G J, et al. 2004. Ultramafic xenoliths from the Bearpaw Mountains, Montana, USA: Evidence for multiple metasomatic events in the lithospheric mantle beneath the Wyoming craton. J Petrol, 45: 1631–1662

Ducea M, Saleeby J. 1998. A case for delamination of the deep batholithic crust beneath the Sierra Nevada, California. Int Geol Rev, 40: 78–93

Duebendorfer E M, Houton R S. 1987. Proterozoic accretionary tectonics at the southern margin of the Archean Wyoming craton. Geol Soc Am Bull, 98: 554–568

Duncan R A, Pyle D G. 1988. Rapid eruption of the Deccan flood basalts at the Cretaceous/Tertiary boundary. Nature, 333: 841–843

Elkins-Tanton L T. 2005. Continental magmatism caused by lithospheric delamination. In: Foulger G R, Natland J H, Presnall D C, et al., eds. Plates, Plumes, and Paradigms. Geol Soc Am Special Paper, 388: 449–461

Ellam R M. 1992. Lithospheric thickness as a control on basalt geochemistry. Geology, 20: 153–156

Fouch M J, James D E, VanDecar J C, et al. 2004. Mantle seismic structure beneath the Kaapvaal and Zimbabwe cratons. S Afr J Geol, 107: 33–44

Frost C D, Frost B R, Chamberlain K R, et al. 1998. The late Archean history of the Wyoming province as recorded by granitic magmatism in the Wind River Range, Wyoming. Precambrian Res, 89: 145–173

Gibson S A, Thompson R N, Leonardos O H, et al. 1995. The Late Cretaceous impact of the Trindade mantle plume: Evidence from large-volume, mafic, potassic magmatism in SE Brazil. J Petrol, 36: 189–229

Gibson S A, Thompson R N, Day J A. 2006. Timescales and mechanisms of plume-lithosphere interactions: $^{40}Ar/^{39}Ar$ geochronology and geochemistry of alkaline igneous rocks from the Paraná-Etendeka large igneous province. Earth Planet Sci Lett, 251: 1–17

Gokarn S G, Gupta G, Rao C K. 2004. Geoelectric structure of the Dharwar craton from magnetotelluric studies: Archean suture identified along the Chitradurga-Gadagschist belt. Geophys J Int, 158: 712–758

Griffin W L, Zhang A D, O'Reilly S Y, et al. 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean craton. In: Flower M F J, Chung S L, Lo C H, et al., eds. Mantle Dynamics and Plate Interactions in East Asia. Am Geophy Union, 27: 107–126

Griffin W L, Ryan C G, Kaminsky F V, et al. 1999. The Siberian lithosphere traverse: Mantle terranes and the assembly of the Siberian Craton. Tectonophysics, 310: 1–35

Griffin W L, Natapov L M, O'Reilly S Y, et al. 2005. The Kharamai kimberlite field, Siberia: Modification of the lithospheric mantle by the Siberian Trap event. Lithos, 81: 167–187

Griffin W L, Kobussen A F, Babu E V, et al. 2009. A translithospheric suture in the vanished 1-Ga lithospheric root of South India: Evidence from contrasting lithosphere sections in the Dharwar Craton. Lithos, 112S: 1109–1119

Guarino V, Wu F Y, Lustrino M, et al. 2013. U-Pb ages, Sr-Nd- isotope geochemistry and petrogenesis of kimberlites, kamafugites and phlogopite-picrites of the Alto Paranaíba Igneous Province, Brazil. Chem Geol, 353: 65–82

Hanson R E, Harmer R E, Blenkinsop T G, et al. 2006. Mesoproterozoic intraplate magmatism in the Kalahari craton: A review. J Afr Earth Sci, 46: 141–167

Harte B. 2010. Diamond formation in the deep mantle: The record of mineral inclusions and their distribution in relation to mantle dehydration zones. Mineral Mag, 74: 189–215

Heaman L M, Machado N. 1992. Timing and origin of Midcontinent Rift alkaline magmatism, North America: Evidence from the Coldwell Complex. Contrib Mineral Petrol, 110: 289–303

Heaman L M, LeCheminant A N. 1993. Paragenesis and U-Pb systematics of baddeleyite (ZrO_2). Chem Geol, 110: 95–126

Heaman L M, LeCheminant A N, Rainbird R H. 1992. Nature and timing of Franklin igneous events, Canada: Implications for a Late Proterozoic mantle plume and the break-up of Laurentia. Earth Planet Sci Lett, 109: 117–131

Heaman L M, Kjarsgaard B A, Creaser R A. 2003. The timing of kimberlite magmatism and implications for diamond exploration: A global perspective. Lithos, 71: 153–184

Heaman L M, Kjarsgaard B A, Creaser R A. 2004. The temporal evolution of North American kimberlites. Lithos, 76: 377–397

Hooper P, Widdowson M, Kelley S. 2009. Tectonic setting and timing of the final Deccan flood basalt eruptions. Geology, 38: 839–842

Howarth G H, Barry P H, Pernet-Fisher J F, et al. 2014. Superplume metasomatism: Evidence from Siberian mantle xenoliths. Lithos, 184/187: 209–224

Ionov D A, Doucet L S, Ashchepkov I V. 2010. Composition of the lithospheric mantle in the Siberian craton: New constraints from fresh peridotites in the Udachnaya-East kimberlite. J Petrol, 51: 2177–2210

Jourdan F, Feraud G, Bertrand H, et al. 2005. The Karoo large igneous province: Brevity, origin, and relation with mass extinction questioned by new $^{40}Ar/^{39}Ar$ age data. Geology, 33: 745–748

Karmalkar N R, Griffin W L, O'Reilly S Y. 2000. Ultramafic xenoliths from Kutch (NW India): Plume-related mantle samples? Int Geol Rev, 42: 416–444

Karmalkar N R, Duraiswami R A, Chalapathi Rao N V, et al. 2009. Mantle-derived mafic-ultramafic xenoliths and the nature of Indian sub-continental Lithosphere. J Geol Soc India, 73: 657–679

Kiselev S, Vinnik L, Oreshin S, et al. 2008. Lithosphere of the Dharwar craton by joint inversion of P and S receiver functions. Geophys J Int, 173: 1106–1118

King S D, Anderson D L. 1998. Edge-driven convection. Earth Planet Sci Lett, 160: 289–296

Krystopowicz N J, Currie C A. 2013. Crustal eclogitization and lithosphere delamination in orogens. Earth Planet Sci Lett, 361: 195–207

Kumar A, Heaman L M, Manikyamba C. 2007a. Mesoproterozoic kimberlites in south India: A possiblr link to ~1.1 Ga global magmatism. Precambrian Res, 154: 192–204

Kumar P, Yuan S, Kumar M R, et al. 2007b. The rapid drift of the Indian tectonic plate. Nature, 449: 894–897

Lee C T, Yin Q Z, Rudnick R L, et al. 2000. Osmium isotopic evidence for Mesozoic removal of lithospheric mantle beneath the Sierra Nevada, California. Science, 289: 1912–1916

Lee C T, Luffi P, Chin E J. 2011. Building and destroying continental mantle. Annu Rev Earth Planet Sci, 39: 59–90

Lenardic A, Moresi L N, Mühlhaus H. 2003. Longevity and stability of cratonic lithosphere: Insights from numerical simulations of coupled mantle convection and continental tectonics. J Geophys Res, 108, doi: 10.1029/2002JB001859

Li H Y. 2013. Destruction of North China Craton: Insights from temporal and spatial evolution of the proto-basins and magmatism. Sci China Earth Sci, 56: 464–478

Lu F X, Han Z G, Zheng J P, et al. 1991. Characteristics of the aleozoic mantle-lithosphere in Fuxian, Liaoning Province (in Chinese with English abstract). Geol Sci Tech Info, 10 (Suppl): 2–20

Ma X, Chen B, Chen J F, et al. 2013. Zircon SHRIMP U-Pb age, geochemical, Sr-Nd isotopic, and *in-situ* Hf isotopic data of the Late Carboniferous-Early Permian plutons in the northern margin of the North China Craton. Sci China Earth Sci, 56: 126–144

McKenzie D, Bickle M J. 1988. The volume and composition of melt generated by extension of the lithosphere. J Petrol, 29: 625–679

Menzies M A, Fan W M, Zhang M. 1993. Palaeozoic and Cenozoic lithoprobe and the loss of >120 km of Archean lithosphere, Sino-Korean craton, China. In: Prichard H M, Alabaster T, Harris N B W, et al., eds. Magmatic Processes and Plate Tectonic. Geol Soc Special Publ, 76: 71–81

Morbidelli L, Gomes C B, Beccaluva L, et al. 1995. Mineralogical, petrological and geochemical aspects of alkaline and alkaline-carbonatite association from Brazil. Earth-Sci Rev, 39: 135–168

Mukherjee A B, Biswas S K. 1988. Mantle derived spinel lherzolite xenoliths from the Deccan volcanic province (India): Implications for the thermal structure of the lithosphere underlying the Deccan trap. J Volcanol Geotherm Res, 35: 269–276

Nehru C E, Reddy A K. 1989. Ultramafic xenoliths from Wajrakarur kimberlites, India. In: Ross J, Jacques A L, Ferguson J, et al, eds. Kimberlites and Related Rocks, Proceedings of the Fourth International Kimberlite Conference. vol. 2. Geol Soc Australia Special Publ, 14: 745–759

O'Brien H E, Irving A J, McCallum I S, et al. 1995. Stronium, neodymium, and lead isotopic evidence for the interaction of post-subduction asthernospheric potassic mafic magmas of the Highwood Mountains, Montana, USA, with ancient Wyoming craton lithospheric mantle. Geochim Cosmochim Acta, 59: 4539–4556

Pearson D G, Canil D, Shirey S B. 2003. Mantle samples included in volcanic rocks: Xenoliths and diamonds. In: Carlson R W, ed. Treatise on Geochemistry: The Mantle and Core. Amsterdam: Elsevier. 171–276

Peslier A H, Woodland A B, Bell D R, et al. 2009. Olivine water contents in the continental lithosphere and the longevity of cratons. Nature, 467: 78–81

Petitjean S, Rabinowicz M, Grégoire M, et al. 2006. Differences between Archean and Proterozoic lithospheres: Assessment of the possible major role of thermal conductivity. Geochem Geophys Geosyst, 7: Q03021, doi: 10.1029/2005GC001053

Qiao Y C, Guo Z Q, Shi Y L. 2013. Thermal convection thinning of the North China Craton: Numerical simulation. Sci China Earth Sci, 56: 773–782

Rajesh H M, Mukhopadhyay J, Beukes N J, et al. 2009. Evidence for an early Archaean granite from bastar craton, India. J Geol Soc London, 166: 193–196

Rao K R P, Rao K N, Dhakate M V, et al. 2001. Petrology and mineralogy of mantle xenoliths of Wajrakarur and Narayanpet kimberlite fields, Andhra Pradesh, India. Geol Survey India Special Publ, 58: 577–591

Read G, Grutter H, Winter S, et al. 2004. Stratigraphic relations, kimberlite emplacement and lithospheric thermal evolution, Quirico Basin, Minas Gerais State, Brazil. Lithos, 77: 803–818

Reichow M K, Pringle M S, Al'Mukhamedov A I, et al. 2009. The timing and extent of the eruption of the Siberian Traps large igneous province: Implications for the end-Permian environmental crisis. Earth Planet Sci Lett, 277: 9–20

Renne P R, Zhang Z C, Richards M A, et al. 1995. Synchrony and causal relations between Permian-Triassic boundary crises and Siberian flood volcanism. Science, 269: 1413–1416

Rosen O M, Manakov A V, Serenko V P. 2005. Paleoproterozoic collisional system and diamondiferous lithospheric keel of the Yakutian kimberlite province. Russ Geol Geophys, 46: 1259–1272

Roy S, Rao R. 2000. Heat flow in the Indian Shield. J Geophys Res, 105: 25587–25604

Sarkar D, Chandrakala K, Padmavathi, et al. 2001. Crustal velocity structure of western Dharwar Craton, South India. J Geodyn, 31: 227–241

Sarkar R K, Saha D K. 2006. A note of the lithosphere thickness and heat flow density of the Indian Craton from MAGSAT data. Acta Geophy, 54: 198–204

Saunders A D, England R W, Reichow M K, et al. 2005. A mantle plume origin for the Siberian Traps: Uplift and extension in the West Siberian Basin, Russia. Lithos, 79: 407–424

Schoene B, de Wit M, Bowring S A. 2008. Mesoarchean assembly and Stabilization of the eastern Kaapvaal craton: A structural-thermochronological perspective. Tectonics, 27: TC5010, doi: org/10.1029/2008TC002267

Sengor A M C. 1997. Continental interiors and cratons: Any relation? Tectonophysics, 305: 1–42

Shalivahan, Bhattacharya B B, Chalapathi Rao N V, et al. 2014. Thin lithosphere-asthenosphere boundary beneath Eastern Indian craton. Tectonophysics, 612/613: 128–133

Sleep N H. 2005. Evolution of the continental lithosphere. Annu Rev Earth Planet Sci, 33: 369–393

Sonder L J, Jones C H. 1999. Western United States extension: How the West was widened. Annu Rev Earth Planet Sci, 27: 417–462

Sun J, Liu C Z, Tappe S, et al. 2014. Repeated kimberlite magmatism beneath Yakutia and its relationship to Siberian flood volcanism: Insights from *in situ* U-Pb and Sr-Nd perovskite isotope analysis. Earth Planet Sci Lett, 404: 283–295

Svensen H, Corfu F, Polteau S, et al. 2012. Rapid magma emplacement in the Karoo large igneous province. Earth Planet Sci Lett, 325/326: 1–9

Taylor L A, Snyder G A, Keller R, et al. 2003. Petrogenesis of group A eclogites and websterites: Evidence from the Obnazhennaya kimberlite, Yakutia. Contrib Mineral Petrol, 145: 424–443

Torsvik T H, Burke K, Steinberger B, et al. 2010. Diamonds sampled by plumes from the core-mantle boundary. Nature, 466: 352–355

Tychkov N S, Pokhilenko N P, Kuligin S S, et al. 2008. Composition and origin of peculiar pyropes from lherzolites: Evidence for the evolution of the lithospheric mantle of the Siberian Platform. Russ Geol Geophys, 49: 225–239

Ulbrich H H G J, Gomes C B. 1981. Alkaline rocks from continental Brazil. Earth-Sci Rev, 17: 135–154

Walter M J, Kohn S C, Araujo D, et al. 2011. Deep mantle recycling of oceanic crust: Evidenc from diamonds and their mineral inclusions. Science, 334: 54–57

Wang T, Guo L, Zheng Y D, et al. 2012. Timing and processes of late Mesozoic mid-lower-crustal extension in continental NE Asia and implications for the tectonic setting of the destruction of the North China Craton: Mainly constrained by zircon U-Pb ages from metamorphic core complexes. Lithos, 154: 315–345

Wu F Y, Lin J Q, Wilde S A, et al. 2005. Nature and significance of the Early Cretaceous giant igneous event in eastern China. Earth Planet Sci Lett, 233: 103–119

Wu F Y, Xu Y G, Gao S, et al. 2008. Lithospheric thinning and destruction of the North China Craton. Acta Petrol Sin, 24: 1145–1174

Wu F Y, Yang Y H, Li Q L, et al. 2011. *In situ* determination of U-Pb ages and Sr-Nd-Hf isotopic constraints on the petrogenesis of the Phalaborwa carbonatite Complex, South Africa. Lithos, 127: 309–322

Wu F Y, Mitchell R H, Li Q L, et al. 2013a. *In situ* U-Pb age determination and Sr-Nd isotopic analyses of perovskite from the Premier (Cullinan) kimberlite, South Africa. Chem Geol, 353: 83–95

Wu F Y, Arzamastsev A A, Mitchell R H, et al. 2013b. Emplacement age and Sr-Nd isotopic compositions of the Afrikanda alkaline ultramafic complex, Kola Peninsula, Russia. Chem Geol, 353: 210–229

Xia Q K, Hao Y T, Li P, et al. 2010. Low water content of the Cenozoic lithospheric mantle beneath the eastern part of the North China Craton. J Geophys Res, 115: B07207, doi: 10.1029/2009JB006694

Xia Q K, Liu J, Liu S C, et al. 2013. High water content in Mesozoic primitive basalts of the North China Craton and implications on the destruction of cratonic mantle lithosphere. Earth Planet Sci Lett, 361: 85–97

Xu Y G, He B, Chung S L, et al. 2004. Geologic, geochemical, and geophysical consequences of plume involvement in the Emeishan flodd-basalt province. Geology, 32: 917–920

Xu Y G, Wei X, Luo Z Y, et al. 2014. The Early Permian Tarim Large Igneous Province: Main characteristics and a plume incubation model. Lithos, 240: 20–35

Yang J H, Wu FY, Wilde S A, et al. 2008. Mesozoic decratonization of the North China block. Geology, 36: 467–470

Yang Y H, Wu F Y, Wilde S A, et al. 2009. *In-situ* perovskite Sr-Nd isotopic constraints on the petrogenesis of the Ordovician Mengyin kimberlites in the North China Craton. Chem Geol, 264: 24–42

Yuen D A, Fleitout L. 1985. Thinning of the lithosphere by small-scale convective destabilizaion. Nature, 313: 125–128

Zandt G, Gilbert H, Owens T J, et al. 2004. Active foundering of a continental arc root beneath the Southern Sierra Nevada, California. Nature, 431: 41–46

Zhang J J, Zheng Y F, Zhao Z F. 2009. Geochemical evidence for interaction between oceanic crust and lithospheric mantle in the origin of Cenozoic continental basalts in east-central China. Lithos, 110: 305–326

Zhang Q. 2011. The evolution from "Lithospheric thinning" to "Cratonic destruction" (in Chinese with English abstract). Prog Geophys, 26: 2262–2269

Zhao G C, Cawood P A, Wilde S A. 2002. Review of global 2.1–1.8 Ga orogens: Implications for a pre-Rodinia supercontinent. Earth Sci Rev, 59: 125–162

Zhao G C, Sun, M, Wilde S A. 2003. Correlations between the Eastern Block of the North China Craton and the South Indian Block of the Indian Shield: An Archean to Paleoproterozoic link. Precambrian Res, 122: 201–233

Zheng J P. 1999. Mesozoic-Cenozoic Mantle Replacement and Lithospheric Thinning Beneath the Eastern China (in Chinese with English abstract). Wuhan: China Uni Geosci Press. 126

Zheng Y F, Wu F Y. 2009. Growth and reworking of cratonic lithosphere. Chin Sci Bull, 54: 3347–3353

Zhou X H. 2009. Major transformation of subcontinental lithosphere beneath North China in Cenozoic-Mesozoic: Revised (in Chinese with English abstract). Geol J China Uni, 15: 1–18

Zhu R X, Xu Y G, Zhu G, et al. 2012. Destruction of the North China Craton. Sci China Earth Sci, 55: 565–1587