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Thermo-Tectonic Destruction of the Archaean Lithospheric Keel Beneath the Sino-Korean Craton in China: Evidence, Timing and Mechanism

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Abstract. Sino-Korean Craton (SKC) in eastern China is an important natural laboratory for studying temporal change to the lithosphere because there is the jutaxposition of Ordovician diamondiferous kimberlites, Mesozoic lamprophyre-basalt and Cenozoic tholeiite-alkali basalts in this craton. While diamond inclusions, xenoliths and mineral concentrates in kimberlites indicate a thick (>180 km), cold and refractory lithospheric keel beneath the SKC prior to the Palaeozoic, basalt-borne xenoliths reveal the presence of thin (<80 km), hot and fertile lithosphere in the Cenozoic. This indicates the dramatic change in lithospheric architecture during the Phanerozoic. Geochemical characterization of late Jurassic to recent basalts further suggests that the lithospheric destruction started since the Jurassic, probably due to the loss of physical integrity of the craton as a result of the Triassic collision between North China and Yangtze blocks. The replacement of old lithospheric keel by "oceanic" mantle has been accomplished during the late Cretaceous. Coupled thermo-mechanical and chemical erosion within the lithosphere-asthenosphere interface is considered as an important mechanism to thin the lithosphere. The lithospheric thinning may proceed with gradual upward migration of the lithosphere-asthenosphere boundary. Alternatively, the lithospheric thinning could proceed in the way that the old lithospheric mantle was penetrated and then desegregated by hot mantle materials which rise along vertical lithospheric shear zones and spread like mushroom clouds.

1 Introduction

Continent of Eastern China comprises several tectonic units including Archaean Sino-Korean craton, Proterozoic Yangtze craton, Hercynian north-east China fold belts, and Caledonian fold system of south-east China (Yang et al., 1986; Fig. 1). The geology of the Sino-Korean Craton (SKC) attracts much attention, not only because it is one of the oldest continental nuclei in the world (Jahn et al., 1987), but also because of the coexistence of Ordovician diamondiferous kimberlites, Mesozoic lamprophyre-basalt and Cenozoic basalts in this craton. Such a configuration contrasts with the Kaapvaal craton in south Africa where diamondiferous kimberlites are located within the craton, while alkali basalts can only be found in the circum Proterozoic mobile belts (Boyd and Gurney, 1986). This makes the SKC as an important natural laboratory for studying temporal change to the lithosphere.

Geochemical mapping of the continental lithospheric mantle (CLM) using geophysical and experimental data has led to the suggestion that there is a correlation between the age of overlying crust and the geochemistry and petrology of the underlying shallow mantle. For example, the Archaean Kaapvaal craton is underlain by a cold (~40 mW/m^2), thick (150 to 200 km), enriched (EM1) lithospheric keel, whereas the Proterozoic circum mobile belts are underlain by relatively hot, thin (< 150 km), depleted oceanic (MORB-OIB) lithosphere (Boyd and Gurney, 1986; Menzies, 1990). This generalization is broadly applicable to the north Siberian and Colorado-Wyoming cratons (Menzies, 1990). Thus, it is expected that the lithosphere under the SKC, whose nuclei formed around 2.5 Ga, should also have a similar petrological and geochemical signature to counterparts under south Africa and western America. However, geochemical studies of xenoliths in Cenozoic basalts from eastern China have revealed that this is not the case. Most of the mantle lithosphere beneath eastern China is predominantly spinel facies (<75 km) and is composed of MORB-OIB mantle whether beneath Archaean craton or post-Archaean terranes (Song and Frey, 1989; Deng and Macdoguall, 1992; Tatsumoto et al., 1992; Xu et al., 1998b; Fan et al., 2000). The presence of such a thin "oceanic" lithospheric mantle is consistent with geophysical observations (Chen et al., 1991) which imply a relatively thin lithosphere (70 to 80 km) and high heat flow (50 to 105 mW/m^2).

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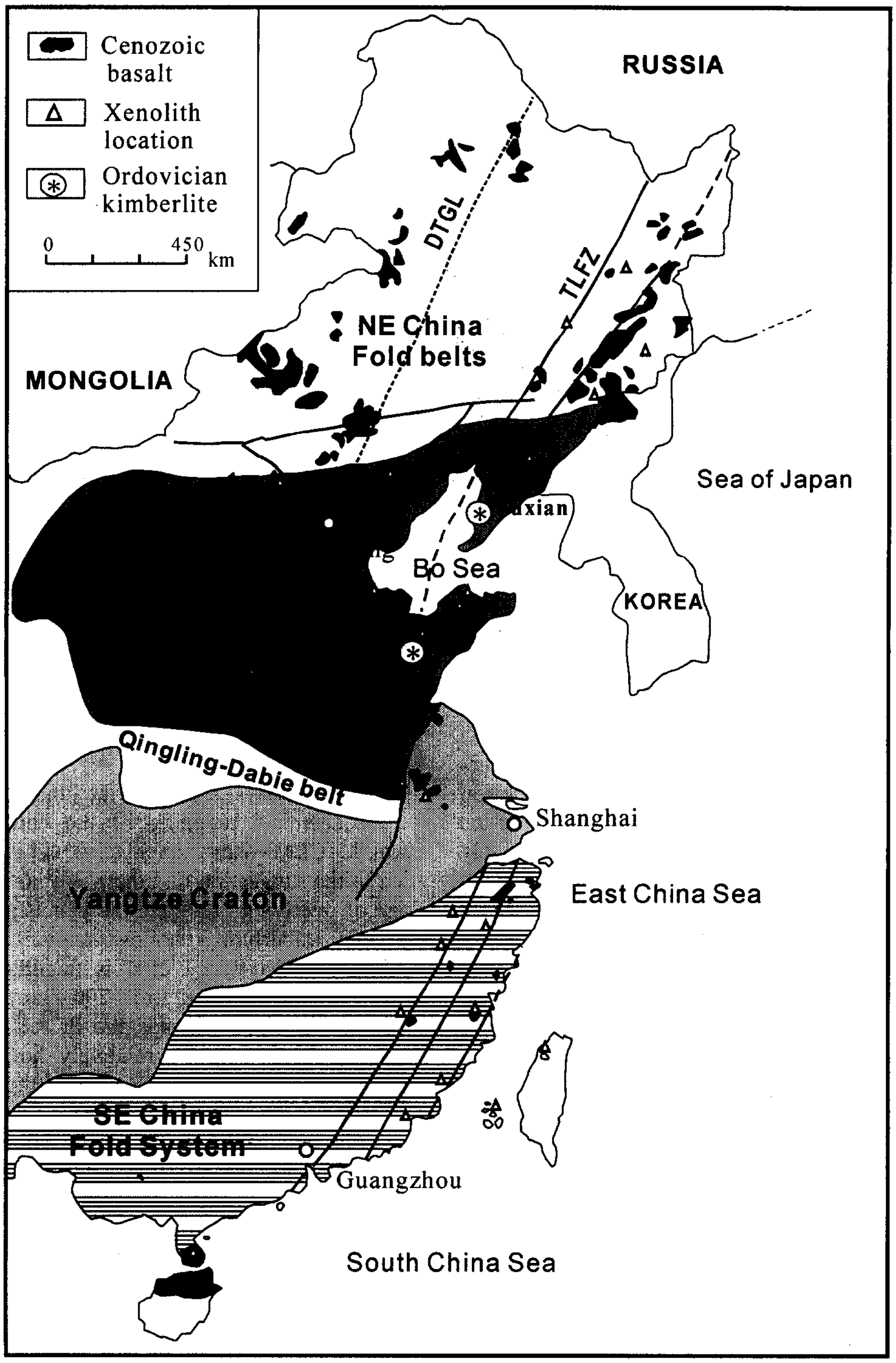

Fig. 1. Simplified tectonic scheme and distribution of Cenozoic basalts and Ordovician diamondiferous kimberlites in eastern China and location of ultramafic xenoliths. Note that the Archaean Sino-Korean Craton is cut by two major geological and geophysical linear zones – Tan-Lu fault zone (TLFZ) to the east and Daxinganlin-Taihang gravity lineament (DTGL) to the west.

Such a comparison led to the suggestion of thermo-tectonic destruction of the lithospheric root beneath eastern China (Fan and Menzies, 1992; Menzies et al., 1993; Griffin et al., 1998a; Menzies and Xu, 1998). This deep process is believed to have significant impact on the surface geology. A number of studies have been recently undertaken with attempt to provide more evidence for and constraints on the lithospheric evolution (Xu, 1999; Lu et al. 2000; X. Xu et al., 2000; Zheng, 2000). The main results of these studies will be summarized in this review in order to: (1) show the contrasting physical properties and chemical compositions of the Cenozoic and Palaeozoic lower lithosphere beneath the SKC; (2) characterize the temporal evolution of the lithosphere mantle from the Palaeozoic to

Cenozoic in the light of the study of Mesozoic volcanic rocks in the region, and (3) discuss the timing and mechanism of the lithospheric destruction beneath the SKC.

2 Contrasting composition of the Palaeozoic and Cenozoic CLM beneath the SKC

Information about the CLM can be obtained by investigating the xenoliths carried to surface by kimberlites, basalts and other volcanic rocks, and the magmas themselves. There exist xenolith-bearing diamondiferous kimberlites and alkali basalts in the SKC (Fig. 1). Recent U-Pb and Rb-Sr dating yields 457-462 Ma for the kimberlites in Shandong province and in Liaoning province (Lu et al., 1995). Thus the composition of the Palaeozoic lithosphere mantle can be obtained from these Ordovician kimberlite and their xenoliths. Due to the severe weathering of xenoliths, however, very little isotopic data are available and thus the characterization of the Palaeozoic lithosphere was largely limited to petrology and elemental geochemistry of minerals. Mantle xenoliths included in the Mengyin and Fuxian kimberlites contain garnet peridotites (lherzolite, harzburgite and dunite), spinel peridotites, eclogites and garnet pyroxenites (Chi et al., 1992). Both sheared and granular textures are observed, similar to the textures observed in the south African xenoliths. The harzburgite represents about 34 to 40% of the xenolith population (Zheng and Lu, 1999). Further evidence for this refractory nature of the Palaeozoic lithosphere can be found in the compositions of minerals in xenoliths (Zheng and Lu, 1999; Zhang et al., 2000) and in kimberlite-hosted diamonds (Zhang, 1991; Zheng, 2000).

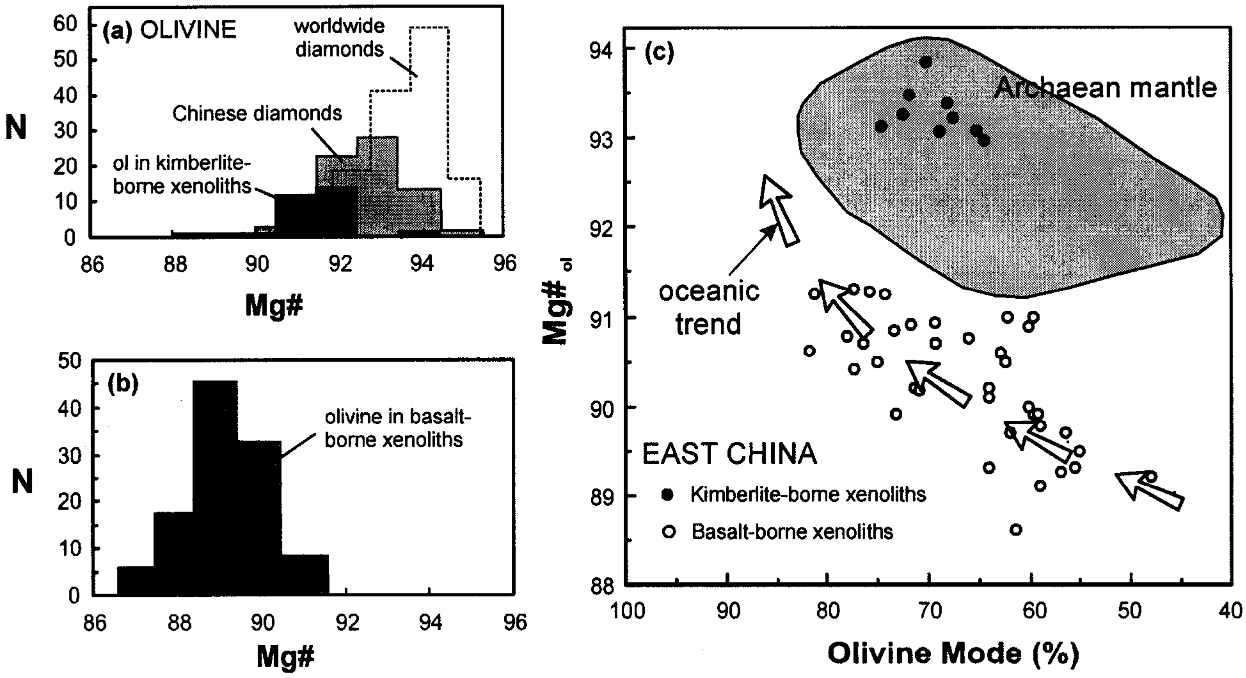

Fig. 2. Compositional and petrologic comparison of the Palaeozoic and Cenozoic lithospheric mantle beneath the Sino-Korean craton. (a) Histogram of Mg# of olivines in xenoliths and diamonds in Ordovician kimberlites (Zhang, 1991; Zheng, 2000) and from worldwide cratons (Meyer, 1987). (b) Histogram of Mg# of olivines in peridotite xenoliths in Cenozoic basalts. (c) A plot of Mg#$_{ol}$ versus modal abundance of olivine in peridotite xenoliths from the Cenozoic alkali basalts. Data are from E and Zhao (1987), Song and Frey (1989), Xu (1994), X. Xu et al. (1998); Xu et al. (1998b) and Zheng (2000). The cratonic lithosphere domain and oceanic trend are after Boyd (1989).

Figure 2 shows that the olivines in the Chinese diamonds are compositionally similar to those from Kaapvaal and Yakatia kimberlites and from worldwide occurrences. Their forsterite (Fo) content varies between 0.91 and 0.94 with majority around 0.93. Olivines in kimberlite-hosted xenoliths have a slightly low Fo (0.92 to 0.93). These high magnesian olivines contrast with the olivines in basalt-borne peridotites that are low in Fo (0.88 to 0.92, with majority at 0.89 to 0.91, Fig. 2b). The fertile feature of the Cenozoic mantle is consistent with the predominant lherzolites (>90%) in the xenoliths in basalts from eastern China. In a plot of modal olivine *versus* Fo (Fig. 2c), most basalt-borne peridotites follow the oceanic trend and significantly differ from the cratonic lithosphere (Boyd, 1989).

The compositional contrast between the Palaeozoic and Cenozoic CLM is also evident in terms of trace element abundance of garnets (Fig. 3). Griffin et al. (1998b) showed that lherzolitic garnets from different tectonic settings have different trace element compositions. This can be illustrated in a plot of Zr/Y *vs* Y/Ga in which different areas correspond to the mantle of different fertility. In general, the Phanerozoic mantle (Tecton) is more fertile than the Proterozoic (Proton) and Archaean (Archon) mantle. Most garnets in xenoliths in Ordovician kimberlites from China are plotted within the Archon domain, whereas the garnets in Cenozoic basalts are plotted within and above the Tecton area (Fig. 3).

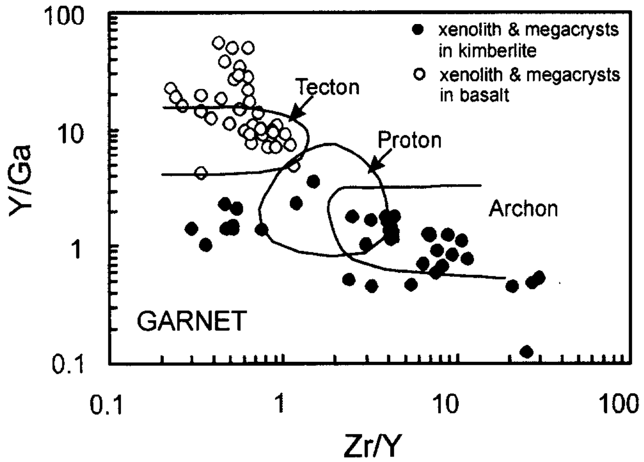

Fig. 3. Y/Ga versus Zr/Y plot for the lherzolitic garnet in Ordovician kimberlites and Cenozoic basalts. Tecton, Proton and Archon areas were defined by Griffin et al. (1998b). Data are from X. Xu et al. (2000), Xu (2000), Zhang et al. (2000) and Zheng (2000).

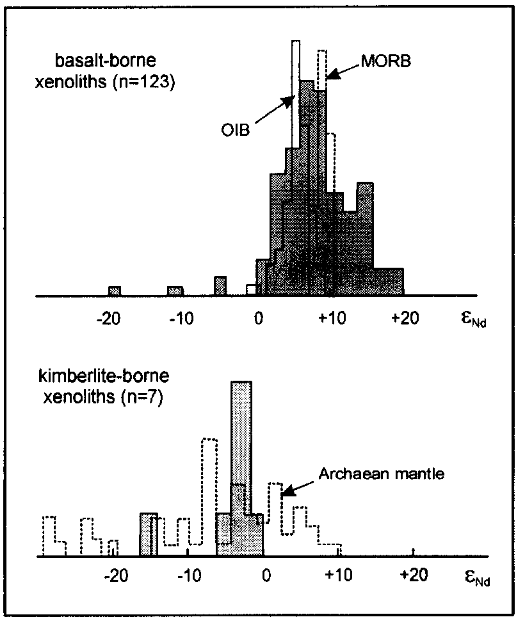

Fig. 4. Comparison of the Palaeozoic and Cenozoic lithospheric mantle in terms of initial Nd isotope ratios of peridotite xenoliths in Ordovician kimberlites and Cenozoic basalts from eastern China. Data sources: Song and Frey (1989), Deng and Macdougall (1992), Tatsumoto et al. (1992), Xu et al. (1998b), Zheng and Lu (1999) and Fan et al. (2000). The ε_{Nd} ranges of MORB and OIB and of the Archaean mantle are after Zindler and Hart (1986) and Menzies (1990), respectively.

Initial Nd isotope ratios (ε_{Nd}) of clinopyroxene in basalt-borne peridotites reveal that the shallow mantle in eastern China is isotopically depleted and similar to mid-oceanic ridge (MORB) and oceanic island basalts (OIB) (Fig. 4). Enriched Nd isotopic components in some samples may point to the presence of relicts of the Archaean mantle in the present-day CLM (Menzies et al., 1993). In contrast, the Nd isotopic composition of xenoliths in Ordovician kimberlites is comparable to that of Archaean peridotites (Fig. 4).

3 Thermal state and lithospheric thickness of the Palaeozoic and Cenozoic lithosphere

Absence of fresh xenoliths in the Chinese kimberlites prevents us from obtaining pressure and temperature estimates for these direct mantle samples. Relevant information about thermal conditions of the lithosphere under the SKC prior to the Palaeozoic come from the thermobarometric studies of silicate inclusions in diamonds recovered from the kimberlites. The major problem with geothermobarometric estimates based on inclusions in diamonds is the lack of co-existing silicates as inclusions in the Chinese diamonds. In contrast to the minerals in mantle peridotites where chemical exchange between coexisting minerals continues until the time of eruption, the mineral grains included in diamonds have compositions fixed since the crystallization. However, there is little choice for the geothermobarometry of diamond inclusions. The P-T calculation was performed assuming that silicate phases in diamonds were in equilibrium with the same bulk composition prior to incorporation in diamonds (Xu et al., 1995a; Lu and Zheng, 1997). The application of thermobarometers of Brey and Kohler (1990) to the minerals (i.e., combination of orthopyroxenes, clinopyroxenes and garnets) from 21 separated diamonds yields temperatures of 1060 to 1180 °C and pressures of 44 to 64 kbar (Fig. 5). Although these P-T estimates are not sufficient to define a geotherm, their location proximal to the continental shield geotherm (~40 mW/m^2, conductive model of Pollack and Chapman, 1977) suggests a low thermal gradient.

The thermal state of the CLM during the Palaeozoic has also been studied using algorithms developed for the mineral concentrates (garnet and chrome spinel) in kimberlites (Ryan et al., 1996; Griffin et al., 1998a). Although different in detail, the "garnet geotherms" constructed for the Mengyin and Fuxian lithosphere are all cold corresponding to surface heat flow of 36 to 40 mW/m^2 (Griffin et al., 1998a). These results are in good agreement with the P-T estimates obtained from diamond inclusions (Fig. 5). It can be concluded that the Palaeozoic lithosphere had stabilized to a depth of about 180 to 220 km and extended to the diamond-stability field.

The Cenozoic lithosphere is characterized by a high geothermal gradient (~ 80 mW/m^2, Fig. 5), as inferred from the geothermobarometry of garnet-bearing peridotites and pyroxenites brought by alkali basalts to the surface (Xu et al., 1995b; X. Xu et al., 1998; Shi et al., 2000). The Cenozoic basalt-hosted xenoliths are mainly spinel peridotites (< 75 km) and rarely garnet peridotites (> 75 km). If the relative proportion of mantle xenoliths at the Earth surface can be taken as indicative of the lithology of the upper mantle, then spinel peridotite is the dominant rock of the shallow mantle. It is thus reasonable to infer that the shallowest depth from which spinel peridotites were sampled by the host basalts defines the maximum thickness of the crust, while the greatest depth of garnet peridotites represents the minimum thickness of brittle lithosphere (O'Reilly and Griffin, 1996). Because the equilibrium pressures of most spinel peridotites are not determined yet, we adopted the method of O'Reilly and Griffin (1985) to estimate the pressures in plotting the equilibration temperatures on the empirical geotherm. The temperature histogram based on 142 spinel peridotites from the SKC shows a temperature range of 750 to 1200 °C. The lowest temperatures correspond to a depth of 22 to 32 km on the xenolith-derived geotherm, which represents the depth of the petrological Moho. The highest temperatures for spinel- and garnet-peridotites are 1150 to 1200 °C and 1200 to 1280°C, respectively (Xu et al., 1995b). These temperatures approach the potential temperature of the asthenosphere (T_p=1280 °C) (McKenzie and Bickle, 1988), indicating that they are derived from the base of the lithosphere. The corresponding pressures of these temperatures (21 to 26 kbar) thus give estimates of lithospheric thickness of about 65 to 80 km, which are comparable with seismic tomographic results (Chen et al., 1991) that indicate a present-day lithosphere thickness of 70-80 km.

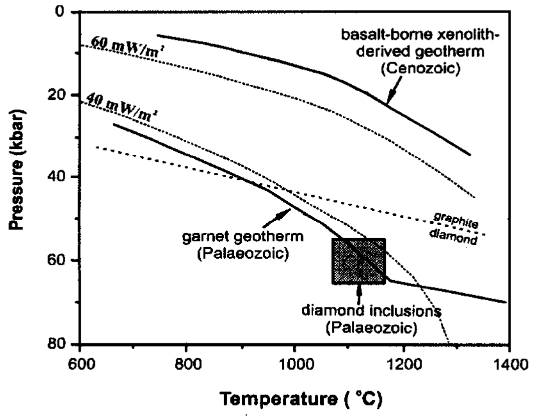

Fig. 5. Comparison between the Cenozoic and the Palaeozoic geotherms of eastern China. The P-T range obtained from diamond inclusions (Xu et al, 1995a; Lu and Zheng, 1997) is represented by the shaded area. This area is traversed by the garnet geotherm determined from garnet and spinel recovered in the heavy-mineral concentrates from the Ordovician kimberlites (Griffin et al., 1998a). The Cenozoic geotherm is constructed based on the equilibration P-T of garnet-bearing xenoliths in Cenozoic basalts (Xu et al., 1995b; X. Xu et al., 1998; Shi et al., 2000). The conductive geotherms are taken from Chapman and Pollack (1977). The graphite-diamond transition (dashed line) is after Kennedy and Kennedy (1976).

The surface heat flow of ~80 mW/m^2 to which the xenolith-derived Cenozoic geotherm corresponds is higher than the present-day measured values in North China (~65 mW/m^2; Wang and Wang, 1986). Such a difference may imply that the lithosphere under the SKC experienced cooling from a hotter temperature regime (Menzies and Xu, 1998), and thermal relaxation at surface is faster than in the lithospheric interior. Therefore the calculated Cenozoic geotherm has a transient character. Alternatively, this difference may be due to the uncertainty associated with the thermobarometric calculations and the scatter in modern heat flow measurements. The first alternative is preferred based on the following considerations: (1) The elevated temperature recorded in the xenoliths is generally related to heat advection involved in magmatism and lithosphere-asthenosphere interaction rather than thermal conduction, as observed in the Kaapvaal craton (O'Reilly and Griffin, 1985). While the Cenozoic geotherm in eastern China is very similar to that in south-east Australia (O'Reilly and Griffin, 1985), it is cooler than that of north-western Spitsbergen (Amundsen et al., 1987). The extremely high thermal gradient at Spitsbergen has been interpreted as a characteristic of an earlier stage of continental rifting associated with thin lithosphere (< 60 km) and intense basaltic volcanism, which added heat to an already elevated temperature regime (Amundsen et al., 1987). If this interpretation is correct and one assumes that the thermal evolution of extended regions proceeds in the similar way, the geotherm in eastern China may correspond to a relatively mature stage during the development of continental rifting and extension; (2) Thermobarometric calculation of rare granulite xenoliths in Mesozoic magmas yields P-T estimates along a geotherm of 90 mW/m^2 (Zheng, 2000); (3) The similarly high geotherm is also inferred for the Eocene lithosphere by Hu et al. (2000). Based on apatite fission track analyses and thermal modeling, Hu et al. (2000) showed that the heat flow in Bohai Basin during the Eocene was as high as 90 mW/m^2, corresponding to the rifting stage in this region. Since the Miocene, the basin experienced a period of thermal subsidence and relaxation, resulting in the low current heat flow (64 mW/m^2).

4 Evidence for the removal of >120 km thick of lithospheric keel

As discussed above, a lithospheric keel was present in the SKC during the Palaeozoic. Similar to that beneath the Kaapvaal Craton, this lithospheric keel sampled by the Ordovician kimberlites had a cold geotherm and was relatively thick (*ca.* 200 km, Fig. 6a). The main rock type was the depleted lherzolite (Griffin et al., 1998a), but harzburgite makes up a significant proportion of the CLM. Such a refractory composition gives a buoyant and gravitationally stable lithosphere. The Mengyin and Fuxian kimberlites are isotopically transitional between the Group I (basaltic) and Group II (micaceous) kimberlites in south Africa (Chi et al., 1992). This together with the Sr-Nd isotopic data for the xenoliths (Zheng and Lu, 1999) reveals the existence of an isotopically enriched mantle during the Palaeozoic in this region. This lithospheric keel had been isolated from mantle convection for some time thereby permitting long-term isotopic decay. This buoyant residual mantle was subsequently invaded by very small volumes of melts released from the underlying convective asthenosphere (McKenzie, 1989). Due to their small volumes and richness of volatile, these melts would solidify when the ambient temperature is colder than the solidus. Repeated small thermal perturbations will result in the further accumulation of asthenosphere-derived melts in the lithosphere and cause re-melting of this zone and its gradual upwards movement. A series of reactions between this fluid/melt and the lithosphere is envisaged to produce the typical rock associations (e.g., Thibault et al., 1993). These melts will finally stabilize at about 80 to 120 km and form a metasome (Waters and Erlank, 1988; Menzies et al., 1993; Fig. 6a). Although there is still disagreement as to whether this zone is composed of a pervasive intergranular component or is made up of veins and dykes, this metasome is now thought to be the likely sources for some mafic ultrapotassic magmas formed by thermal perturbation during lithospheric stretching (McKenzie, 1989).

The major difference between the Kaapvaal craton and the SKC is that the geotherm for the Kaapvaal craton has remained unchanged during more than 3000 Ma (Boyd et al., 1985). In contrast, the Cenozoic lithosphere in the SKC is generally less than 80 km thick with elevated geotherms and primarily consists of fertile "oceanic" peridotites (Fig. 6e). It is apparent that there has been a considerable change in lithospheric thickness, thermal state and composition in the past 400 Ma and the lithospheric keel no longer exists beneath the SKC in the Cenozoic. This requires removal of up to 120 km thickness of a cold, refractory Archaean keel and replacement of fertile "oceanic" mantle (Fan and Menzies, 1992; Menzies et al., 1993; Griffin et al., 1998a).

5 Evolution of the CLM beneath the SKC: constraints from basalt geochemistry

While the thermo-tectonic destruction of the lithospheric keel beneath the SKC is now widely accepted by the international scientific community, the timing and nature of this event still remain poorly constrained. This is largely due to the lack of knowledge about the Mesozoic lithosphere that links the Palaeozoic and Cenozoic lithosphere. The basaltic provinces in eastern China are widespread and represent semi-continuous sampling of the mantle in the past 150 Ma (Liu et al., 1992). Geochemical study of these mantle-derived magmas could provide information on the temporal variation in depth of magma generation and evolution of the lithospheric mantle. However, such an investigation was not possible before because, although a large number of analyses has been performed on the basalts later than the Miocene, the data on the late Mesozoic and early Tertiary basalts were very scarce (Zhou and Armstrong, 1982; Peng et al., 1986). Geochemical knowledge of the Mesozoic basalts is now improved, notably with the recent investigations of drill cores from Xialiaohe basin (Chen et al., 1992; Chen et al., 1997) and of the Mesozoic volcanic rocks from Shandong province (Guo, 1999) and Bohai areas (Gu et al., 2000).

When comparing the geochemistry of basalts from various regions formed during different tectonic episodes, one must ensure that the geochemical signatures of these magmas represent those of mantle sources. This requirement is met because crustal contamination is insignificant in the petrogenesis of the Chinese basalts (e.g., Zhou and Armstrong, 1982; Zhou et al., 1988; Chen et al., 1997; Cong et al., 1996; Guo, 1999). Therefore the isotopic variation in magmas, as illustrated in Fig. 7, reflects that in the source. It is noted that the Mesozoic magmas from Shandong and those from Liaoning define different trends in Fig. 7, probably reflecting the regional heterogeneity of CLM beneath the SKC. Besides this, the data for both areas all suggest that the Mesozoic basalts were derived from an enriched mantle source, whereas the Cenozoic basalts mainly originated from a depleted mantle source (Fig. 7). Moreover, these two episodes of magmatism with different source characters were separated by a period (at 90 to 80 Ma) during which no significant magmatism has been observed so far.

Inferences can be drawn about the depth of the lithosphere-asthenosphere boundary (LAB) as a function of time, based on the temporal ε_{Nd} variation and the silica saturation of the basalts (e.g., DePaolao and Daley, 2000). It is experimentally demonstrated that more silicate-undersaturated and alkaline magmas are produced at higher pressures (e.g., Falloon et al., 1988). For example, Nohda et al. (1991) found that the tholeiites of North China were generated at pressures of 15 to 20 kbar (50 to 60 km) and alkali basalts at 25 to 30 kbar (> 80 km). If alkali basalts have lithospheric isotopic signature, it can be inferred that the lithosphere is more than 80 km thick. If tholeiitic and alkali basalts have asthenospheric signature, the lithosphere is inferred to be less than 60 km thick. Because typical continental lithosphere extends to about 100-km depth, the crust is about 40 km thick, the depth range of the origin of most basaltic magmas corresponds to the depth range of typical continental lithosphere prior to extension. Since significant crustal extension occurred during the late Cretaceous in North China (Deng, 1988), the isotopic composition of Mesozoic magmas likely reflects that of the CLM. The Mesozoic magmas include lamprophyres, basaltic andesites, andesites and subordinate tholeiites and alkali basalts. All these rock types display low $\varepsilon_{Nd\,(t)}$ (<0) suggesting that the lithosphere was at least more than 80 km thick. Moreover, the high Rb/Sr ratios (>0.10) and low Ba/Rb (<20) ratios suggest that some lavas formed through melting of a phlogopite-bearing source. The presence of water can considerably promote lithospheric melting through lowering the solidus of peridotites (Gallagher and Hawkesworth, 1992) despite the thick lithosphere at that time. A likely scenario is that the thermal perturbation associated with initial lithospheric thinning reactivated low-temperature melting components in metasome zones (Menzies et al., 1993), producing Mesozoic magmas (Fig. 6b). The similar ε_{Nd} between the Mesozoic basalts and the Palaeozoic lithosphere indicates the persistence of the old

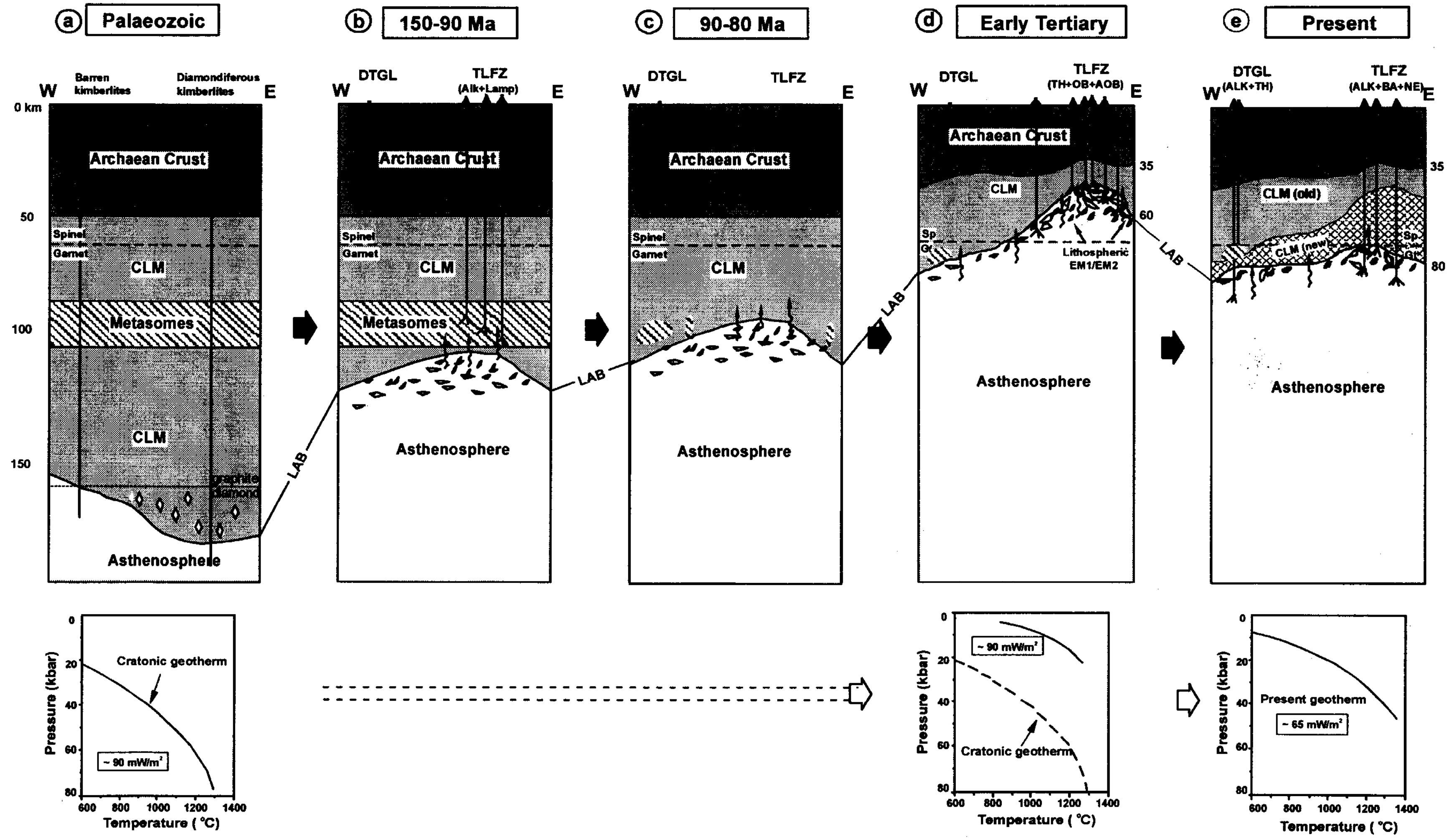

Fig. 6. Schematic illustration of the thermo-tectonic evolution of the lithospheric mantle beneath the Sino-Korean Craton and related magmatism. (a) *Palaeozoic*. A thick lithospheric keel existed under the SKC and extended into the diamond stability field. A metasome horizon was formed at 80 to 120 km through repeated infiltration of small melt fractions derived from the convective asthenosphere (Menzies et al., 1993). The lithosphere was cold corresponding to ~40 mW/m^2; (b) *Jurassic to early Cretaceous*. The low-temperature melting components in metasome zones were reactivated due to thermal perturbation associated with initial lithospheric erosion. The magmas show enriched mantle components. (c) *90 to 80 Ma*. Magmatism during this period was absent. The CLM was essentially dry due to the exhaustion of fusible components during precedent magmatism. The solidus of dry peridotites was not intercepted by the thermal gradient. (d) *Early Tertiary*. The lithosphere was significantly thinned (< 60 km) as a result of lithospheric extension and associated asthenospheric upwelling. The thermal gradient was as high as ~90 mW/m^2. The magmatism is mainly tholeiites (TH) and subalkali basalts (OB+AOB) with minor alkali basalts. The depleted mantle source involved in these rocks suggests that lithosphere erosion may have been accomplished by the end of the Cretaceous. (e) *Present*. The lithosphere thickens (> 70 km) since the Miocene subsequent to the lowering of the LAB as a result of thermal decay (~ 65 mW/m^2). The declining degrees and increasing depth of partial melting result in the formation of alkali- and strongly alkali basalts (ALK+BA+NE). New lithosphere was accreted below remnants of the old keel. This lithostratigraphy is believed to vary from west to east with relics of the old keel being more important in the western part of the craton.

lithospheric keel until late Mesozoic. On the other hand, the gradual increase in ε_{Nd} of the basalts from 150 Ma to 90 Ma (Fig. 7) may point to the increasing role of the asthenosphere in magmatic generation, although the possibility of an isotopically stratified lithosphere cannot be fully ruled out.

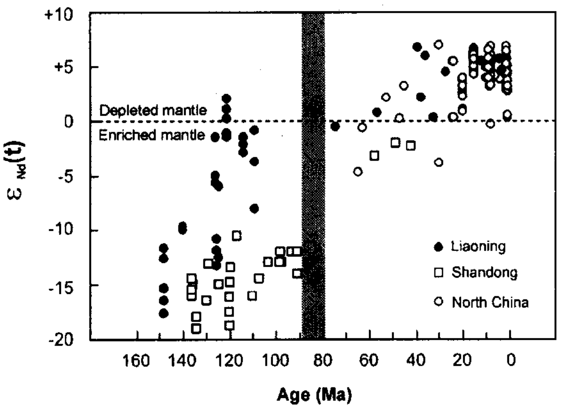

Fig. 7. Temporal variation in the Nd isotopic composition of basalts in the Sino-Korean Craton. Note that Mesozoic magmas have low ε_{Nd}, whereas most Cenozoic basalts are isotopically depleted. The shaded area highlights the period during which no magmatism has been observed so far. Data sources: Liaoning – Chen et al. (1992), Chen et al. (1997); Shandong – Guo (1999); Gu et al. (2000); North China - Peng et al. (1986), Chen et al. (1990), Song et al. (1990), Basu et al. (1991), Deng and Macdougall (1992), Liu et al. (1995), Cong et al. (1996), Zhou and Zhu (1992).

If this interpretation is correct, the occurrence of mantle-derived magmas would mark the onset of the lithospheric destruction beneath the SKC. The oldest magmatic event (at about 200 Ma) has been reported for some andesites from western Liaoning province (Chen et al., 1997). Therefore, the lithospheric destruction in the SKC may have started since the Jurassic. However, the magmatism at that time was very limited because of the relatively thick and rigid lithosphere that prevented melting of large degree and eruption of melts to the surface.

Most fusible components (i.e., metasome) in the lithosphere were consumed up during these early phases of magmatism. This resulted in a relatively dry CLM (Fig. 6c) whose solidus is considerably higher than that for wet peridotites. Given the absence of magmatism at 90 to 80 Ma, the thermal gradient and dry solidus of peridotites was probably not intersected during this period. The lithosphere was more than 100 km thick, according to the theoretical modeling (McKenzie and Bickle, 1988).

The dry mantle can melt only when the lithosphere is sufficiently thinned (McKenzie and Bickle, 1988). The voluminous early Tertiary basalts may be the surface manifestation of significant lithospheric thinning. Most of these basalts are quartz- and olivine-normative tholeiites, sub-alkali basalts (olivine basalts) and some alkali basalts (Liu et al., 1992). The dominant eruption of tholeiites was concomitant with a peak period of lithospheric extension during which a number of basins developed (Deng, 1988). The predominance of the depleted mantle signature in the Eocene tholeiites (Fig. 7) further suggests that the asthenosphere uplifted to very shallow level. The lithosphere at that time was less than 60 km thick and has a very high thermal gradient (Fig. 6d). The enriched components in the Cretaceous magmas are essentially absent in the Early Tertiary basalts. This implies that the lithosphere erosion and replacement beneath the SKC may have been accomplished by the end of the late Cretaceous.

Sub-alkali rocks continued to occur but diminished in quantity in the late Tertiary and the Quaternary, while alkali and strongly alkali basalts (basanite and nephelinite) are progressively becoming the dominant rock types. Enriched mantle components are generally absent in the magma source of these young volcanic rocks. The trend of increasing alkalinity with time has already been recognized by several authors and has been attributed to declining degrees of partial melting and increasing depth of the source region (e.g. Zhou and Armstrong, 1982; Zhou and Carlson, 1982; Xu et al., 1995a). The decrease in partial melting degree is correlated with the thermal decay of the CLM from the Miocene to present, as discussed in the previous sections. It is thus possible that the LAB was lowered and new lithosphere was accreted from late Tertiary to recent (Menzies and Xu, 1998; Fig. 6e).

6 Cause and mechanism of the destruction of the lithospheric keel

The conversion from thick cratonic lithosphere to thin oceanic lithosphere presents a major problem in the study of the cause and mechanism of continental lithospheric thinning. The cratonic lithosphere is depleted in basaltic components and has a density as low as 3.0 g/cm^3 (Boyd and McAllister, 1976), significantly lower than the density estimated for the fertile lherzolite (3.35 g/cm^3). This explains why the thick, cold lithospheric keel can remain stable for a prolonged period. Given the absence of evidence for the ubiquitous presence of eclogites at the root of the Sino-Korean lithospheric keel, delamination due to density contrast cannot be the principle mechanism of the lithospheric destruction (Xu, 1999; Lu et al., 2000).

Several factors including plate subduction, enhanced mantle temperature associated with plumes and extrusion tectonics resulting from the India-Eurasia collision have been proposed as the cause of the destabilization of the cratonic lithosphere (Menzies et al., 1993; Deng et al., 1997; Griffin et al., 1998a). The possibility of mantle plumes, however, can be ruled out because of the lack of surface volcanism associated with plume activity in North China. Menzies et al. (1993) argued against a dominant role of Pacific margin subduction for the dramatic change in the thermal and chemical character of the cratonic lithosphere because of the lack of any evidence for a subduction influence in the geochemistry of early Tertiary to recent volcanic rocks. These authors instead emphasized the role of the collision of India and Eurasia in the lithospheric destruction. However, as discussed above, the thermo-tectonic destruction of the lithospheric keel could have taken place as early as in the Jurassic. This significantly preceded the collision between Eurasian and Indian plates (45 to 50 Ma). It is noted that the onset of lithospheric destruction is roughly coincident with the Triassic collision between North China and Yangtze blocks along the Qiling-Dabie orogenic belt (Li et al., 1993). We thus tentatively propose the destabilization of the lithospheric keel in the SKC was probably triggered by the North China-Yangtze collision (cf., Fan and Menzies, 1996). The stress field associated with this collision may have destroyed the physical integrity of the Sino-Korean Craton, resulting in the formation and/or reactivation of major shear zones/strike-slip faults that penetrated the crust-mantle boundary. These deep discontinuities facilitated fluid ingress, reactivated the old metasome horizon and ultimately caused passive upwelling of adiabatic asthenosphere.

One possible mechanism for thinning the continental lithosphere is the thermal weakening of its base as a result of conductive heating by upwelling asthenosphere (Monnerrau et al., 1993; Davies, 1994). This thermo-mechanical erosion (Davies, 1994) of the lithosphere is now recognized as an important mechanism for lithospheric thinning in the early stage of rifting (Ruppel, 1995). On the other hand, asthenosphere upwelling would be associated with incipient melting of the mechanical boundary layer (MBL), and pervasive reactive porous flow (Kelemen et al., 1995) of deep seated melts into lithospheric peridotites at the lithosphere-asthenosphere interface (Van der Wal and Bodinier, 1996; Bedini et al., 1997; Xu et al., 1998a). It has been demonstrated that melt-peridotite reactions can modify rheology and modal composition of mantle rocks (Kelemen et al, 1992; Bedini et al., 1997; Xu et al., 1996, 1998a). Role of this chemical erosion could be very important too in the lithospheric thinning (Xu, 1999). The thermo-mechanical erosion and chemical erosion are not mutually exclusive. In reality, they may be jointly associated, as chemical erosion can generate positive feedback relationships to mechanical erosion.

The lithospheric erosion process depicted above essentially proceeds within the asthenosphere-lithosphere interface, and the LAB migrates upwards subsequent to lithospheric thinning (Fig. 6). A rather different model (called as "Mushroom Cloud" model) has recently proposed by Yuan (1996) and Lu et al. (2000). Based on the seismic tomographic and refraction data, Yuan (1996) showed the horizontal coexistence of hot mantle materials and cold mantle relicts in eastern China. The boundaries between these different mantle domains are very steeply inclined. Such a mantle architecture is believed to result from upwelling of hot mantle materials along major vertical shear zones (Yuan, 1996). When deep mantle materials reach the Moho discontinuity, they spread out like mushroom clouds. The old lithospheric mantle was thus penetrated and then enveloped by hot mantle materials. The ultimate result of this process is the removal of lithospheric keel and replacement by "oceanic" mantle.

Verification of these models requires more detailed geophysical and petrologic-geochemical investigation on the composition, thickness and thermal state of present CLM in eastern China. For example, the coupled thermo-mechanic and chemical erosion predicts a lithostratigraphy for the present-day lithosphere mantle. The lowest parts of the CLM are relatively young and isotopically similar to the underlying asthenosphere, while the uppermost parts of the CLM could retain components of the old keel (depending on the extent of thermal destruction) and could have a distinct geochemical signature (e.g., EM1). Lu et al. (2000) provided some petrologic evidence to support the "Mushroom Cloud" model. Distinct from the other xenolith localities in eastern China, spinel harzburgite is more abundant than lherzolite at Hebi in Hebei province. These samples have a wide range of equilibrium temperature of 700 to 1100 °C. Lu et al. (2000) suggested that the Hebi peridotites recorded two geotherms. The low and high geotherms correspond to old lithospheric relicts and new created mantle, respectively. While these samples are petrologically interesting, the thermometric interpretation remains problematic because equilibration pressure cannot be precisely determined at present for the peridotites of spinel facies. Clearly, identification of these proposed models is only possible when interpretation of regional geophysical data is improved and lithospheric mapping data of high resolution become available.

7 Summary

Contrasting thermal state and chemical composition have been revealed for the Palaeozoic and Cenozoic lithospheric mantle beneath the SKC in eastern China. Silicate inclusions in diamonds, peridotites and desegregated minerals in Ordovician kimberlites indicate the presence of a thick (>180 km), cold and refractory lithospheric keel beneath the SKC prior to the Palaeozoic. The basalt-borne peridotites point to the presence of thin (<100 km), hot and fertile lithosphere in the Cenozoic. It is thus proposed that the old thick keel has been gradually eroded as a result of passive upwelling of the lower convective asthenosphere. The late Jurassic to recent basalts show a secular increase in $\varepsilon_{Nd}(t)$ from −20 to +8 with time. The transition from enriched mantle source to depleted mantle occurred at about 90 to 80 Ma. Coupled with the silica saturation of basalts and experimental results, it is inferred that the lithosphere erosion started since the Jurassic and has been accomplished by the end of the late Cretaceous.

The destruction of the lithospheric keel was probably related to the collision between North China and Yangtze blocks at Triassic, which may have destroyed the physical integrity of the Sino-Korean Craton, resulting in the formation and/or reactivation of major shear zones/strike-slip faults. These lithospheric weak zones facilitated fluid ingress, melt-rock reactions and ultimately caused passive upwelling of adiabatic asthenosphere. In addition to the conventional thermo-mechanical erosion, the role of chemical erosion in the lithospheric thinning is emphasized, as it can modify the rheology of the MBL and generate positive feedback relationships between chemical and mechanical erosion. Alternatively, the replacement of lithospheric keel by the oceanic mantle could proceed in a way as described by the "Mushroom Cloud" model, in which the old lithospheric mantle was penetrated and then enveloped by hot mantle materials. Different mechanisms of lithospheric thinning have different implications for the lithospheric architecture beneath the SKC. Lithospheric mapping of high resolution will be the key to evaluate these mechanisms.

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