Palaeozoic and Cenozoic lithoprobes and the loss of >120 km of Archaean lithosphere, Sino-Korean craton, China

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Abstract: In eastern China Palaeozoic kimberlites and Cenozoic basalts have been erupted through the same Archaean crust, thus providing deep probes of the cratonic lower lithosphere over a period of 400 Ma. While Palaeozoic diamondiferous kimberlites point to the existence of thick, refractory lower lithosphere in the east, Cenozoic basalt-borne xenoliths reveal the presence of hot, thin, less refractory lower lithosphere. Remnants of the Archaean lithosphere may have survived as harzburgites which are chemically similar to those from the Kaapvaal craton but very different from recently accreted lherzolites. In the absence of convincing evidence for supra-subduction or intraplate processes it is believed that the dramatic change of lithosphere architecture in the Phanerozoic was caused by indentor tectonics resulting from the collision of India and Eurasia. Passive reactivation and remobilization of the Archaean lower lithosphere, in particular metasome horizons, contributed to Cenozoic magmatism aligned along major lithospheric faults.

Traditionally the oldest Archaean cratonic nuclei are thought of as the most stable, inert parts of the Earth's surface. In the case of South Africa, Canada and Western Australia, Archaean cratons (Liu *et al.* 1992) lie atop a thick mechanical boundary layer characterized by high velocity anomalies (Anderson *et al.* 1992). In addition, the occurrence of Archaean P-type diamonds in on-craton kimberlites confirms the presence of an ancient thick lithospheric keel that, in some cases, was stabilized to depths of 200 km in the first billion years of Earth's history (Boyd & Gurney 1986). However, not all cratons have retained their structural integrity. In the case of the Greenland–Hebridean craton, elevated mantle temperatures associated with the Iceland plume and tectonic forces related to the opening of the North Atlantic, may have been responsible for erosion of the craton margin. This would account for the existence of thinned Archaean crust (<30 km) on the eastern Atlantic margin (i.e. Hebridean craton) and the survival of a thick cratonic nucleus in Greenland (Scott-Smith 1987). Similarly a thick cratonic keel does not underlie the Sino-Korean Archaean craton, eastern China. Detailed seismic tomography (Chen *et al.* 1991; Liu 1992) indicates that the 'present-day' lithosphere is <80 km thick (see Fig. 4) with greatly thinned lithosphere around the Bohai Sea (Ma & Wu 1981). The presence of thin lithosphere with a low velocity structure similar to an ocean ridge is substantiated by heat flow studies in eastern China (Teng *et al.* 1983) which reveal a region of very high heat flow on the craton in the vicinity of the Bohai Sea and Beijing (Fig. 1). The measured heat flow (1.2–2.53 HFU) corresponds to geotherms observed in tectonically active continents or ocean basins (50–105 mW m^{-2}).

The aim of this paper is to review the temporal evolution of the lower lithosphere beneath the Sino-Korean craton, a crustal province known to contain some of the oldest crustal rocks on Earth (Jahn *et al.* 1987). In this review we will:

(a) present petrological and geochemical evidence for the character of the Palaeozoic and Cenozoic lithosphere;
(b) review the available geological and geochemical data on eastern China pertinent to lithosphere evolution,
(c) outline a model to explain the temporal changes in lithosphere architecture.

Palaeozoic kimberlite-borne xenoliths

Palaeozic (400 Ma) kimberlites entrain a variety of xenoliths and megacrysts including diamonds (Lu *et al.* 1991; Zhang *et al.* 1991; Chi *et al.* 1992) (Fig. 1). While the petrology, mineralogy and thermal history of peridotite xenoliths and heavy mineral concentrates have been determined across the Sino-Korean craton, very little geochemical data are available for these xeno-

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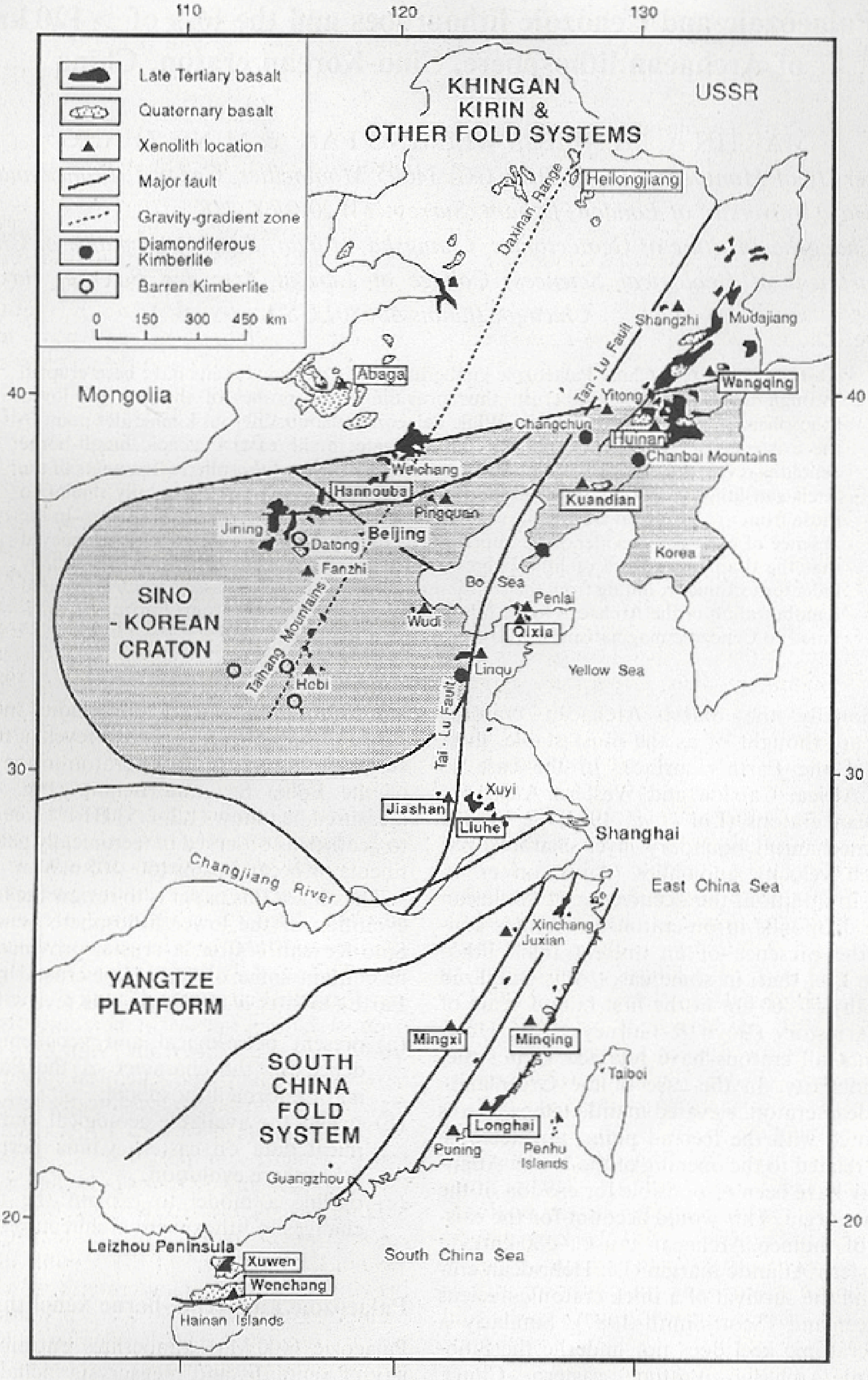

Fig. 1. Map of crustal age provinces and volcanic fields of eastern China. Volcanic rocks and xenolith localities are widespread across the Sino-Korean craton (Fan & Hooper 1989) as are the location of diamondiferous (closed circles) and barren on-craton kimberlites (open circles) (Zhang *et al.* 1991). The age of the Sino-Korean craton is well defined on the basis of multi-isotopic analyses (Jahn *et al.* 1987; Liu *et al.* 1992) with remnants of <3500 Ma crust being reported east of Beijing. Note the presence of major fault zones (Tan–Lu) which traverse the craton and are associated with regions of extremely thin lithosphere (Chen *et al.* 1991).

liths, so discussion will concentrate on the elemental geochemistry and thermal history. He (1987) noted that dunites/harzburgites are widespread in the Palaeozoic kimberlites of eastern China in association with spinel and garnet lherzolites or harzburgites, mica peridotites and eclogites. Zhang *et al.* (1991) reported a similarity in the chemistry of diamond inclusions from the Chinese kimberlite pipes and those from the Yakatia and Kaapvaal kimberlites. In addition, they noted that the lithosphere is dominated by harzburgite, dunite, lherzolite and wehrlite. Zhou *et al.* (1991, 1993) studied indicator minerals from the diamondiferous and barren kimberlites of eastern China. The diamondiferous kimberlites tended to contain abundant high Cr pyrope garnets while the barren kimberlites have higher proportions of low Cr pyropes. Also the elemental geochemistry of the indicator minerals pointed to hydrous metasomatism in the lower lithosphere and the presence of a high temperature group, perhaps related to megacryst formation (i.e. magma movement). In contrast the barren kimberlites are dominated by low temperature garnets with a minor amount of high temperature garnets. Elemental data are characteristic of low temperature, low pressure garnets and any high temperature garnets are believed to reflect short-lived events. The presence of high Cr, moderate Mg chromite (with a chemistry similar to diamond-hosted spinels) is indicative of derivation from harzburgite or lherzolite wall rock. In contrast, low Cr, high Mg spinels represent disrupted lherzolites. On the basis of such data Griffin *et al.* (1992*a,b*) produced lithostratigraphic profiles for the Sino-Korean craton, at Liaoning and Shandong. Griffin *et al.* (1992*a,b*) defined shield geotherms of $<40\,mW\ m^{-2}$ (<1 HFU), at the time of kimberlite emplacement, vertical variability in the petrology of the lithosphere and a change in the thermal structure on either side of the Tan–Lu fault. These authors demonstrated that the Palaeozoic lithosphere was thick and varied from 150–220 km from west to east, thus accounting for the predominance of diamondiferous (180–220 km) kimberlites in the eastern part of the craton (Zhang & Hu 1991). In addition, cratonic lithosphere was found to be more lherzolitic in the west and more harzburgitic in the east, and a metasome level (mica, apatite, carbonate and oxides) was defined around 80–100 km (F. Lu, pers. comm., 1992). Using indicator minerals, Zhou *et al.* (1993) demonstrated the presence of hydrous metasomatism and melt metasomatism in the Liaoning and Shandong pipes. Overall the thermal, petrological and diamondiferous character of the Palaeozoic lower lithosphere of eastern China is consistent with the existence of thick, cold Archaean lithosphere in the eastern part of the Sino-Korean craton.

Cenozoic basalt-borne xenoliths

Basalt-borne xenoliths, from thirty on- and off-craton localities of eastern China (Fig.1), have been studied in much more detail than the kimberlite xenoliths (Cao & Zhu 1987; Lu & Luo 1992). The paucity of garnet peridotite (high pressure) xenoliths from on-craton locations (Fan & Hooper 1989), and the ubiquity of spinel peridotites, indicates that on-craton volcanism has not sampled the thickness of craton that existed in the Palaeozoic. This is either because the cratonic lithosphere had already undergone considerable thinning by the Cenozoic, or that the level of entrainment of xenoliths had changed from deep (Palaeozoic) to shallow (Cenozoic). The presence of garnet lherzolites at Mingxi, a region of high heat flow, may reflect sub-lithospheric processes (i.e. asthenosphere). In general, basalt-borne xenoliths display high temperature dislocations (Jin *et al.* 1989; Xu, Y. G. *et al.* 1992) and most xenoliths, from widespread localities across the craton, conform to an oceanic ridge geotherm (>2.0 HFU) (Fan & Hooper 1989).

On-craton harzburgites of eastern China have high modal percentage of orthopyroxene (20–35% which makes them comparable to the Kaapvaal harzburgites. Clinopyroxenes in harzburgites, from eastern China, are chemically identical to those from Kaapvaal particularly in their Ti/Zr and Sr/Zr ratios and their light rare earth enriched character (Zhang *et al.* 1993). In contrast, clinopyroxenes in lherzolites from eastern China are distinct from the bulk of cratonic harzburgites, and have chemical affinities with mantle lherzolites from tectonically active continental regions (e.g. western USA; eastern Australia; western Europe). Overall, the Chinese ($MgO > 44\%$ and $SiO_2 = 42$–48) and Kaapvaal harzburgites define overlapping trends on element–element plots (Fig. 2) (Zhang *et al.* 1990*a*). Consideration of the possible difference between cratonic, circum-cratonic and oceanic peridotites indicates that the lower lithosphere beneath eastern China is a complex hybrid containing old cratonic nuclei (Archaean harzburgites) and more recently accreted peridotites (post-Archaean lherzolites). However, preliminary ICP-MS data (Menzies & Dupuy, unpublished data) indicate that on-craton and off-craton lherzolites may have experienced different processes. Clinopyroxenes from on-craton

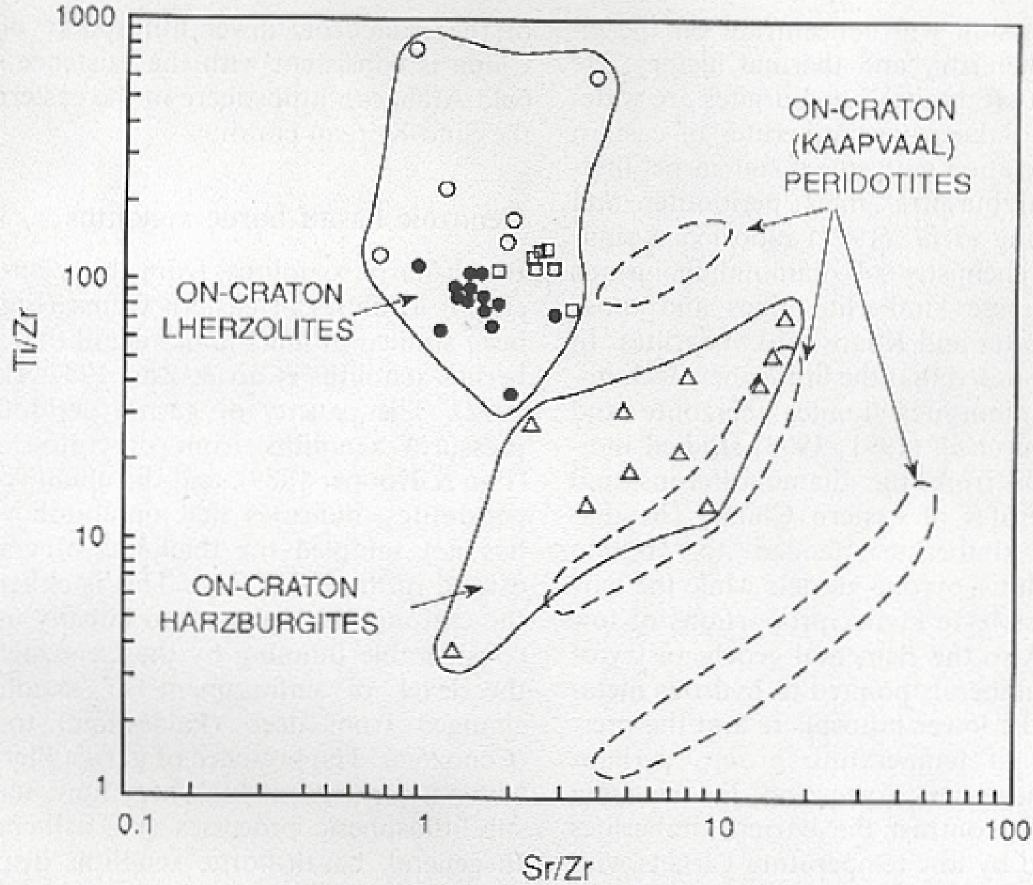

Fig. 2. Elemental variations in clinopyroxenes from harzburgites and lherzolites from eastern China in relation to the Kaapvaal harzburgites (Zhang *et al.* 1993). In eastern China the on-craton lherzolites are compositionally different from the on-craton harzburgites.

lherzolites tend to be U and LREE enriched relative to clinopyroxenes from recently accreted lithosphere (i.e. Hainan Island). Taken in conjunction with elevated Zr/Sm and Zr/Hf ratios this may indicate that the on-craton lherzolites have experienced influx of carbonatitic melts while the off-craton lherzolites (Hainan Island) have evolved in a high Pb and Th environment (sediment subduction).

$^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ data for clinopyroxenes in peridotites, from on- and off-craton locations, reveal that spinel lherzolites (i.e. shallow mantle) are isotopically depleted and similar to mid-ocean ridge and ocean island basalts (Song & Frey 1989; Tatsumoto *et al.* 1992*b*; Menzies *et al.* 1992) (Fig. 3). MORB-like on-craton lithosphere appears to predominate in the east, around the Bohai Sea and Yellow Sea, a region of thin Archaean–Proterozoic crust. While the widespread occurrence of depleted reservoirs must be stressed, on-craton and off-craton provinciality is also evident with mantle domains ranging in composition from depleted (peridotites) to enriched (pyroxenites). Indeed, the existence of on-craton heterogeneous lower lithosphere at Hannuoba may point to the presence of deeper older, enriched reservoirs (garnet-facies) and chemically stratified lithosphere (Song & Frey 1989; Tatsumoto *et al.* 1992*b*; Menzies *et al.* 1992; Fan & Menzies 1992). While Rb–Sr, U–Pb and Sm–Nd isotope data support the presence of Archaean lithosphere (Song & Frey 1989; Tatsumoto *et al.* 1992*b*; Menzies *et al.* 1992), Re–Os data from Hannuoba may indicate the presence of more recently accreted lithosphere (R. Walker, pers. comm. 1992).

These elemental and isotopic data support a hybrid, complex origin for the lower lithosphere beneath the Sino-Korean craton. While some of the elemental and isotopic data are similar to those found beneath other circum-cratonic (tectonically active) continental regions, the existence of older cratonic remnants is also indicated by elemental and isotopic data. Presumably lower lithosphere evolved in a manner similar to the overlying crust, such that relics of Archaean cratonic lithosphere are surrounded by accreted Proterozoic or Phanerozoic lithosphere. Overall, the thermal, petrological, chemical and isotopic character of the Cenozoic subcrustal mantle is consistent with the presence of thin, hot (oceanic) lithosphere that contrasts markedly with the

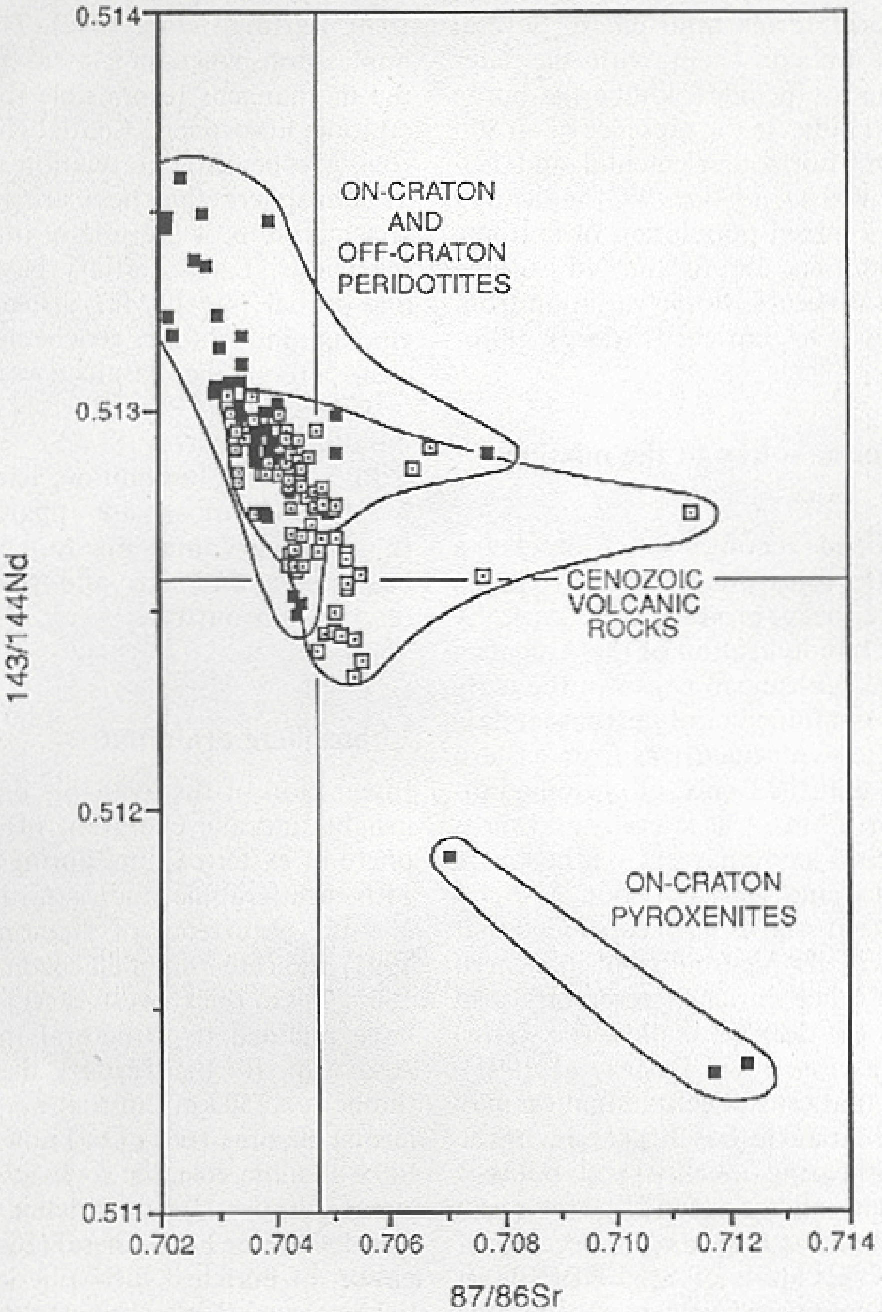

Fig. 3. Variation in Nd and Sr isotopes in Tertiary to Quaternary volcanic rocks (open symbols) and Chinese mantle xenoliths (filled symbols). While Chinese volcanic rocks do not sample the most enriched (high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ ratio) or the most depleted (low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ ratio) reservoirs, as represented by xenoliths, the isotopic data are dispersed in a manner suggestive of possible involvement of lithospheric reservoirs in the genesis of late Phanerozoic volcanic rocks. Data sources: (a) volcanic rocks – Basu *et al.* (1991); Chung *et al.* (1992); Song *et al.* (1990); Tu *et al.* (1991); Fan & Menzies (1992); Zartman *et al.* (1992); (b) xenoliths – Song & Frey (1989); Menzies *et al.* (1992); Tatsumoto *et al.* (1992b)

widespread occurrence of thick, cold (shield) lithosphere across the craton 400 Ma earlier. Greater isotopic heterogeneity exists in western regions of thick ($\geqslant$100 km), cold? lithosphere, than eastern regions of thin ($\leqslant$100 km), hot? lithosphere. This can be interpreted in several ways. In areas of greatest lithospheric thinning (e.g. Bohai Sea), on the craton, the pre-existent cold Archaean lithosphere was totally replaced by the accretion of (homogeneous) hot Cenozoic oceanic lithosphere. However, this is inconsistent with the presence of Archaean remnants in the Cenozoic lower lithosphere (Tatsumoto *et al.* 1992*a,b*) or the presence of old enriched pyroxenites (Menzies *et al.* 1992). Alternatively isotopic heterogeneity was most prevalent in the lowermost Archaean lithosphere (>80 km) and was remobilized during Tertiary–Quaternary volcanism leaving remnants of a depleted shallower lithosphere to be sampled during Quaternary volcanism. Accretion of younger lithosphere associated with late Phanerozoic magmatism produced a hybrid lower lithosphere. Several geological facts are consistent with the later hypothesis. These include kimberlite-borne xenolith data that indicate the presence of an 80–120 km metasome horizon; elemental and isotopic data (Zhang *et al.* 1990*a*, 1993) indicating the existence of a mixed population of cratonic and oceanic peridotites; and Sr and Nd isotopic data indicating a vertical isotopic variation from depleted (shallow) to enriched (deep) lithospheric mantle.

Cenozoic volcanism – key to the missing lithosphere?

The aforementioned xenolith suites bracket a period of basaltic volcanism in eastern China, which may have been produced, in part, by reactivation and remobilization of the Archaean lower lithosphere. Volcanism began in the early Tertiary and has continued until the present day. Pioneering work on volcanic rocks from eastern China suggested that the Cenozoic cratonic lithosphere of eastern China, was laterally and vertically heterogeneous and that such lithosphere participated in magma genesis (Zhou & Armstrong 1980). Recent studies have concluded that oceanic-type reservoirs predominated in eastern China, but that other enriched reservoirs also existed, either in the deep or shallow (i.e. crust) lithosphere (Peng *et al.* 1986; Basu *et al.* 1991). While we accept that crustal contamination may be an important factor in basalt genesis, in the case of xenolith-bearing alkaline and potassic magmas we believe that crustal contamination has played a somewhat minor role. Because of the intrinsically high levels of Sr, LREE, U in these alkaline and potassic volcanic rocks, one would have to invoke assimilation of large amounts of crust to register a change in the Sr, Nd and Pb isotopic composition. Assimilation of large amounts of crust would most probably have been associated with fractionation, and together such processes would not have resulted in the survival of broadly basaltic compositions in the surface eruptives. Comparison of the isotopic composition of Cenozoic volcanic rock and xenoliths indicates the presence of common enriched source components in the lower lithosphere (Fig. 3). Most workers now accept that the depleted oceanic reservoir is probably sub-lithospheric in origin and that the enriched reservoir is a lower lithospheric reservoir (Tu *et al.* 1991; Tatsumoto *et al.* 1992*b*; Menzies *et al.* 1992; Zartman *et al.* 1992; Chung *et al.* 1993). Finally, a subduction influence in the late Cenozoic magmatism of eastern China is not supported by geological and geochemical data (Kimura *et al.* 1990; Zartman *et al.* 1992). This has important implications when, in a later section, we consider the mechanisms responsible for thinning of the cratonic lithosphere. Spatial changes in volcanic rock geochemistry in relation to lateral changes in lithosphere thickness are important in any consideration of the role of lithosphere in magmagenesis. Early Tertiary basalts from Beijing and Bohai (40–70 Ma) display changes in elemental and isotopic geochemistry from west to east. Sub-alkalic basalts (west) have $^{87}Sr/^{86}Sr$ >0.704 and $^{206}Pb/^{204}Pb$ <17.93 and alkalic basalts (east) have $^{87}Sr/^{86}Sr$ <0.704 and $^{206}Pb/^{204}Pb > 18.179$. In addition, temporal changes in basalt geochemistry are apparent from Tertiary to Quaternary times due to temporal changes in lithosphere thickness and possible changes in reservoir chemistry.

Lithosphere evolution

Integration of the available data gives us some insight into the evolution of the lower lithosphere of eastern China during the Phanerozoic. Lithostratigraphic studies (Griffin *et al.* 1992*a,b*) and the occurrence of diamonds (Zhang *et al.* 1991) indicate that Palaeozoic lithosphere was 150–220 km thick (west–east) and, as such, may have retained its structural integrity since the Archaean. By the Tertiary the lithosphere was thinner ($\leqslant 150$ km), in that no young diamondiferous alkaline rocks are known, but some Tertiary alkaline volcanic rocks still appear to have a contribution from enriched (garnet-bearing) sources (lower lithosphere) (Fig. 4). The participation of enriched lithospheric sources in Tertiary volcanism may indicate that the metasome level (80–120 km) in the lithosphere was tapped/consumed in the Tertiary. Indeed the sudden surge in magmatism in the late Phanerozoic may have been triggered by the interception of upwelling isotherms with a low melting metasome layer (40 km thick). If we can interpret the presence of spinel peridotite xenoliths and the widespread lack of garnet peridotite xenoliths as an indicator of lithosphere thickness (and not depth of entrainment) then we can speculate that by the late Cenozoic the lithosphere was around 75–80 km thick. Fortunately such an inference is supported by seismic tomographic data (Chen *et al.* 1991).

Lithosphere thinning could have been brought about by several factors including Pacific plate subduction; enhanced mantle temperatures associated with plumes or extrusion tectonics resulting from the India–Eurasia collision. We will evaluate each of these in turn.

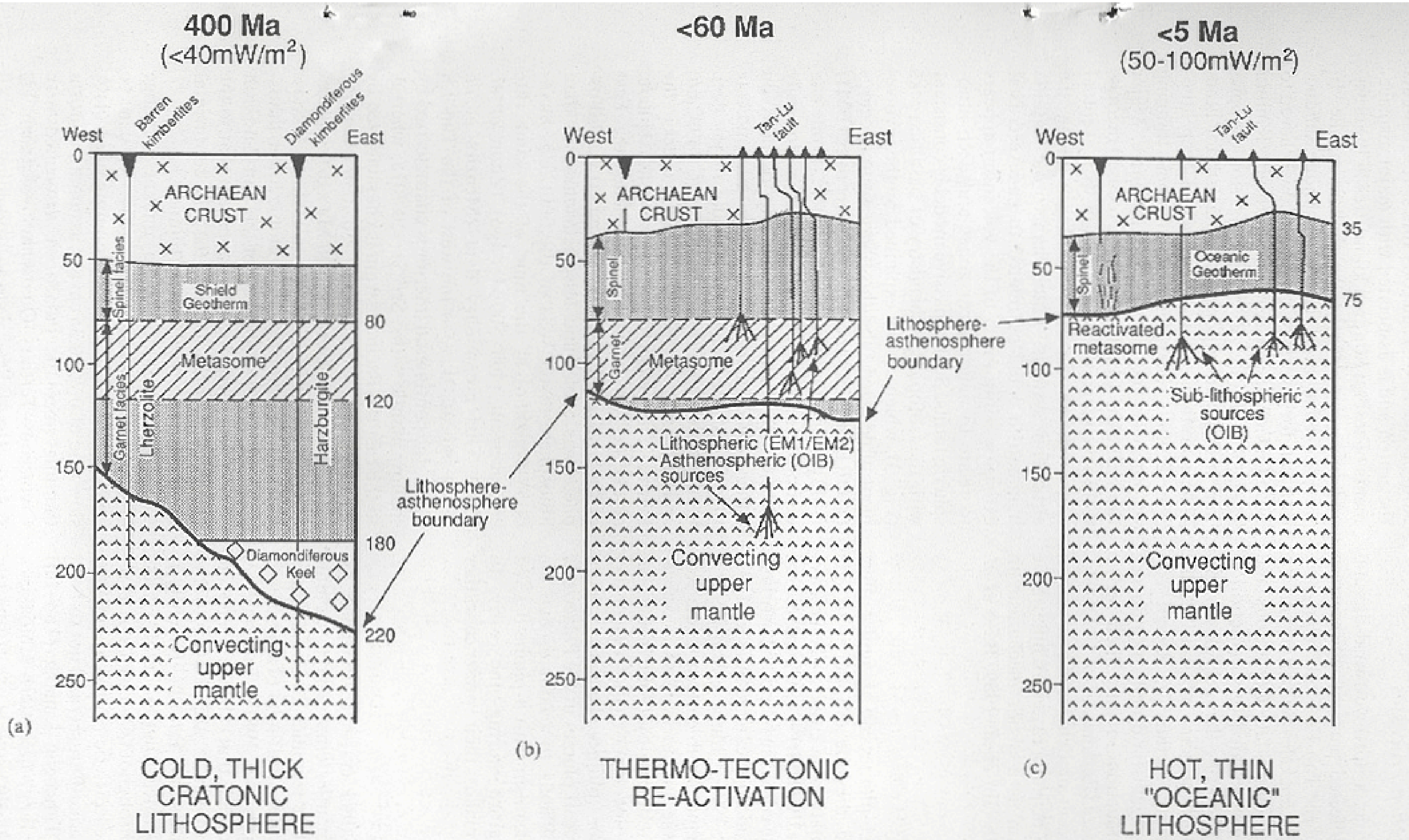

Fig. 4 An interpretation of the possible temporal and spatial changes to the cratonic lithosphere of eastern China over the last 400 Ma. (**a**) 400 Ma. Lithostratigraphic studies indicate the presence of thick cratonic lithosphere which varied in thickness and petrology from west to east (Griffin *et al.* 1992*a*,*b*). A metasome horizon is believed to exist between 80–120 km and a diamondiferous keel in the east between 180–220 km (Lu *et al.* 1991; Chi *et al.* 1992). This cratonic keel may be Archaean in age and appears to have retained its structural integrity until the Palaeozoic. (**b**) <60 Ma. Tertiary magmatism in eastern China defines two end-members – one in the convecting upper mantle (PREMA/OIB) and one/two in the lower lithosphere (EM1/EM2). One can speculate that thermo-tectonic processes in the vicinity of the Tan–Lu Fault may have caused thermal/mechanical erosion of the lower lithosphere. (**c**) <5 Ma. Seismic tomography reveals the presence of <80 km of lithosphere and a low velocity structure between 80–180 km, very similar to modern ocean ridges. High pressure xenoliths point to spinel facies peridotites (<75 km) and an apparent lack of an ancient metasome horizon. However, the past existence of such metasomes is indicated by the presence of pyroxenite veins at Hannuoba. These pyroxenites have $^{87}Sr_i/^{86}Sr > 0.707$ and $^{143}Nd/^{144}Nd < 0.5120$ (Tatsumoto *et al.* 1992*b*; Menzies *et al.* 1992) similar to the enriched (shallow) reservoir (i.e. EM1) tapped by Tertiary magmatism. Quaternary magmas have isotopic ratios similar to oceanic basalts and as such are believed to originate in sub-lithospheric reservoirs, perhaps due to the thinned nature of the lithosphere.

(a) Supra-subduction processes

During the Mesozoic, a northwestward-dipping subduction zone affected parts of southeastern China to the east of the Tan-Lu Fault. Tian *et al.* (1992) argued that episodes of rifting in the Jurassic–early Cretaceous; late Cretaceous and Eocene–Neogene were related to subduction of the Pacific Plate. However, the lack of any evidence for a subduction zone influence in the geochemistry of early Tertiary to Recent volcanic rocks argues against a dominant influence from modern subduction in late Phanerozoic lithospheric processes (Zartman *et al.* 1992). Despite this, some recent models for the evolution of the lithosphere beneath eastern China, have invoked subduction as a major mechanism in lithospheric growth (Jin *et al.* 1989; Basu *et al.* 1991).

(b) Intraplate processes

The degree to which plumes can or cannot affect cratonic keels and the role of plumes in late Phanerozoic magmatism, in eastern China, have been debated recently (Hill 1991; Chung & Sun 1992). The general consensus amongst workers in the field of volcanology (Zartman *et al.* 1992; Chung *et al.* 1992, 1993; Chung & Sun 1992) is that Cenozoic magmatism in eastern China was not related to plume structures. This is consistent with seismic tomography (Anderson *et al.* 1992) which does not support the present-day existence of major plumes beneath eastern China. The presence of plumes in the Palaeozoic or Mesozoic is difficult to evaluate, but the lack of surface volcanism with a plume derived geochemical signature during the early to mid-Phanerozoic makes their presence rather doubtful.

(c) Passive processes

Destabilization of thick cratonic lithosphere requires enhanced mantle temperatures, tectonic thinning due to plate tectonics and/or breakup of the craton due to major faults (Tapponier & Molnar 1977; Ma & Wu 1981). Tapponier & Molnar (1977) argued that all the Cenozoic tectonics of eastern China are related to the convergence of India and Eurasia. Recently it has been demonstrated that a radial stress orientation exists throughout China (Xu, Z. *et al.* 1992) which is believed to be related to indentor collision models (India–Eurasia) and not to local phenomena. The Tancheng–Lujiang (Tan–Lu) Fault (>2400 km long) in eastern China is a major sinistral strike-slip fault active during late Jurassic to early Cretaceous times. It cross-cuts the craton and is associated with major displacements of several hundred kilometres in the crust, and more importantly, the shallow mantle. In the past it has been related to oblique subduction but, for several reasons, it is now believed to have formed due to extrusion tectonics (Kimura *et al.* 1990; Tian *et al.* 1992). Extrusion tectonics may provide an important mechanism for lithosphere destabilization as a result of deep lithosphere faults/shear zones and tectonic thinning of otherwise stable cratonic lithosphere. Major faults like the Tan–Lu may have focused thermo-tectonic change within the craton with eventual alignment of Cenozoic volcanism along the strike-slip systems. Late Phanerozoic basaltic magmatism could be related to passive crustal extension, since much of the volcanism appears to relate to major shear zones and deep lithospheric faults. Such a passive model is consistent with the isotopic geochemistry of basaltic rocks (Fig. 3), which can be explained by the involvement of depleted sub-lithospheric source regions (MORB or OIB) and enriched reservoirs (EM1/EM2) within the shallow lithosphere. If one can demonstrate the juxtaposition of isotopically distinct provinces in the lower lithosphere, on either side of a major fault, this may indicate that faults like Tan–Lu constitute major deep lithospheric fractures. Griffin *et al.* (1992*a*,*b*) and Zhou *et al.* (1993) reported differences in the thermal character of the lower lithosphere, across the Tan–Lu Fault in the Palaeozoic. East of the Tan–Lu Fault (e.g. Liaoning) the lithosphere was cooler and less metasomatized than lithosphere to the west of the fault (e.g. Shandong–Guizhou) at the time of the kimberlite emplacement (400–500 Ma ago) (Zhou *et al.* 1993). Our preliminary data (Menzies *et al.* 1992) indicate that, to the west of the Tan–Lu Fault, the continental interior is characterized by shallow mantle with $^{87}Sr/^{86}Sr < 0.7075$, whereas to the east the Pacific margin is characterized by shallow mantle with $^{87}Sr/^{86}Sr < 0.7038$. This may point to relatively recent (< 60 Ma ago) emplacement of hotter, more oceanic, lower lithosphere (east) against older, cratonic lower lithosphere preserved to the west of the Tan–Lu Fault zone. From these data, it is apparent that to the east of the Tan–Lu Fault the old continental lithosphere has been greatly thinned.

The observed lithosphere thickness change in the Sino-Korean craton (Fig. 4) can be accounted for with different thinning rates. (1) A slow rate of 0.25–0.35 cm a^{-1} assuming uniform thinning since the Palaeozoic associated with Cretaceous–Tertiary–Quaternary volcanism. (2) A fast rate of 1.6–2.3 cm a^{-1} assuming that all the lithosphere thinning post-dated the collision of India with Eurasia (50–55 Ma). Essentially this would mean that the Archaean keel remained intact until the Palaeozoic and survived volcanic episodes in the Permo-Triassic. (3) A variable rate of $0.24\,cm\,a^{-1}$ until the Tertiary and $0.73\,cm\,a^{-1}$ until the present day. Here we assume that by the Tertiary the lithosphere had been thinned to the base of the metasome layer (120–80 km). The presence of an Archaean metasome horizon (80–120 km) would have facilitated participation of the cold, thick Palaeozoic (Archaean?) lower lithosphere (150–220 km) in magmatism (Figs 4a–c). A possible derivative of this ancient enriched horizon in the Cenozoic xenolith record takes the form of pyroxenite veins which infiltrate spinel peridotites at Hannuoba (Song & Frey 1989; Tatsumoto *et al.* 1992*a*; Menzies *et al.* 1992). Tertiary to Quaternary magmatism may have reactivated, and largely consumed, Archaean metasomes, thus accounting for the temporal and spatial change in isotopic composition of volcanic rocks. Tertiary magmas have a mixed asthenosphere–lithosphere signature and Quaternary magmas have a more dominant asthenospheric signature. Alkaline and potassic magmatism erupted through thick lithosphere (Peng *et al.* 1986) have a greater lower lithospheric contribution than magmas erupted through thin lithosphere. Such systematics in basalt geochemistry in relation to lithosphere parameters are also apparent off the craton, where potassic magmas erupted through thick lithosphere (Wudalianchi) are compositionally distinct to those erupted through thin lithosphere in the Songliao Basin (Peng *et al.* 1986; Zhang *et al.* 1990*b*, 1993).

Summary

A review of the geology and geochemistry of kimberlite and basalt xenoliths allows a number of points to be made.

(1) Kimberlite-borne xenoliths point to the existence of thick, cold lithosphere in the Precambrian, particularly in the eastern part of the Sino-Korean craton.
(2) Basalt-borne peridotite xenoliths reveal the presence of thin, hot lithosphere in the Cenozoic and composite peridotite–pyroxenite xenoliths reveal the existence of deeper (garnet facies) reservoirs, with a distinct isotopic signature. Seismic tomography indicates that the lithosphere is 80 km thick (i.e. spinel facies only), so one can speculate that garnet facies mantle must have been consumed in the past.
(3) The involvement of enriched (possibly ancient) lithospheric reservoirs in the genesis of Tertiary to Recent volcanic rocks is indicated by their Sr, Nd and Pb isotopic geochemistry. Since similar enriched reservoirs exist as composite xenoliths one can speculate that thermo-tectonic reactivation and consumption of an ancient metasome layer (80–120 km) may have played a major role in Tertiary to Recent volcanism.
(4) Mantle plumes and Pacific margin subduction are not believed to have been responsible for the dramatic change in the thermal, petrological and chemical character of the cratonic lithosphere. The stress field associated with the collision of India and Eurasia is believed to have destroyed the physical integrity of the craton, with the provision of major shear zones/strike-slip faults that penetrated the crust–mantle boundary; facilitated fluid ingress; reactivated the Archaean metasome horizon and ultimately caused passive continental volcanism in the late Phanerozoic.

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