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Integration of geology, geophysics and geochemistry: A key to understanding the North China Craton

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Abstract

Archaean–Proterozoic crust, atop a thick (180 km), cold (40 mW/m^2), melt-depleted mantle keel, characterised the North China Craton (NCC) at the end of the Precambrian. Differing ages for Pre-Cambrian crust and underlying mantle reveal decoupling brought about by repeated orogenic events over the history of the NCC. The most recent thermo-tectonic episode in the Mesozoic–Cenozoic virtually replaced/transformed all of the Precambrian lithosphere. Whether this was caused by "top-down" rapid delamination (<5 Ma) or "bottom-up" more protracted thermal/chemical erosion (ca. 100 Ma) depends on the interpretation of Jurassic to Cretaceous geological events. The eastern part of the craton east of the North–South Gravity Lineament [lithospheric boundary] has experienced the most re-activation. In the Palaeozoic–Mesozoic this region was intruded by kimberlitic magmas and cross-cut by the Tan-Lu fault zone and in the Mesozoic–Cenozoic, the eastern craton was the site of major mafic igneous activity. By the end of the Cenozoic the eastern craton was characterised by thermal highs [>64 mW/m^2], thin continental lithosphere (<50 km) and thin crust (<32 km) adjacent to the intra-cratonic Bohai Sea.
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1. Introduction

Seismic tomographic models of the Earth reveal *ca.* 200 Ma of recycling of cold, coherent slabs to the transition zone or to D″ (e.g. Karason and Hilst, 2000; Van der Voo et al., 1990; Van der Hilst et al., 1991). This is balanced by upwelling structures evident as geoid highs centered on the southern Pacific Ocean and the southern African continent coincident with the majority of hot spots/plumes at the surface of the Earth. Within continents there are regions, termed cratons (*kratos* = *strength*), which are devoid of any tectonic or volcanic activity, and have been so for the last 2.5 billion years. Cratons are thick (*ca.* 200 km) and cold (45 mW/m^2) and 75% of the cratonic plate (i.e., lower 150 km) comprises a refractory, low-density (*ca.* 3.300 g/cm^3), anhydrous, peridotitic keel. The Mg rich and Fe poor nature of the dry peridotite ensures buoyancy, stability and longevity. While the Kaapvaal craton, South Africa is perceived as the archetypical

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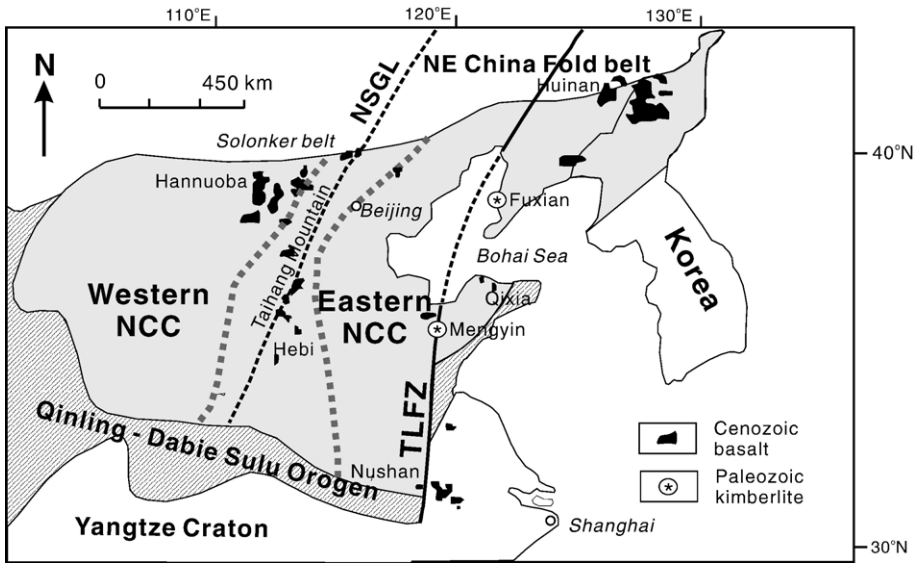


Fig. 1. North China (Sino-Korean) craton (NCC) (after Menzies and Xu, 1998). Note the amalgamation of tectonic blocks around the craton — especially the Yangtze craton in the south which docked with the NCC in the Triassic forming the Qingling Dabie Sulu orogenic belt. Craton stability may have been jeopardised by Mesozoic circum-cratonic orogenic events, or by more recent orogenic processes related to the Pacific Margin to the east.

craton, the Sino-Korean or North China Craton (NCC) (Fig. 1) may be unique amongst cratons in that its formation, and reactivation, has been captured in the Phanerozoic geological record of eastern China.

The temporal and spatial evolution of the NCC, since the Ordovician, has been the subject of considerable debate for the past twelve years (e.g., Menzies et al., 1993; Griffin et al., 1998; Menzies and Xu, 1998; Xu et al., 1998; Zhang et al., 1998; Zheng et al., 1998; Fan et al., 2000; Chen et al., 2001; O'Reilly et al., 2001; Xu, 2001, Gao et al., 2002, 2004; Rudnick et al., 2004; Xu et al., 2004a,b; Niu, 2005). The debate centres on the interpretation of the geological evidence for re-activation, the mechanism(s) and the timing. In trying to understand the evolution and re-activation of the NCC we will consider the following:

(1) Evidence for the existence of cold, thick cratonic lithosphere of Archaean age.
(2) Geological and geochemical evidence for re-activation of the NCC.
(3) Possible mechanisms and timescales of re-activation.

2. Archaean lithosphere

In this section we will outline the main characteristics of cratonic regions from around the world, followed by a summary of the research undertaken on the NCC. In so doing we will highlight the similarities and differences between the NCC and the Kaapvaal craton, South Africa, which is used as an example of a typical craton.

2.1. Age

Table 1 provides a list of the world's cratons (see Ernst and Buchan, 2001 and references therein) indicating that the crustal parts range in age from 2.5–4.4 Ga [i.e., Hadean 4.0–4.5 Ga, Archaean 2.5–4.0 Ga]. Proof that the crust was coupled to the mantle, both in time and space, depends crucially on accurate dating of mantle rocks. Applications of Rb–Sr and Sm–Nd isotope systems to mantle peridotites indicated that cratonic peridotites from South Africa had been isolated from the convecting mantle for several billion years (e.g. Kramers, 1979; Menzies and Murthy, 1980; Cohen et al., 1984; Richardson et al., 1984). However, more precise dating was necessary because the Rb–Sr and Sm–Nd systems are dependent on incompatible elements that can be easily modified by the migration of incompatible element rich melts in mantle rocks. The ideal isotopic system for olivine rich rocks is believed to be Re–Os, as it is linked to compatible elements, and as such should provide age constraints on the formation of the residual peridotite which constitutes much of the lower lithosphere (e.g., Walker et al., 1989; Pearson et al., 1995; Reisberg and Lorand, 1995; Shirey and Walker, 1998; Carlson et al., 1999; Chesley et al., 1999). Geochronological studies have focussed on some 200–300 peridotites and Re–Os model ages for cratonic peridotite

Table 1
The world's cratons as defined on the basis of crustal ages (after Moller et al., 1998; Ernst and Buchan, 2001), the presence (or absence) of melt-depleted peridotites, the Re–Os age of the mantle rocks (Walker et al., 1989; Pearson et al., 1995; Carlson et al., 1999; Chesley et al., 1999; Hanghoj et al., 2001; Gao et al., 2002; Pearson et al., 2003) and the presence (or absence) of diamondiferous kimberlites

Location	Crustal age (Ga)	Komatiites and/or boninites (%)	Melt-depleted peridotites (Y/N)	Mantle Age (Ga)	Diamonds (Y/N)
Amazonian, Brazil	3.0	Komatiites	–	–	Y
Dharwar, India	2.5–3.0	10% boninites komatiites	–	–	–
Fennoscandinavia	2.5–3.0	10–30% komatiites	Y	–	Y
Goias, Brazil	2.9	Komatiites	–	–	–
Greenland–UK	2.8–3.8	Boninites	Y	2.6–3.1	N
Kaapvaal, SA	2.6–3.4	10–20% komatiites	Y	2.5–3.6	Y
North China	2.5–3.5	Komatiites?	Y	2.5–2.7	Y
Pilbara, Australia	2.7–3.5	Komatiites	–	–	–
Sao Francisco, Brazil	2.78	15% komatiites	–	–	–
Siberia	3.2–3.3	15% komatiites	Y	2.5–3.0	–
Slave, Canada	2.7	–	Y	Y	Y
Superior, Canada	2.7–3.0	Komatiites boninites	–	–	–
Ukraine	2.5–3.7	7% komatiites	Y	–	–
Tanzania	2.7–3.1	–	Y	2.5–3.3	–
West Africa	2.6–3.0	–	–	–	Y
Wyoming, USA	2.7	–	Y	2.4	–
Yilgarn, Australia	2.7–3.0	10% komatiites	–	–	–
Zimbabwe, Africa	2.57–3.5	10% komatiites	Y	–	Y

xenoliths define a wide range of Archaean ages with a mode of 2.5–2.75 Gyr (Late Archaean) with some ages ≥3.5 Gyr (Pearson and Nowell, 2002; Carlson et al., in press). In most cratons isotopic data provide unequivocal evidence that the crust and mantle parts of the lithosphere formed in the Archaean.

2.1.1. NCC crust

Pioneering geochronological work by Jahn and Zhang (1984), and Huang et al. (1986) reported Sm–Nd ages of *ca.* 3500 Ma for amphibolites from eastern China. Since that time several studies of basement rocks and crustal xenoliths from the NCC have revealed a range of crustal ages from 2.5–3.8 Gyr (e.g., Jahn et al., 1987; Jahn and Ernst, 1990; Liu et al., 1992; Qui et al., 2000; Liu et al., 2004a,b; Zheng et al., 2004). Zircon U–Pb ages of *ca.* 3800 Ma from upper crustal rocks confirm the antiquity of the upper crust and the fact that the oldest rocks within the NCC range from 3.5–3.8 Ga (Jahn et al., 1987; Liu et al., 1992; Wu et al., 1992; Zheng et al., 2004) (Table 1). Two age clusters at 2.6–2.8 Ga and 3.2–3.6 Ga. were identified by Wu et al. (1992) with most Archaean rocks lying between 2.5–2.9 Ga. Most recently, studies of lower crustal xenoliths (Zheng et al., 2004) indicated the survival of relict ancient crust (*ca.* 3.6 Ga) in regions where the uppermost crust may have "younger" ages. This may reflect more recent re-working of the upper crust (Table 1). Such studies allowed Zheng et al. (2004) to infer prior depletion events and to suggest that protoliths of the lower crustal rocks were extracted from the mantle at 3.9–4.0 Ga. These samples must have been remelted around 3.6–3.7 Ga. Hadean (≥4 Ga) precursors, originally proposed by Jahn et al. (1987), were confirmed by the work of Zheng et al. (2004). It is now believed that 80%, or so, of the NCC is dominated by late Archaean crustal rocks.

2.1.2. NCC mantle

Ideally isotopic and trace element studies of on-craton kimberlite-borne garnet peridotites could provide crucial information on the Archaean history of the NCC. Unfortunately kimberlites and their xenoliths from within the NCC are notoriously altered and so data are limited to a few mantle samples (Zhi et al., 2001; Gao et al., 2002) brought to the surface in Ordovician kimberlites (Lu et al., 1995). Gao et al. (2002) studied the Re–Os geochemistry of garnet peridotites from the Ordovician kimberlites at Fuxian and Mengyin (Fig. 1) in the eastern NCC. The garnet peridotites from Fuxian have low $^{187}Os/^{186}Os$ ratios <0.112 a characteristic of Archaean mantle. In addition kimberlite-borne garnet peridotites from Fuxian gave a considerable range of Re–Os T_{RD} ages ranging from Proterozoic to late Archaean ages (Table 1). Collectively these data indicate that the lithospheric mantle beneath the eastern NCC was complex, but that parts of the eastern NCC contained late Archaean mantle relics. Interestingly several workers reported a general lack of mantle xenoliths with Archaean ages (Deng and

MacDougall, 1992; Zhi et al., 2001; Wu et al., 2003) and it may be that post-Archaean processes reset many of the Archaean ages.

It is apparent that there are differences in the age of crustal and mantle rock within the NCC. If these differences in crust-mantle ages are borne out by more Re–Os or Lu–Hf isotopic data then the NCC may be similar to other cratons (e.g., Davis et al., 2003) where the crustal rocks record a long and complex tectono-thermal history but the mantle rocks, in some cases, retain a record of more recent events. It is not known to what extent the paucity of Archaean "ages" for the NCC mantle, and the preponderance of post-Archaean ages is an artifact of different stabilization ages, de-coupling of the crust-mantle system, or partial resetting of the xenoliths during entrainment. Unfortunately most Precambrian garnet peridotites entrained in the Ordovician kimberlites are highly altered, a feature that discourages intensive study. Assuming that most of the alteration is post-entrainment future research may target (a) Lu–Hf isotope studies as it appears that this system is unaffected by more recent metasomatic/alteration processes, and (b) Re–Os studies of primary sulphides.

2.2. Thermal state of the lithosphere

In a pioneering study of cratonic peridotites from Kaapvaal, South Africa, Boyd (1973) and Boyd and Nixon (1975) demonstrated that granular peridotites were low temperature/low pressure mantle rocks (i.e., shallow) and sheared peridotites were high temperature/high pressure mantle rocks (i.e., deep). Collectively these mantle peridotites define a linear array that matched a "shield" geotherm based on surface heat flow measurements. A marked inflexion at 180–200 km depth was interpreted as the lithosphere–asthenosphere (1300 °C) boundary, possibly where granular, cold peridotites gradually gave way to sheared, hot peridotites. Whether this inflexion is real, or not, remains controversial, but what was significant was the systematic change in temperature with depth as recorded in garnet facies peridotites. Importantly inferences drawn from xenolith-based geotherms could be cross-validated against surface heat flow measurements (e.g., Pollack and Chapman, 1977). As such thermobarometric data (e.g., Brey et al., 1990) help constrain several aspects of the thermal history and architecture of the craton including the depth to the base of the lithosphere (i.e., low velocity zone) at the time of entrainment of the xenolith/megacrysts, the extent of intra-cratonic variations in geothermal gradients, and, the existence or otherwise of intra-lithospheric thermal perturbations within the craton (e.g., Rudnick and Nyblade, 1999; Pearson et al., 2003). The existence of diamonds in kimberlite pipes [from which the xenoliths were extracted] confirmed that the cratonic lithosphere beneath Kaapvaal was >150 km thick (>5 GPa) (Boyd and England, 1960; Kennedy and Kennedy, 1976) but some discussion arose around whether the keel was 200 or 400 km thick (e.g., Jordan, 1978, 1988). Seismic tomographic models helped resolve this issue with a detailed assessment of craton architecture in Kaapvaal (James et al., 2001) and an indication of thicknesses of 200± 50 km.

2.2.1. NCC P–T

Kimberlite-borne xenoliths and xenocrysts from the NCC (Fig. 1) (He, 1987; Zhang et al., 1989) are dominated by garnet facies peridotites (>80 km, 3 GPa) and diamond megacrysts (150–200 km, 5–6 GPa). Although the altered state of the garnet peridotite xenoliths, makes accurate thermobarometry of co-existing minerals impossible, the garnet concentrates provide a suitable alternative. Griffin et al. (1999) pioneered the use of trace elements in garnets in establishing the P–T regime and the nature of the peridotite/pyroxenite precursor, allowing for re-construction of litho-stratigraphic sections. The Mengyin (Shandong) and Fuxian

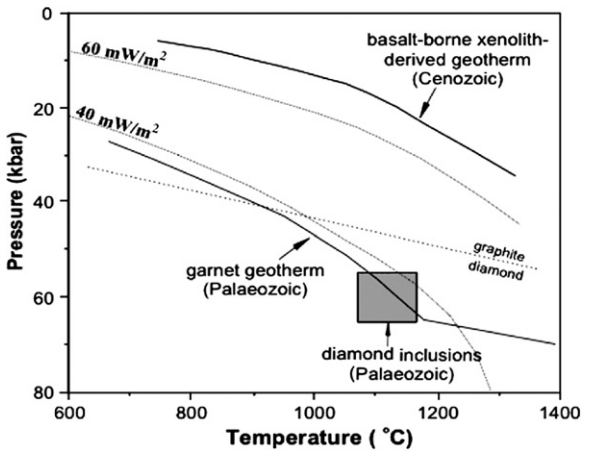


Fig. 2. Thermobarometry of kimberlite-borne garnets and basalt-borne peridotites 40 mW/m^2 — "Shield" geotherm best fits the thermo-barometric data from kimberlite (400 Ma) hosted garnet concentrates (i.e., Palaeozoic geotherm) (after Griffin et al., 1998; Xu, 2001). 80 mW/m^2 — "Oceanic" geotherm best fits thermo-barometric data from basalt-borne spinel and garnet peridotite xenoliths (i.e., Cenozoic geotherm) (Xu et al., 1995; Xu et al., 1998; Chen et al., 2001; Xu, 2001). 60 mW/m^2 — The present-day geotherm based on surface heat flow measurements. The temporal change from a "shield" to "oceanic" geotherm in the eastern NCC, is consistent with the loss of *ca.* 100 km of lithosphere over a period of 100 Ma.

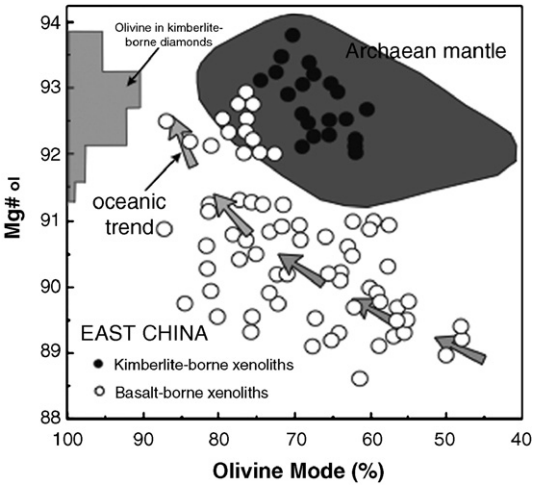


Fig. 3. Mg# vs. olivine mode [or olivine/orthopyroxene ratio] for peridotite xenoliths from the NCC. Histogram on the vertical axis shows the range in Mg# in olivine solid inclusions in diamonds entrained by Palaeozoic kimberlites which overlaps with that of kimberlite-borne garnet peridotite xenoliths from the NCC. Kimberlite-borne xenoliths plot within the same field as cold, granular peridotites from the Kaapvaal craton, South Africa (i.e., Archaean mantle). Basalt-borne xenoliths plot primarily on the oceanic trend as defined by off-craton peridotites and oceanic peridotites (i.e., abyssal, ophiolitic, and some orogenic peridotites). Note that some of the basalt-borne xenoliths overlap with the field of "Archaean mantle" (after Xu, 2001 and references therein). This has been interpreted as evidence of relics of Archaean mantle having survived until the Cenozoic. However it should also be noted that several cratonic suites plot outside the Archaean mantle field and as such the link between composition, mode and age is unresolved.

(Liaoning) kimberlites (Fig. 1) I the eastern NCC contain garnets believed to have formed in garnet-facies harzburgites, lherzolites and pyroxenites. "Garnet geotherms" for the lithosphere, beneath this region, corresponded to a surface heat flow of 36–40 mW/m^2 (Griffin et al., 1992, 1998, 1999) (Fig. 2). This "shield or continental" geotherm is similar to that reported from other cratons and correlates with low surface heat flow. In addition to garnet concentrate work, the thermal state of the lowermost lithosphere (180–200 km) can be constrained by the study of solid inclusions in diamonds [i.e., orthopyroxene, clinopyroxene and garnet]. In many instances these data yield temperatures of *ca.* 1100 °C at pressures of 4–6 GPa (e.g., Zhao, 1998; Menzies and Xu, 1998), and plot on the continental shield geotherm (Fig. 2).

2.3. Composition

In a fundamentally important contribution, Boyd (1987) and Boyd and Mertzmann (1987) demonstrated a marked difference between Archaean and post-Archaean mantle on the basis of olivine/orthopyroxene modes and olivine chemistry (Fig. 3). Archaean peridotites, from Kaapvaal, South Africa, were shown to be more magnesian than post-Archaean peridotites for a given olivine/orthopyroxene ratio. As such they defined a "cratonic" field/trend compared to an "oceanic" trend defined by abyssal, orogenic and ophiolitic metamorphic peridotites. The highly magnesian nature of Archaean peridotites was believed to have resulted from the extraction of highly magnesian melts (e.g., komatiites or boninites) whereas the "oceanic" trend was linked to the extraction of less magnesian basaltic melts (1300 °C). Since that landmark paper several other studies have shown that the nature of the cratonic mantle is complex and that other lower temperature/lower pressure mechanisms might equally well explain the differences in composition (e.g., Walter, 1998). In addition Kelemen et al. (1992) and Rudnick et al. (1994) proposed that the lower temperature migration of silica rich melts through a residual peridotite could modify its mineralogy and chemistry and produce orthopyroxene rich "reactive" harzburgites (e.g. Zhang et al., 2001; Xu et al., 2003). Although the classic plot of Boyd (1987) is used to differentiate between broadly cratonic and non-cratonic peridotites several cratonic peridotites deviate from the "cratonic" field (e.g., Greenland, Hanghoj et al., 2001). This has raised the possibility that the "cratonic" field may be much larger and overlap with the oceanic trend. As such the link between composition and age of peridotites is not fully understood.

Importantly the depth to which highly magnesian cratonic mantle extends is largely constrained from the study of solid inclusions in diamond. Diamond

Table 2
Mineral inclusions identified in diamonds from the NCC (Zhao, 1998, 2005 and references therein)

Peridotite paragenesis (P-type)	Eclogite paragenesis (E-type)
Forsterite	Omphacite
Enstatite	Coesite
Diopside	Rutile
Pyrope	Pyrope
Spinel	Apatite
Ilmenite	Sanidine
Sulfides	Ilmenite
Zircon	Graphite
Diamond	
Graphite	
Native iron	
Native chromium	
Magnesite	

megacrysts trap high-pressure primary phase assemblages (e.g. garnet, clinopyroxene, olivine, enstatite) and/or secondary phase assemblages (e.g. carbonate, mica, apatite and quartz). Mineral inclusions in diamonds can be assigned to either peridotitic (P-type) or eclogitic (E-type) parageneses (Meyer, 1987), corresponding to the two major mantle xenolith types. P-type are characterised by silicates found in harzburgite and lherzolite (olivine, clinopyroxene, orthopyroxene, garnet, spinel) and E-type by silicates found in eclogites (garnet and omphacitic pyroxene) (Table 2).

2.3.1. NCC chemistry

Solid inclusions in diamonds from kimberlites of the NCC have been the focus of several decades of study (Zhang and Liu, 1983; Meyer, 1987; Miao, 1992; Zhao et al., 1993; Harris et al., 1994; Meyer et al., 1994; Gorshkov et al., 1997; Zhang et al., 1994, 1999). Diamonds for Liaoning and Shandong (Meyer, 1987) contain solid inclusions dominated by peridotitic minerals — i.e., olivine and enstatite (76–83%) with spinel (6%), Cr-pyrope garnet (1–7%), diopside (<1%), and sulphide (1%). Meyer (1987) concluded that these were predominantly P-type inclusions and that only a few samples contained garnet and omphacite which would indicate the existence of eclogite (i.e., E-type inclusions). Although similar to what has been reported from many kimberlite pipes from around the world, Meyer (1987) noted that the ratio of peridotite/eclogite was unusually high. This was interpreted to mean that the keel at 180–200 km was composed of magnesian peridotite or harzburgitic (i.e., olivine + orthopyroxene + low Ca clinopyroxene [<5%]) so that at the depth of the diamond stability field (150–200 km) the mantle was melt-depleted peridotite with little or no eclogite. Compositionally garnet inclusions plot on a CaO vs. Cr_20_3 diagram in the field of "harzburgite and dunite" thus supporting the inferences drawn from other solid inclusions. This is consistent with other cratonic keels (e.g., Lee, 2006).

Studies of indicator minerals, used in diamond exploration, and mantle xenoliths (Fig. 3) reveal the presence of olivines from NCC kimberlite-borne xenoliths with Mg# ≥90 (Xu, 2001) (Fig. 3). These olivine data overlap with worldwide diamond inclusion data and with the compositional data from kimberlite-borne garnet peridotite xenoliths from the NCC. Fig. 3 illustrates the variation in Mg# vs. olivine/orthopyroxene ratio (Zheng et al., 1998; Xu, 2001) for kimberlite-borne xenoliths (garnet facies) from the NCC. These garnet facies (>80 km) peridotites plot in the "cratonic" field occupied by the Kaapvaal and Yakutia cratonic peridotites (Fig. 3) (Boyd, 1987). Similarly a limited number of Cenozoic basalt-borne spinel peridotites from Hebi, NCC (Fig. 1) (Zheng et al., 2001) also plot in the field of cratonic peridotites. One can conclude that the "cold" Precambrian keel was composed primarily of melt-depleted peridotite, formed from the extraction of komatiite/boninite. This melt-depleted, dry protolith may have been been modified as evidence exists for possible metasomatic processes in the lower keel. Zheng et al. (1994) studied diamonds from pipe 50 in Fuxian and reported the presence of rutile, phlogopite, and graphite as well as normal P-type inclusions. In a study of diamond inclusions from Liaoning Province, Zhao (1998) proposed that metasomatic processes must have played a role in diamond formation (5–7 GPa) due to the occurrence of hydrous silicate phases and carbonate inclusions in some diamonds. In a reconstructed lithostratigraphy, Griffin et al. (1998) argued for the existence of a melt-modified lower part to the NCC.

In conclusion it is clear that many of the characteristics of cratons worldwide apply to the NCC as sampled by Ordovician kimberlites. At the time of entrainment in the Ordovician, the NCC was composed of Archaean–Proterozoic crust and mantle, with a thickness of 180–200 km extending into the diamond stability field, with low heat flow such that the rocks defined a shield geotherm [40 mW/m^2] and buoyant because of a melt-depleted [high Mg] chemistry and presumed low density (Fig. 3). Using peridotite stability fields one can infer the gross nature of the lithosphere in the Palaeozoic. The occurrence of diamondiferous kimberlites at Fuxian and Mengyin (Fig. 1) indicates that the Precambrian lithosphere was at its thickest in the east. Studies of garnet concentrates from kimberlite pipes have shown that the petrology/mineralogy of the Precambrian lithosphere varied from west to east (e.g., Griffin et al., 1998). Interestingly the diamondiferous keel is sub-parallel to the Tan-Lu fault and one could speculate whether or not the Tan-Lu trans-lithospheric fault provided a fundamentally weak zone/conduit that allowed for magmatic influx and re-activation of the craton.

3. Craton re-activation: the evidence

The reports of Proterozoic ages within the crust and mantle parts of the NCC indicate that during the Proterozoic (i.e.,0.7–2.5 Ga) significant changes occurred to the NCC. It has been suggested that during this time much of the Archaean lower lithosphere may have been replaced with younger material (Zhi et al., 2001; Gao et al., 2002; Wu et al., 2003). In fact

Proterozoic Re–Os model ages are more abundant within the mantle peridotite suites than Archaean ages. Despite that it appears that the NCC has retained a broadly Archaean lithostratigraphy in terms of thickness, temperature and mantle facies. This raises the issue of whether the Proterozoic ages are Archaean ages partially reset by more recent events, or actually record Proterozoic events. Whatever the reason it appears that the NCC had a highly complex Precambrian history recorded in the crust-mantle lithologies, the age spectrum and the possible decoupling of crust and mantle segments. Tectonic re-activation of the NCC continued in the Ordovician with the intrusion of kimberlitic magmas through the thickest part of the craton. Throughout the Phanerozoic (400–0 Ma) major orogenic events affected the craton, such that the present-day eastern NCC is more like "oceanic" than continental lithosphere. In general the western part of the NCC is relatively stable while the eastern part is tectonically active, with on-caton extensional basins and volcanic fields, in many senses similar to the Basin and Range province of the western USA. The Mesozoic Tan-Lu fault cross-cuts the craton and the NE–SW Daxin'anling–Taihangshen Gravity Lineament (DTGL) (equiv. North–South Gravity Lineament (NSGL))(Figs. 1 and 4) is believed to represent a major lithospheric/terrane boundary (e.g., Niu, 2005). The NSGL separates the NCC into western and eastern sectors, which can be shown to have fundamentally different architectures. Below we summarise some of the evidence for re-activation of the eastern NCC.

3.1. Craton compressional and extensional tectonics

Several significant tectonic events affected the NCC during the Mesozoic–Cenozoic. In the late Permian–Triassic, the North China block was in collision with the South China Block (equiv. to Yangtse block+Cathaysia block)(Ames et al., 1993; Li et al., 1993). During the Triassic–Jurassic obduction and crustal thrusting along the Qinling–Dabie–Sulu orogen (Fig. 1) resulted in exhumation of ultrahigh-pressure rocks. Some crustal rocks were subducted to *ca.* 200 km during this collision and now exist as coesite-bearing eclogites. Mesozoic calc-alkaline magmatism in the southeastern North China Block has been interpreted (Zhang et al., 2002, 2005; Zhang and Sun, 2002; Wu et al., 2005) as evidence of melts from subducted crustal materials having interacted with the lithosphere to produce a fertile peridotite–pyroxenite mantle source. Subsequent to this these blocks docked with Siberia in the early Jurassic with concomitant closure of the Mongol–Okhotsk Ocean and the formation of Mesozoic high-Mg basaltic andesite (Zhang et al., 2003). In late Jurassic–Cretaceous times the southeast margin of China was akin to an Andean-type margin. In the Tertiary to recent times extension and lithospheric thinning was associated with basaltic volcanism possibly an artefact of the Indo-Eurasian collision (e.g., Ye et al., 1985, 1987).

The plate tectonic changes, involving collision and accretion, were initially expressed as extensional basins on the NCC. In the Triassic, most likely subduction was responsible for development of the Ordos extensional basin in the western NCC. In the Jurassic, a major extensional basin [the Songliao basin] formed, to the north of the NCC, as did many other minor elongate basins. It is believed that these basins formed in transtensional environments [Li et al., 1988] and some basins were bounded by major strike-slip faults, continuations of the Tan-Lu fault. The development of Mesozoic extensional basins on the craton continued into the late Jurassic and early Cretaceous. During the Cretaceous, the North China, Nanyang, Zhoukou, Sixian and Hefei basins formed within the NCC. In the early Tertiary, pull-apart basins developed because of the collision of India with Eurasia such that China is one of the most tectonically active countries in the world.

The source of post-collisional Mesozoic magmatism in the NCC was affected by Triassic collision and continental subduction between the Yangtse 'craton' and the NCC. In the Jurassic, extensional volcanism began in conjunction with basin formation and continued into the late Jurassic and early Cretaceous. Mid to late Cretaceous calc-alkaline magmatism occurred along an Andean-type destructive plate margin, or was intra-plate, and derived its signature from the sub-continental mantle. Development of Andean-type margins and extensional basins were associated with variable amounts of calc-alkaline/adakitic magmatism and intra-plate alkaline and tholeiitic volcanism (Zhang et al., 2002, 2003, 2004, 2005). Wilde et al. (2003) used the convergence of zircon ages (i.e., 80–180 Ma) in lower crustal xenoliths as evidence that the late Mesozoic was a period of intense lithospheric activity in the form of reactivation and magmatism (see also Guo et al., 2001; Wu et al., 2005). Wu et al. (2005) argued that major mafic events were the surface expression of mantle delamination. Indeed the spatial and temporal variations in the geochemistry of on-craton Mesozoic mafic magmatism (Zhang et al., 2004) has been interpreted in terms of secular changes in mantle source region. The mantle source for mafic magmas in the central NCC has elevated isotopic ratios (i.e. EM1) similar to the Taihang Mountains (Fig. 1). In contrast the mantle source for

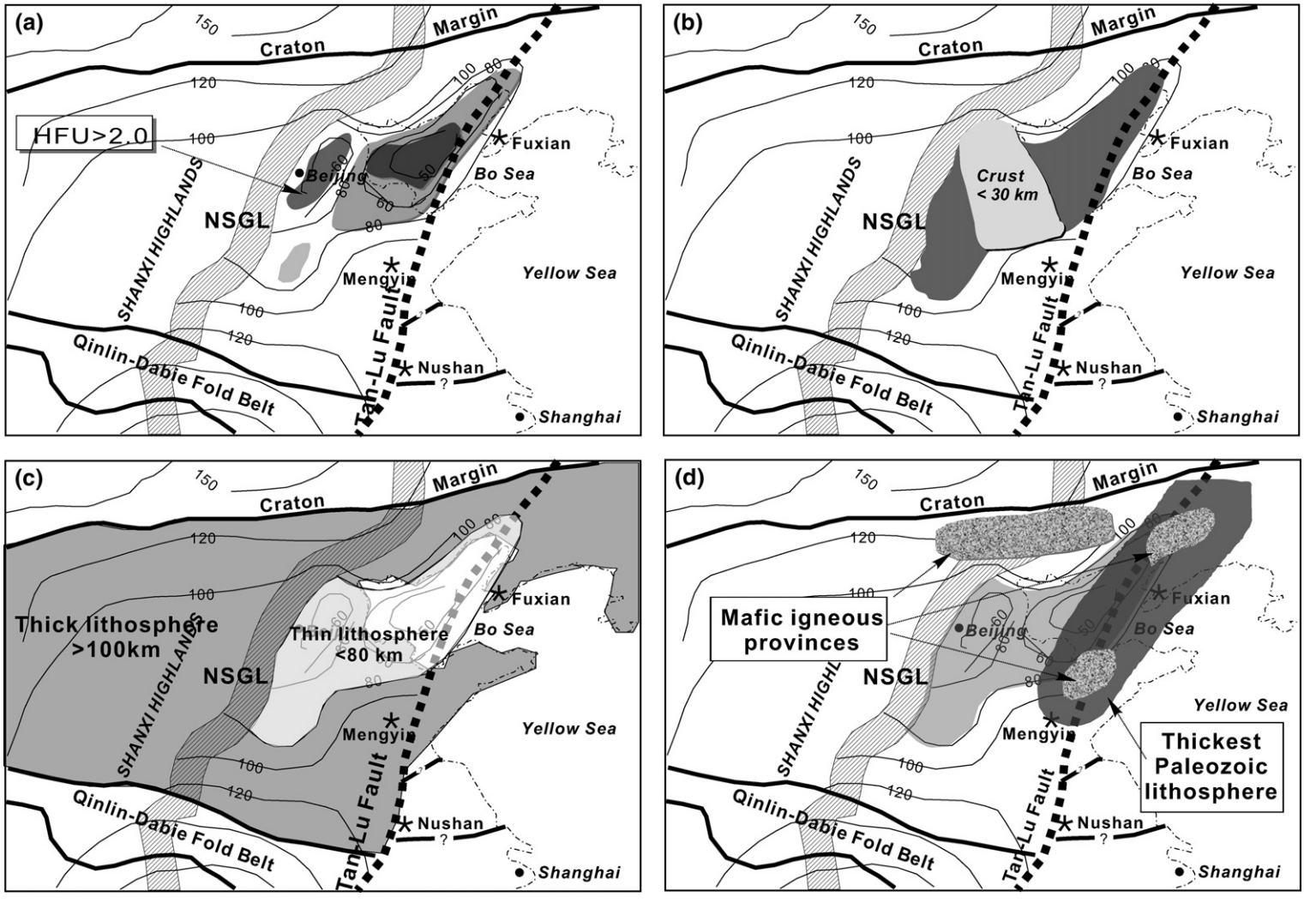


Fig. 4. (a) Present-day on-craton relationships between lithosphere thickness and heat flow (>1.8 HFU) based on geophysical data (after Ma, 1987; Liang et al., 2004). Note the NE–SW orientation of the thermal "highs" sub-parallel to the NSGL and the Tan-Lu fault. (b) Inferred mantle facies beneath the eastern China. Spinel facies mantle (<80 km) [dark shading] in eastern China is consistent with the dominance of spinel peridotites in basalt-borne xenolith suites throughout the eastern NCC. (c) Inferred mantle facies (e.g., light shading=spinel facies; dark shading=garnet facies) and observed variation in lithosphere thickness across the NCC. Note the change in lithosphere thickness across the NSGL. (d) Spatial coincidence between the thinnest and hottest present-day lithosphere (geophysical data), the occurrence of Mesozoic mafic provinces (geochemical data), and the thickest Palaeozoic lithosphere (geological data). Re-activation appears to have been focussed on the thickest part of craton giving rise to a magmatic peak in the Mesozoic and leading to the formation of highly extended lithosphere in the Cenozoic.

mafic magmas in the southern NCC is distinctively different. A subduction and collision model is proposed by Zhang et al. (2003) to explain the evolution of the secular lithospheric mantle. This model suggests that Palaeozoic subduction of oceanic crust beneath both the northern and southern margins of the NCC was responsible for destabilization of the eastern NCC, resulting in thinning and replacement of the lithospheric mantle. Destruction of the lithosphere in this region continued during Mesozoic subduction and continent–continent collision between the Yangtse craton and the NCC. Interaction between the refractory lithospheric mantle and slab-derived silicic melts during the Cretaceous led to the formation of the young fertile lithospheric mantle from which the Mesozoic mafic volcanic rocks were derived. This fertile Mesozoic mantle was then replaced by oceanic lithospheric mantle in the Cenozoic (Fan et al., 2000).

3.2. Hot, shallow mantle

The thermobarometry of Cenozoic basalt-borne peridotites (Xu et al., 1995; Xu et al., 1998; Chen et al., 2001; Xu, 2001) reveals a temperature range of 750–1200 °C at lower crustal depths in contrast to temperatures of 1200–1280 °C in the sub-Moho mantle (Fig. 2). Around the Tan-Lu fault (Fig. 1), Xu et al. (1996) noted that the lithosphere was relatively thin with shallow (35–45 km), cool (742–967 °C), sheared peridotites over deeper (50–60 km), hotter (950–1073 °C), granular peridotites. Xu et al. (1998) demonstrated that, at Nushan in the south-eastern NCC (Fig. 4), the architecture of the lithosphere was *ca.* 100 km thick, with 30 km thick crust, spinel facies mantle rocks (30–55 km) and garnet facies peridotites to 100 km, the base of the lithosphere. The overall P–T relationships are similar to the eastern Australian geotherm for tectonically active continental margins (e.g, O'Reilly and Griffin, 1985). At Nushan the low velocity zone occurs at around 100 km (Xu et al., 1998) in contrast to *ca.* 200 km for a craton. Co-existing minerals in basalt-borne spinel-garnet facies xenoliths define an "oceanic" geotherm for xenoliths entrained in the Cenozoic (*ca.* 80 mW/m^2) in contrast to kimberlite-borne diamond inclusions/mineral concentrates which define a "shield" geotherm for Palaeozoic times (*ca.* 40 mW/m^2) (Fig. 2). Menzies and Xu (1998) proposed that heat flow had peaked in the Mesozoic (>100 mW/m^2) and had subsided through the Cenozoic (90 mW/m^2) to the present-day (64 mW/m^2). This is supported by basin analysis and apatite fission track data that point toward high geothermal gradients in the Eocene (Hu et al., 2000a,b). Since then thermal subsidence and relaxation has resulted in low heat flow (64 mW/m^2).

Shallow (<80 km) spinel facies mantle rocks dominate late Cenozoic basalt-borne xenolith suites and comprise spinel facies lherzolites and harzburgites, spinel and garnet pyroxenites and rare spinel-garnet lherzolites (e.g., Cao and Zhu, 1987; Fan and Hooper, 1989; Song and Frey, 1989; Tatsumoto et al., 1992; Fan et al., 2000; Xu, 2001; Rudnick et al., 2004). This is in marked contrast to the predominance of garnet facies harzburgites and lherzolites entrained by Ordovician kimberlites. The Cenozoic xenolith population may well be an artifact of significantly thinner lithosphere.

Surface heat flow data, seismic data and seismic tomographic models reveal that, today, the eastern part of the NCC has been reactivated (Fig. 4a). Regional variations in the depth to the base of the lithosphere or the seismic low velocity zone (Ma, 1987) across the NCC highlight a major linear feature, the North–South Gravity Lineament (Fig. 4) that stretches from Guiyang to Beijing (Fig. 1). The NSGL separates lithospheres of fundamentally different character within the NCC (Fig. 4a). Fig. 4a illustrates the high heat flow (>1.8 HFU) in the region around Beijing and the low heat flow west of the NSGL. The region of high heat flow coincides with an area of very thin crust (<32 km) and lithosphere with a thickness of 50 km (Ma, 1987; Liang et al., 2004) (Fig. 4b). Surface heat flow measurements define an "oceanic" like geotherm, supported by mineral thermobaraomtry of basalt-borne spinel and garnet peridotites from the eastern NCC (Fig. 2). However marked contrasts exist across the craton. The western NCC is characterised by thick lithosphere (100–150 km), with low heat flow and a negative gravity anomaly and the eastern NCC by thin crust (e.g., ≥30 km), thin lithosphere (≥50 km) and high heat flow (≥2 HFU) with weakly negative to positive gravity anomalies. This is further supported by shear wave velocities for China (Zhang, 1998), which reveal that the eastern NCC is not associated with strong, fast anomalies (i.e., seismic lid) like other cratons. Zhang (1998) showed that 50 km beneath the craton (and elsewhere) shear-wave velocities tend to be slow, and not fast as one would associate with a stable craton. In addition shear-wave velocities correlate with crustal thickness. Equally significant is the lack of strong, fast velocities at 150 km beneath the eastern NCC, unlike the Tarim (W China) and Siberian cratons. Fast velocities would be expected if the cratonic lithosphere was cold and stable to 200 km. In contrast to this Zhang (1998) reported a vertical variation in velocity structure beneath the NCC with slow to moderate anomalies in

the upper 100 km and fast anomalies between 100 and 250 km. Also marked differences are apparent in the velocity structure [at 50 km] between the western and eastern parts of the NCC across the North South Gravity Lineament (Ma, 1987) (Fig. 1). Recent studies of P wave velocity variations (Zhao, 2004) under eastern China reveal that the P wave velocity changes from "high" at 60 km to "low" at 120 km, consistent with *ca.* 90 km thick lithosphere under the eastern NCC and the predominance of spinel-facies (<80 km) mantle peridotite xenoliths in Quaternary volcanic rocks. Under the Bohai Bay strong low velocities are reported consistent with high surface heat flow (Fig. 4a) adjacent to the thinnest continental crust within the NCC (Liang et al., 2004).

Geophysical and thermobarometric data can be used to infer the architecture of the late Cenozoic/present-day lithosphere beneath the eastern NCC (Fig. 4b). Using the P–T stability field parameters for plagioclase, spinel and garnet peridotites, the peridotite facies immediately beneath the crust can be inferred as can the peridotite facies at the base of the lithosphere adjacent to the asthenosphere. Fig. 4b shows how the region around the Bohai Sea is characterized by a lithospheric architecture that can best be described as "oceanic". Indeed very little difference is apparent from the continental to the oceanic realm of the Bohai Sea. The inferred lithostratigraphy comprises spinel peridotite beneath thin crust (30–32 km) to the lithosphere–asthenosphere boundary at 80 km. Indeed so thin is the crust that the potential exists for the presence of plagioclase facies peridotites in areas where the crust is *ca.* 30 km thick. To date these have not been reported in basalt-borne xenolith suites from the eastern NCC. However, given their presence in similarly tectonically active regions [Basin and Range, USA; Ross Sea Antarctica] the possibility exists for their occurrence in the eastern NCC. Elsewhere in the eastern NCC thicker crust is underlain by spinel facies mantle (<80 km) and garnet facies mantle to depths of 150 km (Fig. 4c). Interestingly a considerable change in lithosphere architecture occurs across the NSGL (Figs. 1 and 4) and to the south-east of Beijing. The inferred lithosphere architecture matches that reported from detailed thermobarometry of spinel and garnet peridotite xenolith suites (e.g, Xu et al., 1998).

3.3. On-craton magmatism

Cenozoic volcanism across the eastern NCC provided a probe into the composition of the lower lithosphere. Pioneering geochemical work by Zhou and Armstrong (1982) on volcanic rocks was used as a basis to suggest that the Cenozoic lithospheric mantle beneath eastern China was laterally and vertically heterogeneous and more "continental" to the west. On- and off-craton Cenozoic basalts from eastern China were shown to have isotopic characteristics similar to oceanic volcanic rocks and continental rift basalts. These isotopic ratios, as well as incompatible trace elements in Cenozoic alkali basalts, required an "enriched" component in their mantle source and it was proposed by several authors that this enriched source was shallow and located within the sub-lithospheric mantle (Zhang et al., 1990, 1993, 1998; Peng et al., 1986). Peng et al. (1986) noted that the Archaean crustal rocks of eastern China were "rootless", a very interesting conclusion since at that time there was no suggestion that the keel had been removed/replaced. Temporal and spatial Sr–Nd–Pb isotopic systematics indicated the presence of depleted and enriched reservoirs interpreted as mobilisation of pre-existent lithospheric mantle (enriched) by upwelling asthenosphere (depleted).

Xu (2001) used Nd isotopes to monitor the temporal change in the composition of the source of volcanic rocks (see also Zhang et al., 2004) from the Mesozoic to Cenozoic. He noted that Mesozoic volcanic rocks had "enriched" mantle sources while Cenozoic volcanic rocks had "depleted" mantle sources. Xu (2001) inferred involvement of enriched cratonic sources in magma genesis during the Mesozoic and the availability of "depleted", more oceanic, upper mantle sources in the Cenozoic. The nature of Cenozoic volcanism varies from west to east across the NCC perhaps due to diachronous extension as suggested by Xu et al. (2004b). They noted that initial extension occurred east of the NSGL and subsequent extension west of the NSGL. On-craton mafic igneous provinces formed between 120 and 130 Ma. (Wu et al., 2005) and were located in the thickest part of the craton or along the northern craton margin (Fig. 4d). It appears that re-activation preferentially affected the easternmost part of the NCC, evident today as Mesozoic mafic intrusives and thinned lithosphere.

3.4. Oceanic mantle

An "oceanic trend" is apparent in basalt-borne spinel facies peridotites (Xu et al., 1998; Fan et al., 2000; Rudnick et al., 2004) which plot in the region defined by abyssal, orogenic and ophiolitic peridotites (Fig. 3) (Boyd, 1987). This differs considerably from the "cratonic" trend apparent in kimberlite-borne xenoliths, and demonstrates the fundamental change from a melt-depleted keel to a fertile lower lithosphere. However, it

should be noted that some Cenozoic basalt-borne spinel (and possibly garnet) facies peridotites contain hybrid populations of peridotites that plot on both the "oceanic" and "cratonic" trends (Zheng et al., 2001). Very importantly such hybrid suites reveal that peridotites with a "cratonic" affinity did not just exist in Palaeozoic times. Clearly the process of lithospheric change was such that "cratonic" peridotites survived, in part, the re-activation of the eastern NCC.

An "oceanic" provenance can be assigned to basalt-borne spinel peridotite xenoliths on the basis of isotopic ratios and trace element abundances (e.g. Song and Frey, 1989; Tatsumoto et al., 1992; Xu et al., 1998; Fan et al., 2000; Xu, 2001; Gao et al., 2002; Rudnick et al., 2004). Tatsumoto et al. (1992) noted the presence of "young" mantle components in spinel peridotite xenoliths entrained during the Cenozoic history of the NCC. These had elemental abundances and isotopic ratios similar to oceanic rocks. This was further confirmed in a study of some twenty xenolith localities "on" and "off" the NCC (Fan et al., 2000). Fan et al. (2000) demonstrated the widespread existence of "oceanic" like spinel facies peridotites with MORB and OIB-like Sr–Nd isotopic compositions regardless of their location within the craton or with respect to the craton margin. The predominance of spinel facies oceanic type mantle is similar to what had been observed in areas like the Basin and Range western USA, where extensional tectonics dominate lithosphere architecture.

Wu et al. (2003) used Re–Os systematics within the NCC to show that the lithospheric mantle was a hybrid of Proterozoic and Phanerozoic mantle. Gao et al. (2002) studied the Re–Os geochemistry of spinel peridotites for the Hannuoba and Qixia basalts (Fig. 1) and noted that the peridotites from Qixia had Os isotopic ratios that overlapped with "modern" abyssal peridotites from the ocean basins raising the possibility of replacement/transformation of pre-existent mantle by asthenospheric mantle. In contrast the Hannuoba peridotites produced an elegant Re–Os "pseudoisochron" dating the mantle at 1910 Ma. This may indicate the presence of Precambrian mantle beneath this region. In a detailed study of two on-craton localities, Hannuoba and Qixia, Rudnick et al. (2004) showed the xenoliths to be compositionally similar but markedly different from the compositions of xenoliths found beneath Archaean cratons. Zheng et al. (2001) revealed that mixed populations of xenoliths occurred beneath the NCC. Some peridotites had the characteristics of Precambrian (cratonic?) mantle and other peridotites the characteristics of "oceanic" mantle (see also Xu, 2002).

4. Craton re-activation — the processes

4.1. The causes

Clearly since the Ordovician, the NCC has been re-activated and thinned by various processes — thermal, chemical and/or tectonic. However the exact mechanism that triggered these processes remain controversial (e.g., Fan and Menzies, 1992; Menzies et al., 1993; Griffin et al., 1992, 1998; Menzies and Xu, 1998; Xu et al., 1998; Zhang et al., 1998; Zheng et al., 1998; Fan et al., 2000; Fan et al., 2001; Zhang and Sun, 2002; Chen et al., 2001; O'Reilly et al., 2001; Xu et al., 2001; Zhang et al., 2002, 2003; Fan et al., 2004; Zhang et al., 2004; Gao et al., 2004; Rudnick et al., 2004; Xu et al., 2004a,b; Zhang et al., 2005; Niu, 2005; Wu et al., 2005). Various mechanisms have been proposed to explain the re-activation and destruction of lithosphere (e.g., Bird, 1979). These include instabilities, plume erosion, rifting and subduction, in many cases leading to delamination (or transformation) of the lithosphere. These processes and others are considered below.

4.1.1. Continent–continent collision

Collision is believed to be inextricably linked to a multiplicity of processes including mantle flow around cratonic keels, detachment of slabs, and delamination of lithosphere. Together these have the potential for erosion of refractory lithospheric mantle (e.g., Flower et al., 1998; Li, 1998; Menzies and Xu, 1998; Xu et al., 2001; Gao et al., 2002; Zhou et al., 2002; Gao et al., 2004; Liu et al., 2004a,b). Progressive subduction and accretion in Permo–Trias times resulted in a major orogenic belt (i.e., Solonker Belt (Fig. 1) between the north side of the NCC and southern Mongolia (e.g., Heubeck, 2001, Xiao et al., 2003). On the south side of the NCC collision between the NCB and the SCB was proposed as a mechanism for detaching the crust and thinning cratonic lithosphere (e.g., Li, 1994). Gao et al. (2002) also invoked the collision of the SCB and the NCC in order to explain mantle age data from within the NCC. Li (1998) believed that the collision of the SCB and the NCB caused mid-Mesozoic compressional tectonics that was associated with thin-skinned crustal thrusting on the southeastern edge of the NCC. Zhang et al. (2002) proposed that subduction and collision of the Yangtze craton and the NCC had a considerable effect on the evolution of the lithosphere beneath the southeastern NCC. Geochemical data on Mesozoic basalts (Zhang et al., 2002) was used as evidence for a causal link between the destruction of the cratonic lithosphere and the formation of Dabie-Sulu ultrahigh pressure metamorphic belts (Fig. 1). It was also

believed that tectonic underplating of crustal materials from the Yangtse craton (Fig. 1) beneath the NCC was inextricably linked to enrichment processes beneath the southeastern NCC (Zhang and Sun, 2002), which ultimately acted as a source for widespread Mesozoic calc-alkaline magmatism. Seismic tomographic modelling reveals the presence of low velocity asthenospheric mantle beneath eastern China (to Tibet) (Liu et al., 2004a,b). Liu et al. (2004a,b) interpreted this model as support for extrusion tectonics being associated with lateral flow of the asthenospheric mantle under the Asian continent as a result of the Indo-Eurasian collision. Liu et al. (2004a,b) argued that this would have fuelled rifting, mantle upwelling and volcanism.

4.1.2. Extensional tectonics

Ma and Wu (1981) suggested that rifting in eastern China triggered mantle upwelling. With regard to the loss of the cratonic keel upwelling of the asthenosphere (1300 °C) and related extension has been proposed as a mechanism for the accretion of "oceanic" mantle beneath the NCC (e.g., Ye et al., 1985, 1987; Xu et al., 1998, 2000; Zheng et al., 2001). Menzies and Xu (1998) argued that the presence of extensional basins atop the craton was evidence for craton re-activation in the Triassic. Off-craton, Zhang et al. (1990, 1998) invoked upwelling asthenosphere as a source of thermal erosion of the thick, enriched, lithospheric keel. This mechanism could re-activate enriched reservoirs with the concomitant acquisition of enriched isotopic signatures by intra-lithospheric magmas. O'Reilly et al. (2001) proposed a model of mantle replacement rather than wholesale delamination. They integrated geochemical data with seismic tomographic models (Yuan, 1996) as a basis for what became known as the "mushroom-head" model. Seismic tomographic models were interpreted in terms of "cold" lithosphere being transformed by "hot" mantle upwelling from below. Any model proposing a hybrid of Pre-Cambrian and Phanerozoic mantle is consistent with Re–Os data on several xenolith suites (Wu et al., 2003) and elemental geochemistry which shows relic "cratonic" mantle amongst "oceanic" mantle (Zheng et al., 2001). Wu et al. (2005) reviewed the evidence for the tectonic regime within eastern China in the early Cretaceous and concluded that this was a period of extension in eastern China thus explaining the A-type granites, metamorphic core complexes, and the mafic dyke swarms.

4.1.3. Plumes

The involvement of plumes in the re-activation/delamination of the NCC has been suggested by many investigators (e.g., Flower et al., 1998; Peng et al., 1986; Zhao et al., 2003, 2004; Wilde et al., 2003), some involving the Pacific Superswell. In eastern China and eastern Asia dispersed volcanic activity and DUPAL anomalies in volcanic rocks led Flower et al. (1998) to suggest that this signature might be inherited from elsewhere. Plate tectonic reconstructions show that the NCC was located over the Pacific superswell (geoid high) in the recent past (<200 Ma) and this may have provided the thermal (plume-related?) pulse to begin to transform the cratonic lithosphere. This is necessary because the present-day existence of plumes beneath eastern NCC is negated by seismic tomographic modelling which reveals a paucity of upwelling low velocity structures from, or below, the 660 km discontinuity (Van der Voo et al., 1990; Pei et al., submitted for publication). Recent P wave velocity studies reveal that slab graveyards under eastern Asia have acted as effective barriers to upwelling plumes and any associated helium anomalies (Zhao, 2004). In addition within the volcanic rocks of the eastern NCC there appears to be no unequivocal evidence for recent plume activity. Indeed many of the studies of volcanic rocks invoked involvement of enriched sub-continental mantle (i.e., post-Archaean) to explain their geochemistry (e.g., Zhou and Armstrong, 1982; Peng et al., 1986; Song et al., 1990; Tatsumoto et al., 1992). Plume involvement would also be expected to result in a large igneous province or mafic event at the Earth's surface but such associations are rarely reported from the NCC. To evaluate the role of plumes or upwelling structures on the NCC we can use the Kaapvaal craton, southern Africa as a reference frame. Southern Africa sits atop one of the main global geoid highs yet the Kaapvaal craton has retained its physical and chemical integrity (James et al., 2001). If plumes are responsible for flood basalts the lack of any spatial overlap between flood basalts and cratons has been used as evidence that the thick cratonic keel deflects plumes rather than being eroded or transformed by their presence. This is also evident in the North Atlantic Igneous Province, where the Iceland plume appears to have skirted the craton such that Cretaceous–Tertiary flood volcanism occurs in east and west Greenland but not in the centre of the craton. This is not to minimise the possible effects of melt ingress into the base of the lithosphere atop the geoid high and the possible transformation of the chemistry of the cratonic keel such that DUPAL signatures are found in basalts erupted, at a later date, through the NCC (Flower et al., 1998).

4.1.4. Subduction

Supra-subduction processes have been proposed by several investigators (e.g., Basu et al., 1991; Tatsumoto et al., 1992; Griffin et al., 1998; Niu, 2005). Basu et al. (1991) described the variability of the isotopes in

Cenozoic volcanic rocks from eastern China in terms of subduction of the Kula plate and/or ridge. Griffin et al. (1998) proposed that subduction-driven convective overturn led to thermal erosion and lateral displacement of the lithosphere that may have triggered thinning of the NCC. They argued that lithospheric erosion was underway by the early Jurassic because of rifting and extensional basin development. Jurassic–Cretaceous subduction of the Kula Plate beneath eastern China initially affected most of eastern China because of a shallow dipping Benioff zone and rapid subduction. This suggestion is based on the presence of calc-alkaline volcanism at this time within 200 km of the eastern seaboard and as such affecting the NCC (Griffin et al., 1998). Subduction-related processes are consistent with the suggestion that the fluids found in the mantle at Mingxi, Niutoushan and Qilin (Fig. 1) contain both water and carbon dioxide (Xu et al., 2000). Elsewhere in eastern China subduction related signatures (e.g., high $^{87}Sr/^{86}Sr$ ratios) have been reported in spinel peridotites from Huinan (Xu et al., 2003). However the process is more complex than simple supra-subduction processes, because Xu et al. (2000) report the presence of fertile peridotites at the base of 100 km thick lithosphere while Xu et al. (2003) report the presence of reactive harzburgites. The latter are more consistent with supra-subduction processes whereas the presence of fertile peridotites is more associated with accretion of asthenosphere. In both instances these data indicate that replacement/transformation of pre-existent lithosphere was widespread. Wu et al. (2003) explained Re–Os data using a subduction model. They argued that the addition of "young" mantle along a roughly NNE trend better suited a causal link to the Pacific rim subduction than collision of the SCB and the NCC on the Triassic.

Using seismic tomographic modelling, several groups have highlighted the fact that subducted slabs were deflected at the 660 km discontinuity a factor that would have repercussions for upper mantle convection (e.g. van der Voo, 1990; Van der Hilst et al., 1991; Karason and Hilst, 2000; Pei et al., submitted for publication). The NCC is within reach of active Pacific plate subduction, which has been active for 200 Ma, and may have affected the immediate continental margin and beyond. Pei et al. (submitted for publication) presented a convincing argument for vigorous convection in the mantle wedge above subducting Pacific lithosphere. They demonstrated that the wedge is horizontally expanded such that the influence of subduction registers in eastern China. Slab graveyards in the transition zone have effectively shielded the eastern NCC from any deep mantle plume activity such that any chemical signatures in Cenozoic volcanic rocks must be from the asthenosphere or the sub-lithospheric mantle. The presence of a "slab graveyard" at 660 km on the transition zone (Van der Voo, 1990) differs from what has been observed on other continental margins (e.g. western USA, western Europe).

In the case of the west Pacific plate, shallow subduction (i.e. $\leq$660 km) appears to have focussed the effects of convection and exacerbated thermal erosion of lithospheres of all ages. This would account for the fact that the eastern NCC, proximal to the Pacific rim, is much more affected than the western NCC, distal to the Pacific rim. The thinnest crust, thinnest lithosphere, strongest shallow low velocity structures, highest heat flow all occur east of Beijing on the margins of the Bohai Sea (Figs. 4a,b) ironically in the region characterised by the thickest lithosphere in the Palaeozoic (Fig. 4d). Why the location of the thick diamondiferous keel became the site of re-activation, mafic magmatism and eventually maximum lithospheric thinning remains unknown.

4.2. Timing and mechanisms — rapid delamination or protracted thermal processes

Although the tectono-thermal destruction of the lithospheric keel beneath the NCC was recognized a decade ago (Griffin et al., 1992; Menzies et al., 1993), the timing and the mechanisms still remain controversial (e.g.. Niu, 2005). Some models suggest that the early Cretaceous was an important period of lithospheric thinning in the NCC (Zhang et al., 2002, 2003; Yang et al., 2003). However the debate continues as to whether the mafic igneous activity was instantaneous and marked a rapid, delamination event lasting 10 Ma duration or was it part of a more protracted 100 Ma long transformation of the lithospheric keel?

Tectonic regimes have changed during the Mesozoic–Cenozoic from compressional in the Triassic–late Jurassic, to largely extensional in the early to mid Cretaceous. Indeed an inversion in tectonic regime is proposed for the period 140–100 Ma with a peak at 120–110 Ma. A change in thermal regime accompanied such multi-stage tectonic changes. It is believed that the change from 40 mW/m^2 to a present-day heat flow of 60 mW/m^2 involved a period of high heat flow (80 mW/m^2) in the Cretaceous coincident with peak magmatism and extension (130–110 Ma). Little on-craton magmatic activity happened during the Palaeozoic and episodic magmatism has occurred since the late Jurassic to the present-day. Various episodes are shown in Fig. 5 with an apparent "peak" around 110–130 Ma. Studies of the geochemistry of volcanic rocks, arguably mantle-derived, reveal a change in the isotopic characteristics from low $^{143}Nd/$

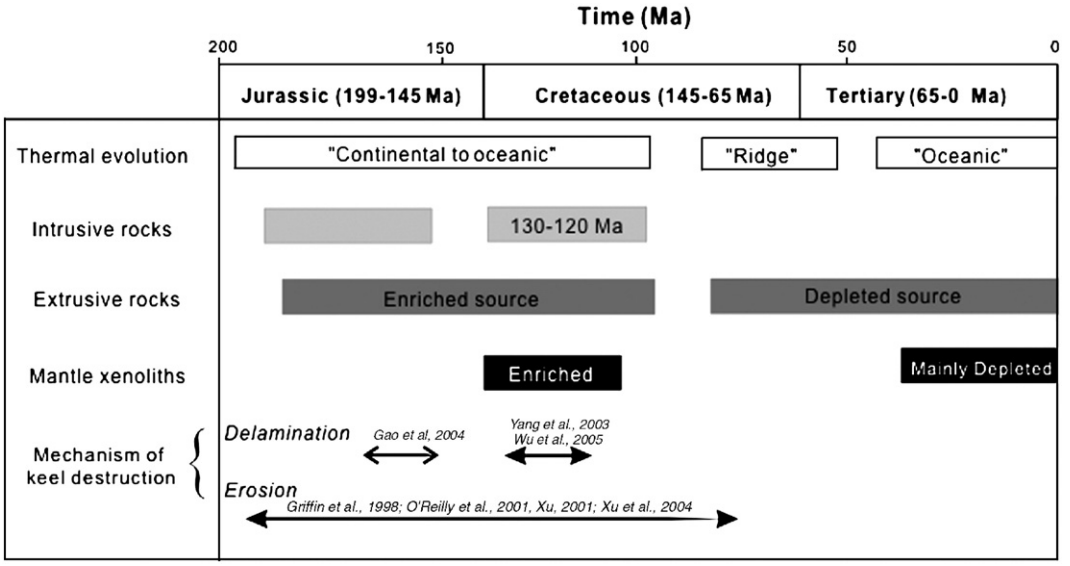


Fig. 5. A 200 Ma event history for NCC including (from top to bottom)

- "*Continental to oceanic*" geotherms based on basalt- and kimberlite-borne xenoliths and surface heat flow measurements. Note the temporal change peaking in the Cenozoic.
- *Intrusive rocks* with a magmatic peak at 130–120 Ma and a possible magmatic hiatus.
- *Extrusive rocks* (i.e. volcanism) with a temporal change in mantle source from enriched to depleted largely inferred from Sr–Nd isotope variation (Xu, 2004).
- *Mantle xenoliths* primarily found in Cenozoic volcanic rocks with a characteristic "depleted" isotopic signature (i.e. oceanic affinity).
- *Keel delamination* on a timescale of 10 Ma as the major force in lithospheric thinning.
- *Keel transformation* occurring over a 100 Ma timescale primarily based on the presence of "enriched" signatures in volcanic rocks over that time period.

^{144}Nd ratios (enriched mantle sources: lithosphere?) to high ^{143}Nd/^{144}Nd ratios (depleted mantle sources: sub-lithosphere?). Most mantle derived peridotite xenoliths entrained by Cenozoic volcanic rocks have high ^{143}Nd/^{144}Nd ratios in contrast to garnet peridotites in Palaeozoic kimberlites that have low ^{143}Nd/^{144}Nd ratios (Zhang, 2005, *unpublished data*). The timing of lithospheric delamination or transformation is also shown on Fig. 5. Dependant on the interpretation of the data summarised above accretion of new lithosphere occurred rapidly over 5–10 Ma. [delamination] or more slowly over 100 Ma [transformation by convective processes] (i.e., Griffin et al., 1998; Menzies and Xu, 1998; Xu, 2001; Wilde et al., 2003; Yang et al., 2003; Gao et al., 2004; Xu et al., 2004a,b).

Menzies and Xu (1998) suggested that lithospheric reactivation began in the Triassic period with extensional basin formation. The presence of mantle derived plutonic rocks around 180–190 Ma is believed to mark the reactivation of the cratonic lithosphere (see also Gao et al., 2002; Xu et al., 2004a,b; Zhang et al., 2005). According to Xu (2001) this re-activation ended in the late Cretaceous having lasted 100 Ma. The most marked change is the switch in magmatic source region from lithosphere (i.e., enriched) to asthenosphere (i.e., depleted) (Fig. 5). Xu (2001) argued that the loss of an old "enriched" keel and the influx of deeper (hotter) asthenosphere adequately explained this change. However it remains to be seen whether the low ^{143}Nd/^{144}Nd ratios could also be explained in terms sub-lithospheric contributions (subduction-related?) or involvement of upper lithosphere in magma genesis. In contrast to a period of re-activation stretching from the Triassic to the late Cretaceous (Xu, 2001), Yang et al. (2003) proposed that lithospheric delamination and thinning took place in a much shorter period of time, primarily in the Early Cretaceous (Fig. 5). This was based on the evidence for widespread crustal melting between 130 and 110 Ma which would require the extent of lithospheric thinning to be relatively advanced. Gao et al. (2004) argued for Jurassic delamination of the lower crust, and the involvement of eclogite in magmagenesis to account for crustal melting in the early Cretaceous. Magmatism with low ^{143}Nd/^{144}Nd ratios continued for some 90 Ma (i.e., 180–90 Ma)(Fig. 5) and this could be used as evidence against Jurassic delamination if the isotopic geochemistry is inherited from the lithospheric mantle. However it could be equally well argued that delamination exposed the crust to involvement in magma-

genesis and that this adequately explains the continued formation of magmatic rocks with low $^{143}Nd/^{144}Nd$ ratios. The prolonged period of magmatism in eastern China is not consistent with some mantle delamination models. In other regions, like the Alboran Sea (Mediterranean), where mantle delamination has been demonstrated using geophysical and geochemical data the switch in magmatism occurred on a scale of several million years (Duggen et al., 2005). One would expect an influx of voluminous asthenosphere-derived magmatism (i.e., depleted) in association with rapid Jurassic–Cretaceous delamination. This appears to be largely absent in the Mesozoic of the NCC. In contrast to rapid catastrophic delamination (<10 Ma), Xu (2001) argued that destruction of the thick lithospheric keel (180–200 km) beneath the NCC, took place by convective thinning over a much longer time period (≤100 Ma).

Delamination or removal of the highly magnesian lower lithospheric mantle has been suggested as a viable mechanism assisted by transformation of the lower crust to eclogite. Widespread formation of eclogite in the lower crust should (a) trigger basin subsisdence (e.g. Williston Basin Canada) and/or (b) result in eclogites with lower crustal provenance occurring within the xenolith population. Also, loss of the lower lithosphere would radically increase heat flow into the base of the crust and would trigger lower crustal melting or crustal foundering. Gao et al. (2004) reported inherited zircons [with an NCC provenance] in adakites from the NCC. On this basis they proposed that lithospheric thinning had reached such a stage by the late Jurassic that lower crustal rocks could be delaminated, converted to eclogite, incorporated into the convecting mantle and melted. Late Jurassic andesites, dacites and adakites from the NCC have chemical signatures consistent with their derivation as partial melts of eclogite that interacted with mantle peridotite. A major consequence of mantle delamination and the exposure of the crust to the asthenosphere is a switch to asthenosphere-derived magmatism and a relatively short duration of magmatism. One might also expect generation of silicic/rhyolitic melts by melting of the lower crust, melts that could be erupted as ignimbrites. To date these have not been reported from China. So rapid delamination models need to explain why the majority of Mesozoic magmatism appears to be sourced in the sub-lithospheric mantle [EM1, EM2] and why such magmatism lasted for a prolonged period of time 80–100 Ma.

Niu (2005) argued against delamination or melt transformation/metasomatic models. He used geological and geophysical data to propose that the Mesozoic thinning in eastern China may have occurred due to a process of hydration that "transformed" the basal portion of the lithosphere. Addition of water to the keel would decrease its viscosity, and if associated with a change to chemistry, increase the specific gravity. In this case the water came from dehydration of subducted oceanic lithosphere occurring along the Pacific Rim. Seismic tomographic models indicate that this recycled lithosphere is present as a slab graveyard, lying horizontally in the transition zone (660 km) beneath eastern Chinese continent. This slab graveyard absorbs heat and prevents hot mantle plumes from rising from the lower mantle and traversing the upper mantle (Niu, 2005).

Fig. 5 is an attempt to summarise some of the relevant geophysical, geological and geochemical data on a 200 Ma time line so that events can be cross-correlated. However several aspects of the data on Fig. 5 need to be carefully considered as their interpretation is open to debate. (1) *Crust or enriched mantle source?* The "enriched" Nd isotopic composition of late Jurassic–early Cretaceous magmas (Guo et al., 2001; Xu, 2001; Zhang et al., 2002, 2003, 2004, 2005; Xu et al., submitted for publication) has been interpreted to mean that the lithospheric mantle was still relatively thick (>80 km) and was participating in magmagenesis (Fig. 5). However what must be considered is to what extent the enriched signature observed in these magmas is truly "mantle keel derived" given that melt-depleted keels are notoriously difficult to melt. Even with metasome horizons it is more likely that potassic-alkaline melts would be generated than large mafic provinces. It would also have to be shown that crustal contamination, in no way, contributed to this enriched signature. This is important because as the thermal regime changes the upper lithosphere (crust and mantle) becomes hotter and more liable to be involved in magma genesis. (2) *Enriched lower lithosphere?* The enriched lithospheric mantle, presumed to be present during the early Cretaceous, contrasts with the current depleted mantle apparent as observed in peridotite xenoliths in Cenozoic basalts from eastern China (Fig. 5) (Fan et al., 2000; Xu, 2001). Therefore, lithospheric thinning/replacement must have prevailed after the early Cretaceous. However only limited, unpublished data exist on the isotopic characteristics of garnet peridotites from the NCC (Zhang, unpublised data 2005). Even assuming enriched signatures like the Kaapvaal craton, all that can be deduced is that enriched signatures existed until the Cretaceous and afterwards depleted xenoliths prevailed. In no way does this constrain whether the switch took 5 M or 100 Ma.

4.3. Any role for the Tan-Lu fault?

One of the major problems is how one begins the process of re-activation given that the cratonic lithospheric keel has been relatively stable for 4 Ga. During

this time it has remained cold and stable to 180–200 km (Fig. 2). Its refractory chemistry (Fig. 3) has helped keep it buoyant and it is unlikely that it can be delaminated because of its inherent buoyancy. A mechanism must be found to allow change to permeate the keel and the Tan-Lu trans-lithospheric fault (Figs. 2 and 4) is the most obvious conduit for change (Figs. 4a–d). Studies of xenoliths show that the Tan-Lu is associated with sheared peridotites (e.g., Xu et al., 1996) and deformation and melt ingress are inextricably linked. Perhaps the very tectonic processes that triggered crack propagation allowed for concomitant melt formation. At some stage the lowermost lithosphere must have been warmed conductively by heat transported from the vigorously upwelling asthenosphere by melts presumably potassic. Is it a coincidence that the diamondiferous kimberlites are erupted around the Tan-Lu and that they define a NE–SW trend somewhat like the orientation of the Tan-Lu fault? Transfer of kimberlitic or potassic melt would enhance the conduction of heat into the overlying lithosphere and progressive magma movement would increase the thermal gradient of the lithospheric mantle. This might have promoted minor amounts of intra-lithospheric magma generation especially where metasomatic horizons existed (e.g. 100 km). During the Mesozoic some mafic extrusive–intrusive events occurred in close proximity to the Tan-Lu fault (Fig. 4d) again indicating that perhaps this major lithospheric weakness acted as a conduit for thermo-chemical change. Re-activation mostly (Fig. 4b) affected the craton immediately adjacent to the Tan-Lu such that by the present-day the highest heat flow is recorded just west of the Tan-Lu and the thinnest lithosphere occurs in a NE–SW trending region.

5. Conclusions

The eastern NCC is a classic example of a reactivated craton with decoupled crust and mantle components making up the present-day lithosphere. The crust of the eastern NCC is predominantly Archaean–Proterozoic in age while the mantle is Phanerozoic. Palaeozoic kimberlite-borne xenoliths and megacrysts reveal the presence of a cold, old, dry, highly magnesian/iron-poor peridotitic lower lithosphere giving rise to a viscous and buoyant keel. In contrast Cenozoic basalt-borne xenoliths and megacrysts reveal the presence of hot, young, fertile lower lithosphere consistent with present-day geophysical constraints. Mesozoic to Cenozoic geological constraints indicate that the change occurred during the Jurassic–Cretaceous, evidence of the timing being found in the age and thermal history of on-craton extensional basins, the peak of magmatism (10 Ma) and crustal melting in the early Cretaceous, the 100 Ma long change in the Nd isotopic composition of mantle-derived volcanic rocks, the nature and provenance of mantle-derived peridotites, and the geochronology of mantle-derived rocks. What mechanism caused the change is debated and the options are

(a) "rapid" delamination driven by continental collision/subduction over 10 Ma,
(b) hydration of the keel driven by dewatering of recycled slabs
(c) "slow" transformation driven by vigorous mantle convection.

We would argue that "rapid" delamination models (e.g. Gao et al., 2004) are faced with the problem of the huge density/viscosity contrast between a 150 km thick, dry, magnesian keel and the asthenosphere. It is important for proponents of delamination models to define exactly how large tracts of buoyant (3.30–3.32 gm/cm^3) refractory peridotitic keel was converted to fertile denser (>3.34 gm/cm^3) mantle. If eclogitisation of the lower crust is part of this model then some explanation needs to be given as to why there is a paucity of eclogites in on-craton xenolith-suites. Proponents of hydration transformation (e.g. Niu, 2005) need to quantify exactly how much water is available in recycled, presumably dehydrated, slab remnants and how this mechanism differs from melt refertilisation. Our preference is for the "slow" transformation model (e.g. Xu, 2001) driven by melt-rock reaction. We are aware that this requires vast volumes of mafic melt to impregnate and refertilise the refractory protolith over a long time period and in the absense of evidence for plume-related processes, the source of mafic melt needs to be resolved. We prefer this model as it explains the protracted switch in the source regions of volcanic rocks from enriched (keel) to depleted (sub-lithosphere) over 100 Ma. In addition we believe that tecton-magmatic processes occurring sporadically throughout the Phaneorozic weakened the eastern craton. The eastern craton has been the site for kimberlite magmatism which added volatiles to the keel reducing its viscosity, these diatremes weakened the keel with final expression in the trans-craton, Tan-Lu fault zone. This area and the craton margins may have facilitated the transfer of sub-lithospheric mafic magmas to the surface in Mesozoic and Cenozoic times.

Future research possibilities include:

(a) *Denudation/erosional history.* The erosional response to rapid delamination over 10 s of millions of years would have been fundamentally different

to lithospheric transformation occurring over 100 Ma. Is this evident in the cooling history of crustal rocks ? Can the denudational history be balanced by input into major extensional basins on and off the craton?

(b) *Tectonics and magmatism.* The nature of intra-cratonic fault systems is pivotal to understanding craton re-activation and magmatism. What age are the major intra-cratonic fault systems? Do magmatic pulses coincide with periods of maximum extension? Is there a relationship between lithosphere architecture and magma composition?

(c) *Lithosphere formation.* The geochemistry and geochronology of major lithosphere-forming events provide a clue to unravelling the temporal and spatial evolution of the craton. Can isotopic data in volcanic rocks be used as unequivocal proof of the existence of thick lithosphere?

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