Lithospheric thinning in eastern Asia; constraints, evolution, and tests of models

T. M. KUSKY[1], B. F. WINDLEY[2] & M.-G. ZHAI[3]

[1]*Department of Earth and Atmospheric Sciences, St. Louis University, St. Louis, MO 63103, USA (e-mail: kusky@eas.slu.edu)*

[2]*Department of Geology, University of Leicester, Leicester LE1 7RH, UK*

[3]*Key Laboratory of Mineral Resources, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China*

Abstract: The North China Craton (NCC) is the only place currently recognized where an Archaean craton developed a continental root in the Archaean, and subsequently lost half of that root in younger tectonism. In this volume, various authors have advanced different models of root loss, and provided geological, geophysical and geochemical data that help constrain the geometry and timing of root loss. Understanding why and how roots are lost may help us understand how often this process may have occurred in the geological past, and how much lithospheric material has been recycled to the convecting mantle through this mechanism, potentially drastically changing our current understanding of crustal growth rates and processes. With current data, there are several equally plausible possibilities that require further data collection for testing. There are several possible tectonic triggers that may have caused half the root to be lost, acting either separately or together. These include collisional, extensional, plume-related, fluid-weakening, spontaneous, and more complex hybrid mechanisms. We also do not know why only the eastern half of the root was lost, and not the root from beneath the whole craton. One tantalizing idea is that the root grew independently, by tectonic underplating of subducted buoyant oceanic lithosphere, beneath the previously separate eastern and western halves of the craton by 2.5 Ga, with modification at 1.8 Ga. If so, perhaps only the eastern half of the root was lost in younger tectonism because there was some physical or geometric difference between the two halves. Alternatively, collisional or subduction-related tectonic processes acting only on the Eastern Block may have caused the disruption of the tectosphere there in the Mesozoic. The timing of and mechanism for loss of the root is not uniquely resolvable with current data, but a solution to the problem is in reach. Possible triggering mechanisms include, but are not limited to, collision of the South China (Yangtze) and North China Cratons in the Triassic, the India–Asia collision, closure of the Solonker and Mongol–Okhotsk oceans, Mesozoic subduction of the Pacific plate beneath Eastern China, impingement of mantle plumes, mantle hydration from long-term subduction, and several rifting events. In this concluding review, we link studies of crustal tectonics with investigations aimed at determining the nature and timing of the formation and loss of the root, to better understand mechanisms of continental root formation, evolution and recycling–removal.

Cratons are structurally complex regions that attained prolonged stability ($\geq$1 Ga) within the continents and thus, by definition, are Precambrian in age (Fig. 1). Indeed, most formed in the Archaean (Rudnick 1995; Windley 1995; Kusky & Polat 1999). Some first-order observations about Archaean cratons include the following.

(1) Many are preserved in the centre of continental masses, surrounded by younger fold belts (Fig. 1).

(2) Surface heat flow is typically low within cratons, averaging 41 ± 11 mW m^{-2} (Morgan 1984; Nyblade & Pollack 1993; Artemieva & Mooney 2001).

(3) Cratons are underlain by regions of fast P and S velocities, extending to depths of at least 200–250 km, and perhaps deeper (Jordan 1975; James *et al.* 2001; Gung *et al.* 2003).

(4) Kimberlites erupted within Archaean cratons carry diamonds interpreted to be derived from the lithospheric mantle, consistent with the presence of a cool and thick keel (Boyd & Gurney 1986).

(5) Mantle xenoliths from craton-penetrating kimberlites are highly refractory peridotites, which experienced large degrees of melt extraction (Boyd 1989), followed by variable degrees of metasomatic overprinting (Erlank *et al.* 1987).

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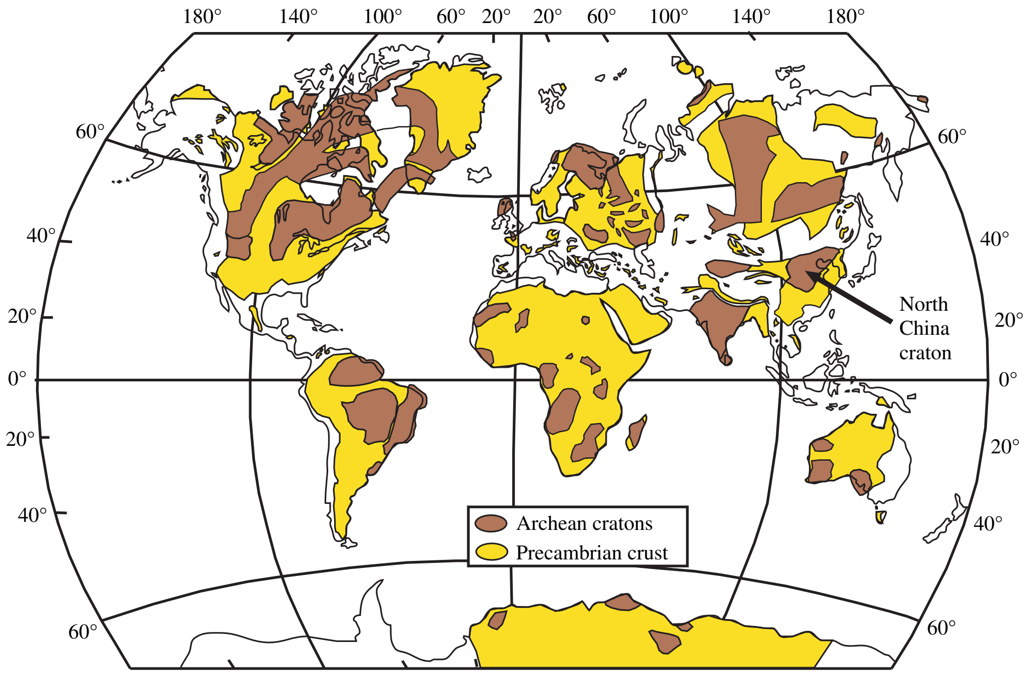

Fig. 1. Map showing the worldwide distribution of Archaean cratons, and the location of the North China Craton (after Kusky & Polat 1999).

(6) Osmium isotope investigations of cratonic peridotites demonstrate that the lithospheric keel formed more or less coincident with the overlying crust (at least within the precision of Os models ages, e.g. ± 200 Ma) (Pearson *et al.* 1995*a*, *b*; Chesley *et al.* 1999; Hanghoj *et al.* 2001; Irvine *et al.* 2003).

Thus, in general, Archaean cratons are characterized by cold, thick, structurally complex lithosphere whose density is offset by its refractory composition, giving rise to chemical buoyancy (Jordan's tectosphere hypothesis (Jordan 1975, 1981)). The lack of high elevation or free-air gravity anomalies over cratons suggests that they are in isostatic equilibrium and have a density profile that matches those of off-craton regions (i.e. Jordan's isopycnic hypothesis is generally correct). The presence of these thick, refractory and anhydrous peridotite residues beneath Archaean crustal regions is widely held responsible for the inherent stability of Archaean cratons (Pollack 1986; Durrheim & Mooney 1994; Griffin *et al.* 2003; Kaban *et al.* 2003).

The Archaean North China Craton (NCC), however, is an anomaly. Whereas it formed in the Archaean, complete with a thick, diamond-bearing lithospheric keel, and behaved as a stable lithospheric block throughout the Proterozoic and Palaeozoic, this stability ended abruptly during the Mesozoic, when the Eastern Block of the craton became reactivated, as witnessed by voluminous magmatism and widespread deformation (Liu 1992; Li & Yuan 2001; Xu *et al.* 2002; Meng 2003; Zhang, H. F. *et al.* 2003; Huang & Zhao 2004; Wu *et al.* 2005; Xu *et al*. 1991). Today, the Eastern Block of the craton has anomalously high heat flow and is seismically and volcanically active (six of the 10 deadliest earthquakes in recorded history have occurred in the eastern North China Craton; Kusky 2003; Zhang, Y. Q. *et al*. 2003). Estimates of lithospheric thickness are less than 100 km (Ma *et al.* 1984; Ma & Wu 1987; Yuan 1996; Yang 2003) and mantle xenoliths carried by Cenozoic basalts have relatively fertile bulk compositions (Menzies *et al.* 1993; Xu *et al.* 1998; Griffin *et al.* 1998; Zheng *et al.* 1998; 2001; Xu *et al.* 2002; Wu *et al.* 2003*a*, *b*; Lee & Walker 2006), contrasting markedly with the refractory peridotites characteristic of Archaean cratons (and found in Palaeozoic kimberlites from this very region) and the evidence for thick lithosphere preserved in the diamonds. Thus, the Eastern Block of the NCC is no longer a craton (see Kusky *et al.* 2007), and it appears that more than 150 km of mantle keel was removed from the base of the lithosphere sometime in the Mesozoic.

Summary of evidence for root loss beneath the North China Craton

A variety of types of data indicate that the eastern half of the subcontinental lithospheric mantle of the North China Craton has been dramatically thinned or lost during the Mesozoic. These include geophysical surveys of gravity, magnetic and seismic data for deep crustal structure, geochemical and petrological data from magmas and entrained xenoliths, and other less direct indicators such as changes in topography, regional tectonics, and basin and thermal evolution. Many of these aspects of the root loss have been discussed elsewhere in this volume, and we summarize the more salient features here.

The north–south gravity lineament is a major gradient in Bouguer gravity anomalies that corresponds roughly to the border between the Eastern and Western Blocks (or areas with and without root loss), but also extends north and south for thousands of kilometres past the borders of the NCC (Fig. 2). As the gravity lineament also corresponds to a major elevation change, areas of Tertiary basin formation along major faults, and a change in mantle seismic velocity at 150–200 km depth (e.g. Niu 2005), it may represent a major crustal structure that parallels the Pacific subduction margin. The region to the east of the lineament has experienced Late Mesozoic–Tertiary extension, whereas the area to the west generally has not and has thicker crust. The north–south gravity lineament is interesting also because it bounds areas that to the west have thick crust and 150–200 km thick lithosphere, large negative Bouguer anomalies, and low heat flow. Sub-Moho seismic V_p velocities west of the lineament are high, with values ranging from *c.* 8.1 to 8.3 km s^{-1} (Fig. 3). However, to the east the crust and lithosphere are generally thinner, there is high heat flow, and the

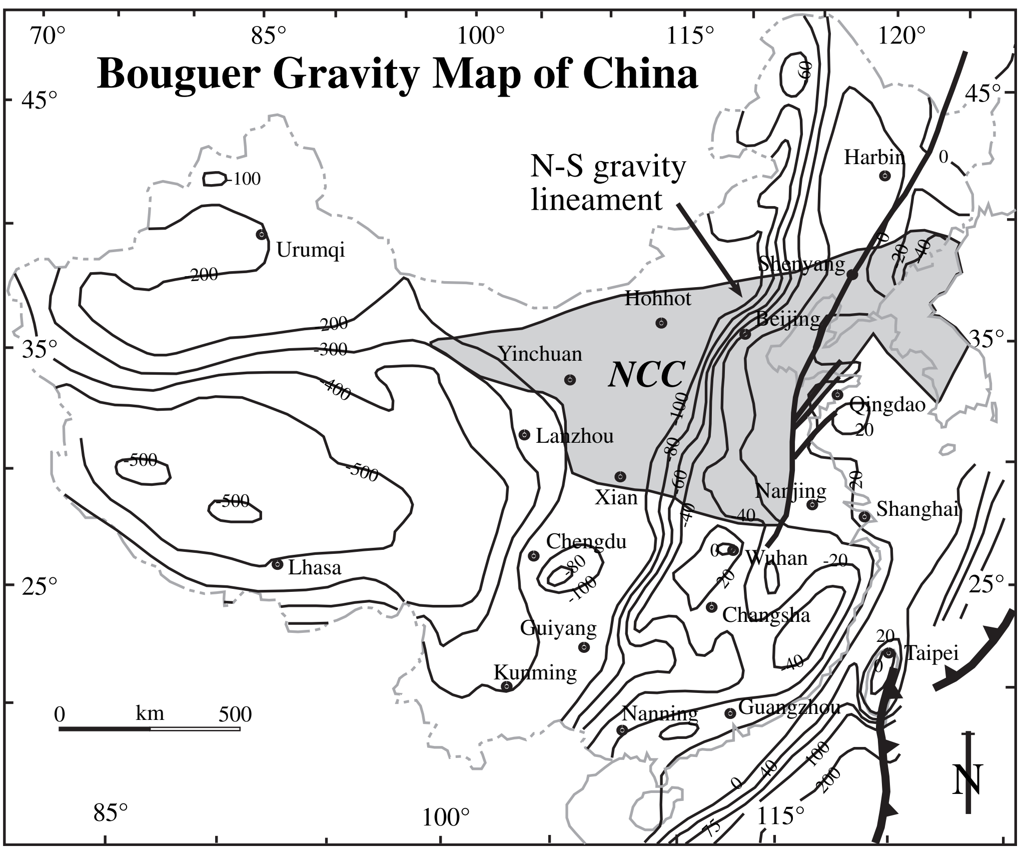

Fig. 2. Map showing Bouguer gravity and the prominent north–south gravity lineament that strikes across China, crossing the NCC along the approximate boundary between thick lithosphere to the west and thin lithosphere to the east. The north–south gravity lineament is parallel to the Pacific subduction margin, perhaps suggesting a causal link. Gravity data from Ma (1987); map modified from Griffin *et al.* (1998).

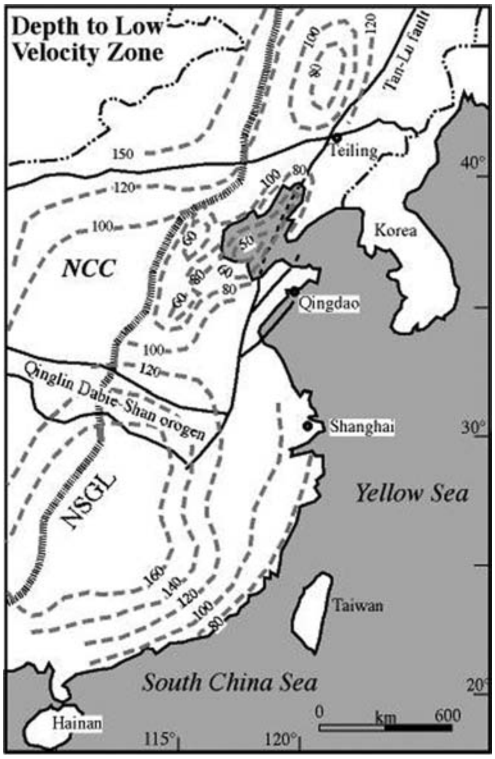

Fig. 3. Map showing depth to the low-velocity zone (modified after Griffin *et al.* 1998). NSGL, north–south gravity lineament.

regional Bouguer anomalies are zero to slightly positive. Sub-Moho seismic velocities are lower than to the west, ranging from 7.6 to 7.7 km s^{-1}, with some faster regions (implying partial root loss?). Tomographic profiles from the Eastern Block (Yuan 1996) show a 'blobby' velocity structure for the lower lithosphere, suggesting only partial root loss.

The Eastern Block is seismically very active, experiencing many earthquakes of magnitude ≥ 8, which include six of the 10 most deadly events in recorded history (Kusky 2003) that left more than one million people dead in total. Whatever the process of root loss, it appears to have caused continuing lithospheric instability that is currently poorly understood. Understanding root loss may shed light on this active seismicity, potentially saving numerous lives.

Although extending for thousands of kilometres along the Pacific rim, Mesozoic granitoids and gold deposits form a ring around the Eastern Block, perhaps reflecting some interaction between subduction-related processes and loss of the lithospheric root (Fig. 4). The granitoids, and associated ore-bearing fluids, may contain one of the best and most detailed records of the history of root loss beneath the NCC, and detailed study of these plutons may yield insights into the chemical and physical environments associated with foundering of subcrustal lithosphere and the mechanisms of root loss.

Loss of the lithospheric root is also shown by the compositional data for mantle xenoliths entrained in Early Palaeozoic and Mesozoic to Tertiary kimberlites and volcanic rocks. The oldest kimberlites (450–490 Ma) are the Fuxian and Mengyin pipes in the west (Fig. 5), whereas the Teiling intrusions are of Cretaceous to Tertiary age. Xenoliths from Nushan are only 0.5–0.8 Ma old, and these, together with the older examples, provide a 500 Ma history of mantle samples from beneath the NCC. Geotherms based on mantle xenolith data (Ryan *et al.* 1996; Griffin *et al.* 1998; Gao *et al.* 2006) and garnet concentrates show that in the Ordovician, the Eastern Block had a low conductive cratonic geotherm, with many samples coming from beneath the diamond stability field. The Ordovician lithosphere–asthenosphere boundary is estimated to have been at about 180 km depth (Yuan 1996; Griffin *et al.* 1998, 2003). In contrast, compositional data for the younger mantle samples reveal a high geotherm and a lithosphere–asthenosphere transition that had risen to about 80 km depth. Compositional data for xenoliths thus clearly show the loss of the lithospheric root beneath the eastern NCC, but do not yield information on exactly when this loss may have occurred, why it occurred, or what the loss means for cratonic evolution. Basalts erupted through the crust of the Eastern Block also show a change in composition from Mesozoic to Tertiary, with high-Mg andesites or adakites showing evidence for lower crustal foundering in the Jurassic–Cretaceous.

Understanding root loss timing and mechanisms

It appears that a major difference in crustal thickness between the eastern and western parts of the North China Craton is coincident with the prominent north–south-striking topographic change and gravity anomaly (e.g. Griffin *et al.* 1998; Niu 2005). The present-day distribution of tectospheric root provides constraints on the timing and causes of the loss of the root under the eastern half of the craton.

A review of the papers in this volume (and references therein) reveals several themes that may be relevant for understanding the loss of the root, as follows.

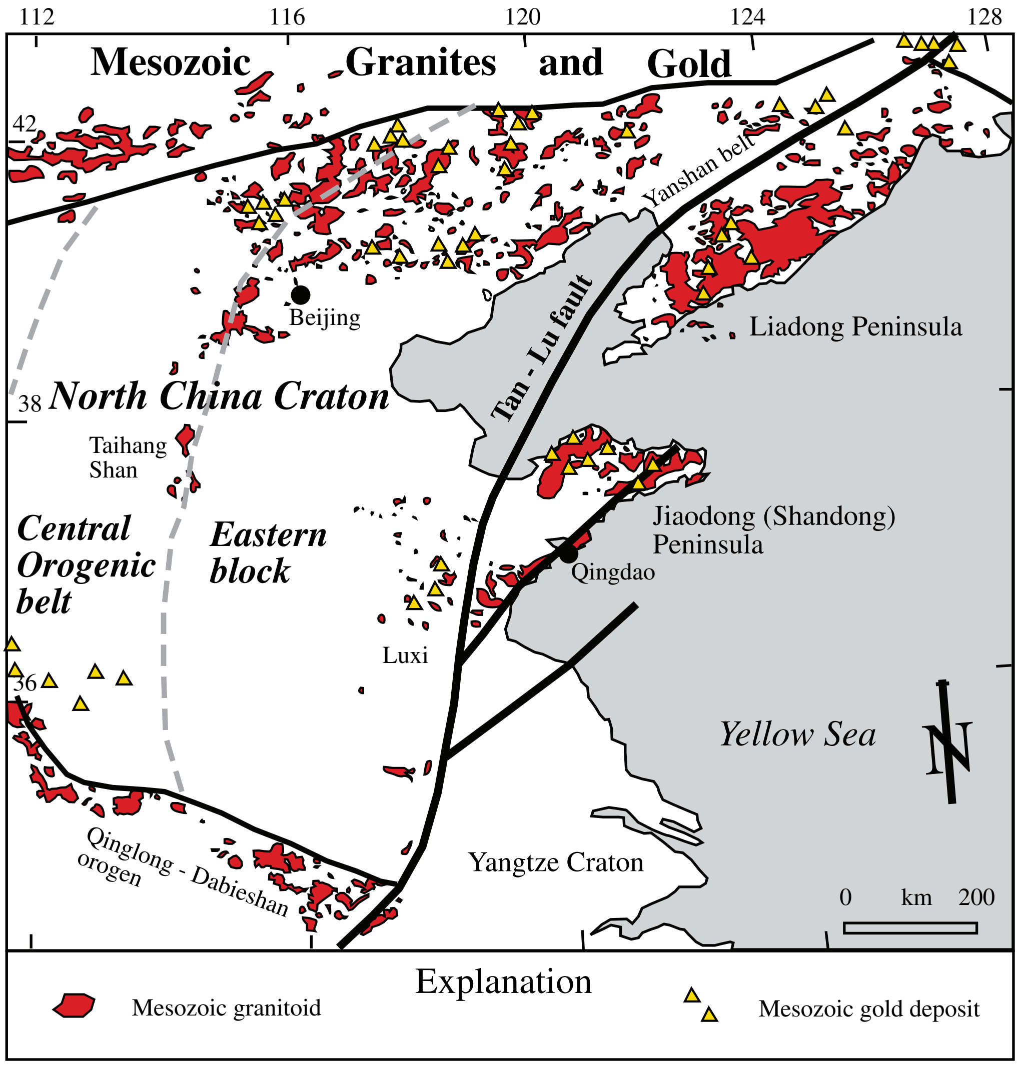

Fig. 4. Mesozoic gold and granite provinces of the NCC. (Note how the gold deposits and granites outline a ring around the Eastern Block of the craton (EB), suggesting that they may delineate the limits of the area of root loss.) Modified after Goldfarb *et al.* (2001), Hart *et al.* (2002), Zhou *et al.* (2002) and Wu *et al.* (2005). COB, Central Orogenic Belt.

(1) The timing of loss seems to be *c.* 140–120 Ma, based on the change in character of magmatism, structural evolution, basin formation, and types of xenoliths entrained in magmas and kimberlites.

(2) The timing of the loss is roughly coincident with and slightly younger than continent–continent collisions in the Dabie Shan–Su-Lu orogen in the south and along the Solonker suture in the north.

(3) Before root loss, the sub-continental lithospheric mantle experienced considerable hydration from dehydration reaction above subducting slabs. This might have caused significant hydration-related weakening of the sub-continental lithospheric mantle.

(4) The root loss seems to be associated with a change from contraction to extensional tectonics in the upper crust; thus, root loss may have triggered upper crustal extension, or upper crustal extensional collapse of thickened orogens may have been the final trigger for root loss.

(5) The boundary between parts of the sub-continental lithospheric mantle that were lost and were not lost is near the Archaean suture in the

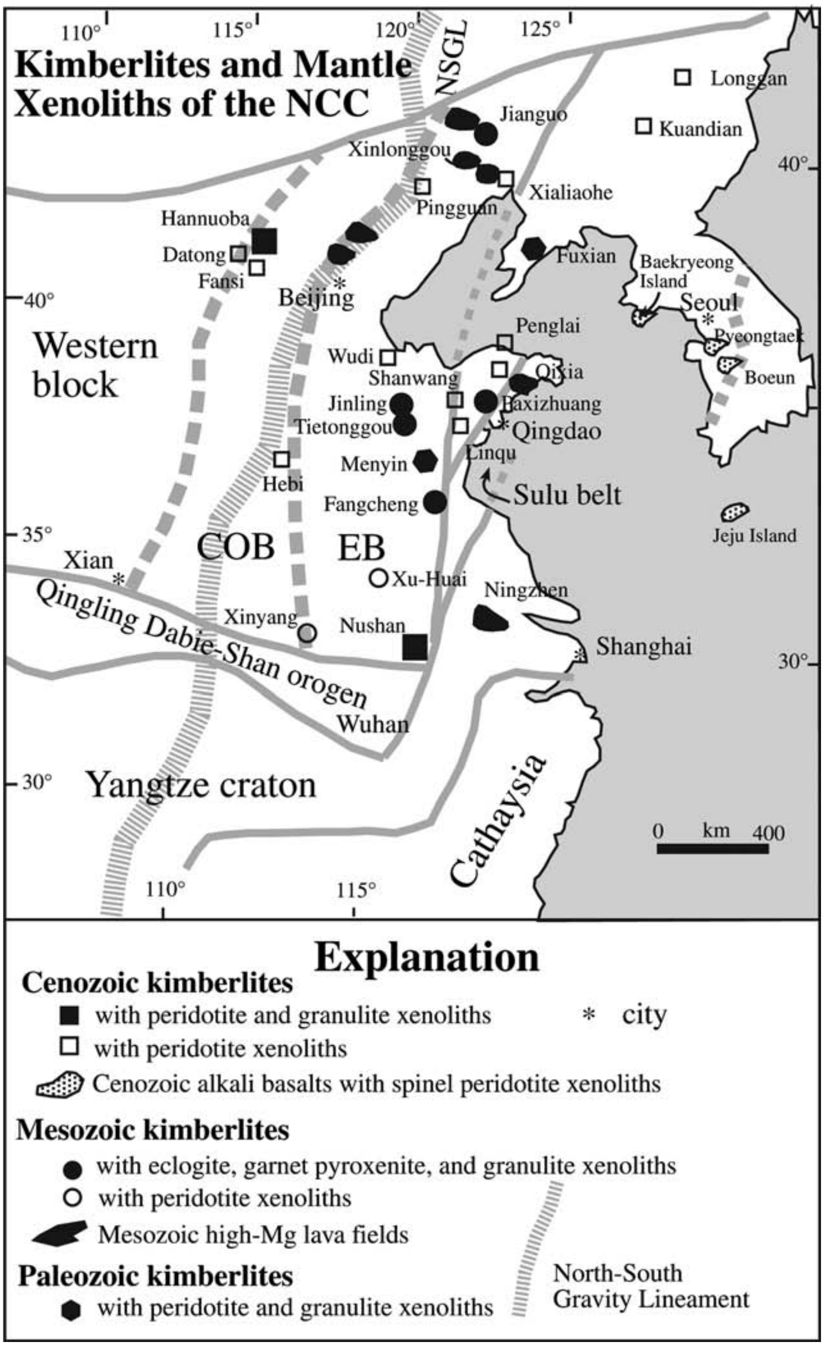

Fig. 5. Map of the eastern NCC showing distribution of kimberlites of different ages that contain mantle xenoliths.

Central Orogenic Belt, suggesting that some inherent difference in the root between the Eastern and Western Blocks may have led to the eastern side being lost whereas the western side was retained. Alternatively, the eastern side of the root may have been more greatly affected by

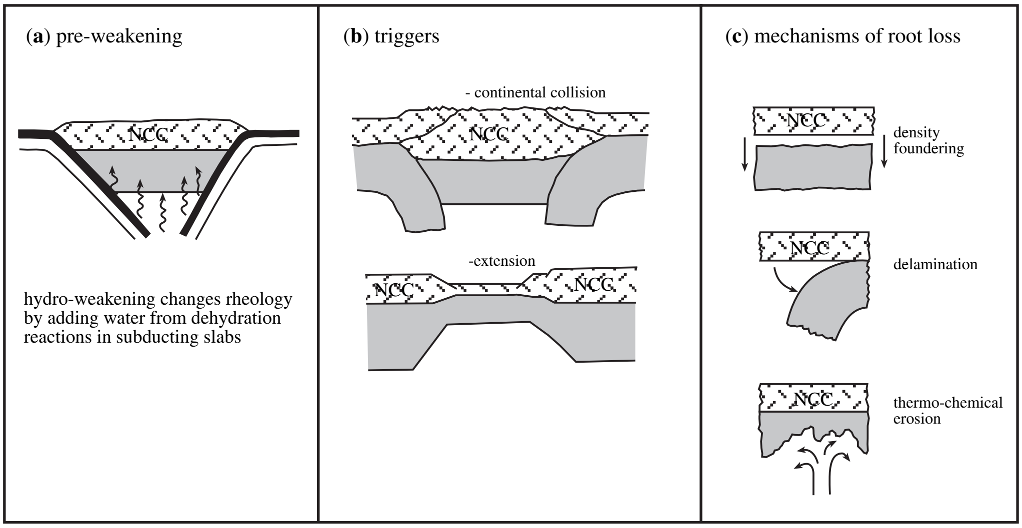

Fig. 6. Model showing mechanisms of root loss, and possible triggers for these mechanisms. Hydro-weakening may aid any of the mechanisms. Delamination and foundering may be triggered by collision, extension, or strike-slip faulting, and may in turn cause thermo-chemical erosion. Plume impingement may also independently cause thermo-chemical erosion.

Palaeopacific-related processes such as greater hydration (from the Pacific), leading to its preferential loss.

Hypotheses

Various hypotheses have been advanced in attempts to explain the cause of the loss of the lithospheric root beneath the NCC; these can be broken down into four general physical categories (Fig. 6), as follows.

(1) Mechanical disruption: this includes collision and rifting, both active and passive.

(2) Thermo-chemical erosion: upwelling asthenosphere in the mantle wedge erodes lithospheric keel incrementally.

(3) Density foundering or delamination: sinking of tectonically thickened lithosphere into convecting mantle.

(4) Hydro-weakening of the subcontinental lithospheric mantle by multiple subduction events pre-weakens root for delamination during younger collisions; hydration also lowers the melting temperature of the root, allowing easier extraction of a silicic melt phase, and thereby increasing the density of the root and favouring delamination.

Data presented in the papers in this volume provide some clues that help distinguish between these types of physical models. Understanding the timing of root loss and correlating this with regional tectonic and global (mantle) events helps differentiate between specific triggering mechanisms, and provides tests for further work. For instance, mechanical disruption of the lithospheric root, by collisional, strike-slip or other mechanical processes, should lead to the development of steep physical gradients related to tectonic boundaries, which themselves should show a relationship to surface tectonic features. In contrast, thermo-chemical erosion, if related to upwelling asthenosphere in the mantle wedge, may erode the mantle root incrementally, forming smooth boundaries. If the thermo-chemical erosion is related to arc- or slab-derived fluids, associated magmas should possess some subduction-like geochemical signature, and show a geometric relationship to subduction-zone, shallow gradients that may cut across crustal structures. However, if the thermo-chemical erosion were related to plume impingement (Wilde *et al.* 2003; Deng *et al*. 2004), we would expect sharp lithospheric boundaries to be truncated and smoothed by longer-wavelength plume-related mantle. These trends should be resolvable with future seismic, petrological and structural studies in the NCC.

Density foundering, or 'delamination' of tectonically thickened lithosphere might be sudden and simultaneous across a region the size of the Eastern Block of the NCC (e.g. Schott & Schmeling 1998). Such catastrophic loss of the mantle root should be detectable by the almost simultaneous responses across the eastern half of the craton, a pattern that has not yet been established or tested for.

Mantle weakening by hydration is able to work with the other mechanisms described above and contribute to the ability of the sub-continental lithospheric mantle to delaminate or be lost by other mechanisms (Fig. 6). When greenschist-grade oceanic lithosphere subducts, it hydrates the upper mantle. In the Western Pacific, where 90% of the world's small ocean basins are concentrated, subduction from the Pacific (westwards) combined with Indo-Australian (northwards) plates has doubled the amount of water transported to the mantle. The dual subduction of the Pacific and Indo-Australian plates has created a double-sided, triangular or Y-shaped zone, implying that double the amount of water has been transported into the mantle for a total at least 700 Ma, the combined length of time of subduction from the Pacific and Indo-Australian plates (Maruyama *et al.* 2004). Therefore double subduction allowed twice the amount of water to reach the transition zone under the marginal basins of the Western Pacific and under the North China Craton. Besides being subducted by the Pacific plate from the east and the Indo-Australian plate from the south, the Eastern Block of the North China Craton was affected by other subduction zones. The craton is surrounded by sutures that are the sites of former oceans that were subducted in all cases towards and under it; the Solonker suture on the immediate northern side, the Mongol–Okhotsk suture farther north in eastern Mongolia, the Qinling–Dabie Shan suture on the immediate southern side, and the Song Ma suture farther south in Indo-China.

The water in oceanic basalts is transported by subduction into the mantle transition zone and stored in nominally anhydrous minerals in hydrogen-related point defects, if the geotherm is cold enough (Maruyama 2003). Wadsleyite (β-Mg_2SiO_4; stable below 350 km) and ringwoodite (γ-dimorph of forsterite), the principal components of the transition zone, can contain up to 3.3 wt% and 2.2 wt% H_2O respectively (Smyth *et al.* 2003). If saturated, a transition zone containing 70 modal % wadsleyite could contain four times the amount of water in the Earth's hydrosphere, and would form the largest reservoir of hydrogen in the planet (Smyth & Frost 2002). Olivine, generally considered to be the most abundant mineral phase in the upper 400 km of the mantle, can store up to 2000 ppm by weight of H_2O at 13 GPa and 1100 °C (Smyth *et al.* 2003). The major cause of the 410 km seismic discontinuity at the top of the transition zone is believed to be the reaction of olivine to modified spinel, and modified spinel can store up to 3.1 wt% H_2O at 15.5 GPa (Inoue *et al.* 1995). Thus it is generally considered that water in a subducting slab would react with olivine to form hydrous modified spinel that would transport considerable amounts of water into the transition zone (Inoue *et al.* 1995).

This mantle hydration lowered the mantle viscosity, and lowered the melting temperature of the mantle to promote magmatic activity. Perhaps the hydro-weakening of the upper mantle has allowed fragmentation of the oceanic lithosphere and the formation of multiple micro-plates. The small ocean basin basalts are 0.2 wt% richer in water than normal mid-ocean ridge basalt (MORB); this lowers the solidus temperature by 150 °C. At 200 km depth addition of 0.2% water lowers the melting temperature (solidus) by 500° (Maruyama *et al.* 2004). Only 100–1000 ppm addition of water decreases mantle viscosity by about two orders of magnitude (Maruyama *et al.* 2004; Niu 2005; Windley *et al.* 2005). Stored water in hydrous wadsleyite and ringwoodite at 410–660 km depth would become unstable with time as a result of conductive heating from underlying lower mantle (Maruyama *et al.* 2004; Niu 2005; Windley *et al.* 2005), and would eventually decompose into anhydrous phases to release free water, which would result in mantle melting and hydrous plumes. This was possibly the principal cause of the fragmentation of the oceanic lithosphere in the Western Pacific.

Hydro-weakening by the cumulative effects of subduction has the potential to work with some of the other mechanisms described above to contribute to root loss beneath the NCC. The sub-continental lithosphere under Eastern China has been subjected to subduction of both the Pacific and the Indo-Australian plates for *c.* 150 Ma and *c.* 550 Ma, respectively, but also to northwards subduction on the site of the Dabie Shan suture for *c.* 500 Ma (Sengör & Natal'in 1996; Ratschbacher *et al.* 2003; Oh & Kusky 2006) and to southwards subduction on the site of the Solonker suture (in Inner Mongolia) for *c.* 250 Ma (Xiao *et al.* 2003). The total length of slabs subducted under Eastern China in the last 150 Ma is *c.* 18 000 km, which is more than twice that subducted under any other area of the circum-Pacific. Clearly more oceanic lithosphere has been subducted under Eastern China than under any other part of the continents; this probably contributed to the ability of the NCC to lose its root. Accordingly, the multiple subduction must have excessively hydro-weakened the upper mantle under Eastern China. However, it did not cause the break-up of the continental lithosphere into several micro-plates. In contrast, the hydro-weakened mantle, being the keel of the eastern half of the Archaean North China Craton, apparently responded by delamination. A question remains: was there a tectonic mechanism that triggered the delamination? Considering that the most likely time of delamination was in the Cretaceous, tectonic forcing by orogenic collapse at the southern and northern ends of the delaminated zone provides a viable mechanism. Both the

Dabie Shan and Solonker orogens underwent massive Himalayan-style collisions, and intense post-collisional thrusting during the Jurassic (Hacker *et al.* 2000; Xiao *et al.* 2003; Li *et al.* 2006). Extensional collapse of the thrust-thickened lithosphere of these orogens could have triggered the delamination of the hydro-weakened lithosphere situated between them. In the case of the Solonker orogen the thrusting was accompanied by widespread granitic magmatism in the Jurassic, which was followed by the formation of many metamorphic core complexes in the Cretaceous, and crustal-scale extension in Eastern China gave rise to the many sedimentary basins, including the North China basins on top of the delaminated zone in the eastern North China Craton. If this were the mechanism responsible for the delamination in the Cretaceous, new fertile asthenosphere would have risen into the foundered zone of the upper mantle, and would have given rise to many alkali basalts and possibly some barren kimberlites in the Cenozoic.

Hypothesis testing

Below, we propose tests of these and other related hypotheses, by dividing the models into their main characteristics that should produce features that are resolvable with future studies. Table 1 shows these hypotheses and their likely manifestation in terms of observables. The main observable features of the sub-continental lithospheric mantle will be seismic properties, mantle samples from xenoliths, melts and fluids from mantle-derived magmas, and surface structural and topographic responses to changing mantle thermal and density conditions. Elsewhere in this volume (Kusky *et al.* 2007) we outlined some of the main tectonic events in the crust that may relate to formation and loss of the root, and other papers have described detailed aspects of igneous, sedimentary, structural, hydrothermal and tectonic processes that may be related to root loss, and geophysical tests of the deep structure. Further work is needed to test these links, and it is clear that an integrated multidisciplinary programme is needed to further understand root loss beneath the NCC.

Conclusions

The North China Craton is the best-known place in the world where a craton grew a sub-continental lithospheric root in the Archaean then lost part of

Table 1. *Specific hypotheses that have been advanced to explain root loss, and their tests*

Model and proponents	Tests of model
Regional extension and rifting caused mechanical dispersal of old, cold mantle and caused upwelling of new hot asthenosphere (Yuan 1995; O'Reilly *et al.* 2001)	New lithosphere would be present only beneath rifts, and ancient root would still be present as intra-rift 'islands'; these ancient relicts may be detected from both xenolith and seismic tomographic investigations
Convective overturn (upwelling?) accompanying Jurassic–Tertiary subduction of Pacific plate (Griffin *et al.* 1998); subduction of the Pacific plate caused plume-like upwelling (Deng & You 1985)	Root loss should occur in zones related to subduction geometry
Collision of NCC and Yangtze Cratons (Griffin *et al.* 1998; Gao *et al.* 2002), Solonker block and northern margin of NCC	Timing should be shortly after collision
Subduction under Dabie Shan and Mongol–Okhotsk regions caused destabilization, thinning and replacement of lithospheric mantle in the Mesozoic followed by new underplating in the Cenozoic (Zhang, H. F. *et al.* 2003)	This mechanism may work independently, or may 'pre-weaken' mantle root preparing it for loss in later events such as collisions
Active rifting as a result of plume impingement	If plume related, gradients will be smooth and may cut across all tectonic boundaries
Thinning during Gondwana fragmentation, subduction, mantle overturn, downwelling and mantle delamination (Wilde *et al.* 2003)	Boundaries should be diffuse between lost and retained keel; timing should correlate with break-up; chemistry of basalts should be plume-like
Collision of India and Asia (Menzies *et al.* 1993)	Timing should be post-collision

this root in Phanerozoic tectonism (Marotta *et al.* 1998; Meisner & Mooney 1998). Understanding of the processes of root formation and loss is in its infancy, yet some salient points appear relevant. First, the root of the North China Craton was apparently formed during initial formation of the craton between 3.8 and 2.5 Ga, with roots of different character forming beneath the Eastern and Western Blocks, which collided at 2.5 Ga (Kusky 2001, 2004; Li & Kusky 2006). A major continent–continent collision at 1.85 Ga on the north margin of the craton significantly modified the root, and locally replaced part with Paleoproterozoic mantle (Kusky & Li 2003).

The North China Craton was surrounded by subduction zones for much of the Palaeozoic and Mesozoic. Dehydration reactions in these slabs released fluids that significantly hydrated the mantle above the subduction zones (the root of the NCC), changing the rheology of the mantle root and causing significant hydration-related weakening. The idea that subduction of water into the mantle caused hydro-weakening of the sub-continental lithosphere and was responsible for the thinning–delamination under the Eastern block of the North China Craton came independently from Niu (2005) and Windley *et al.* (2005). However, whereas Niu (2005) considered that subduction by the Pacific plate was sufficient to carry water to the upper mantle, Windley *et al.* (2005), building on the ideas of Maruyama *et al.* (2004) and Komiya & Maruyama (2006) of double subduction, as summarized above, extended the process to include the subduction zones sited on the Solonker, Dabie Shan and Mongol–Okhotsk sutures.

Some Western Pacific marginal basins physically link with onshore areas in Eastern China underlain by thinned lithosphere, demonstrating a probable genetic relationship between the processes of hydration of the mantle transition zone responsible for formation of the marginal basins, as outlined above, and the processes that gave rise to the thinning of sub-continental lithosphere. The most prominent example is the Bohai Basin, the initial extension of which began in the Palaeocene, probably triggered by subduction roll-back of the oceanic Pacific plate (Allen *et al.* 1997). Extension continued until the end of the Oligocene (Zhao & Zheng 2005). Within Eastern China the Bohai Basin is an area with thickest Cenozoic sediments (4000–7000 m; Allen *et al.* 1997), the highest surface heat flow 1.8–2.0 heat-flow units (hfu), Ma 1987), and thinnest lithosphere (50–60 km; Ma 1987).

Major continent–continent collisions on the southern and northern margins of the craton in the Mesozoic may have mechanically triggered the loss of the hydration-weakened lithospheric root, triggering massive replacement of the sub-continental lithospheric mantle with new fertile mantle in the late Mesozoic and Cenozoic. The tectonic style in the crust changed at this time, from contraction to extension, and the processes of root loss and tectonic regime seem intimately related, although cause and effect have yet to be separated.

We propose that post-collision thrusting in the Jurassic in the Dabie, Solonker and Mongol–Okhotsk orogens triggered collapse by the early Cretaceous of the hydro-weakened and eclogitized crustal roots of these orogens, which in turn triggered delamination of the intervening sub-continental lithosphere that itself had been hydro-weakened. Replacement, either physically or chemically, by fertile asthenosphere in the Cenozoic led to extrusion of extensive alkali flood basalts throughout the Eastern Block of the North China Craton and in the Songliao Basin to the north.

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