Destruction of the North China Craton: a perspective based on receiver function analysis

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The North China Craton (NCC), which is composed of the eastern NCC and the western NCC sutured by the Palaeoproterozoic Trans-North China Orogen, is one of the oldest continental nuclei in the world and the largest cratonic block in China. The eastern NCC is widely known for its significant lithospheric thinning and destruction during the Late Mesozoic. Models on the destruction of the eastern NCC can be principally grouped into two: (1) thermal/mechanical and/or chemical erosion, and (2) lower crustal and (or) lithospheric delamination. The erosion model suggests that the NCC lithospheric thinning resulted from chemical and/or mechanical interactions of lithospheric mantle with melts or hydrous fluids derived from the asthenosphere, whereas the delamination model proposes lithospheric destruction through foundering of eclogitic lower crust together with lithospheric mantle into the underlying convecting mantle. However, those models lack seismic evidence to explain the destruction process. Here, we analyse the crustal structure and upper mantle discontinuity by employing the H–k stacking technique of receiver function as well as the depth domain receiver function. Our results indicate deep mantle upwelling and lower crustal delamination beneath the eastern NCC, and suggest that either or both of these processes contributed to the unique lithospheric thinning and destruction of the eastern NCC. © 2013 The Authors. Geological Journal published by John Wiley & Sons, Ltd.

KEY WORDS receiver function; crustal structure; upper mantle discontinuity; upwelling mantle plume; lower crustal and lithospheric delamination; North China Craton

1. INTRODUCTION

The North China Craton (NCC) refers to the Chinese part of the Sino-Korean Platform, comprising a triangular region covering approximately 1 500 000 km², and bound by faults and younger orogenic belts. The Early Palaeozoic Qilianshan Orogen and the Late Palaeozoic–Late Mesozoic Central Asian Orogenic Belt bound the craton to the west and the north, respectively (Ren et al., 1987; Zorin et al., 2001; Zhao et al., 2001; Xiao et al., 2013). To the south, the craton is bordered by the Qinling–Dabie–Sulu ultrahigh-pressure metamorphic belt that separates the NCC from the Yangtze Craton (Yang et al., 2003; Wu and Zheng, 2013; Santosh and Somerville, 2013).

The NCC is composed of two major Precambrian blocks, the eastern and western NCC, sutured along a Palaeoproterozoic collision zone known as the Trans-North China Orogen (central NCC) (Zhao et al., 2001, 2005, 2012; Zhai and Santosh, 2011; Zhao and Zhai, 2013; Zheng et al., 2013). The eastern NCC has undergone significant tectono-thermal reactivation and destruction with a dramatic change in lithospheric architecture during the Ordovician to the Cenozoic (Chen, 2010). Recent evidence gathered from geological and geophysical studies confirm that the Eastern Block of the NCC has lost a considerable part of its lithospheric keel (Zhang, 1993, 2007; Cope and Graham, 2007; Li et al., 2007; Gao et al., 2008; Wu et al., 2008; Xu and Zhao, 2009; Zheng et al., 2009; Chen, 2009; Santosh, 2010).

Models on the destruction of the eastern NCC can be principally grouped into two: (1) thermal/mechanical and/or chemical erosion (e.g. Menzies et al., 1993; Deng et al., 1994; Zheng et al., 1998); and (2) lower crustal and (or) lithospheric delamination (Deng et al., 1994; Gao et al., 1998; Xu et al., 2002; Ling et al., 2009). The erosion model suggests that the thinning of the NCC lithosphere resulted from chemical and/or mechanical interactions of lithospheric mantle with melts or hydrous fluids derived from the
asthenosphere. The delamination model proposes that the destruction of the lithosphere was caused by foundering of eclogitic lower crust together with lithospheric mantle into the underlying convecting mantle (Ling et al., 2009). However, the processes of erosion and delamination remain controversial and lack robust evidence from seismic investigation.

The depth domain receiver function can effectively delineate the 410 and 660 km interfaces, and 410 and 660 km discontinuity topography displays the thermal state of the upper mantle from which any upwelling mantle plume from the lower mantle can be tracked (e.g. Chen and Ai, 2009; Huerta et al., 2009; He, 2010). The \( H-k \) stacking technique can be used to derive the thickness and the average composition of the continental crust, which in turn is used to estimate the composition of the lower crust and its geodynamic implications (Zandt and Ammon, 1995, Christensen, 1996; Niu and James, 2002; Nair et al., 2006; Thompson et al., 2010; He et al., 2013a, 2013b). In this study, we analyse the crustal and upper mantle structure by employing the \( H-k \) stacking technique (Zhu and Kanamori, 2000) and depth domain receiver function (Yuan et al., 1997), and address their dynamics implications. Based on the results, we suggest an integrated model for the cratonic destruction of the eastern NCC.

2. METHODS AND DATA

This study performs a careful analysis of the receiver functions in the NCC, in order to characterize the bulk seismic properties of the crust with local estimates for the crustal thickness and \( V_p/V_s \) ratio (Zandt and Ammon, 1995; Zhu and Kanamori, 2000). For this purpose, we apply the stacking procedure of Zhu and Kanamori (2000) to 314 seismic stations located in the NCC (Fig. 1). These stations have been in operation from July 2008 to the present-day by the China Earthquake network (Zheng et al., 2010). We selected a total of 441 events with magnitude \( m_b \geq 5.8 \) recorded by those stations (Figs. 1 and 2 and Supplementary Table S1). For each event–station pair, data were selected within the ranges of 30°–95° with reasonable back azimuth coverage and initially windowed 15 s before and 120 s after the \( P \)-wave pick.
Data are filtered using a zero-phase Butterworth bandpass filter with corner frequencies of 0.03–3 Hz (or 0.05–1 Hz for upper mantle discontinuity study). We then used a modified frequency domain deconvolution (Langston, 1979; Owens et al., 1984; Zhu and Kanamori, 2000), and the Gaussian factor and water level were set to 3 and 0.01 (or 1 and 0.01 for upper mantle discontinuity study), respectively.

The stacking is usually done in the time domain for a cluster of events (Owens et al., 1984; Zhu and Kanamori, 2000). Here we chose unequal weights (0.6, 0.3 and 0.1) for $Ps$, $PpPs$ and $PpSs+PsPs$ phases of the Moho, respectively. Using the Taylor expansion at the maximum and omitting the higher-order terms to quantitatively estimate the uncertainty (Zhu and Kanamori, 2000) of our results, we measured error bars for $h$ and $\kappa$, which line up with longitude, by taking into account uncertainties (Fig. 3). We also show two examples of $H$–$k$ stacking computed at two stations located at the NCC (Supplementary Fig. S1).

Generally, each amplitude on the radial receiver function is produced by a primary $P$-to-$S$ conversion at some depth. Depth is determined by the time delay of the amplitude with respect to the direct $P$ using the 1D IASP91 velocity model (Kennett and Engdahl, 1991). Based on it, we converted the time domain receiver functions into the depth domain after corrections for the incidence angle effect (correcting the move out of $Ps$ conversions to the same incidence or near vertical incidence) (Yuan et al., 1997). By stacking all depth domain receiver functions from different back azimuths at each station respectively, we obtain the average receiver function at each station (Owens et al., 1984). The average receiver function can clearly delineate the upper mantle discontinuity (Zhu, 2000) (Supplementary Fig. S2).

3. CRUSTAL THICKNESS AND $Vp/Vs$ RATIO

The crustal thickness of the NCC identified by this study shows a gradual increase in a northwestward direction from 32 to 48 km (Fig. 3a, Fig. 4, arrow a) and in a westward direction in the western part (outside the NCC) (Fig. 4, arrow b). The central and southern parts of the eastern NCC display a flat Moho interface with a crustal thickness of 32–34 km (Fig. 4). Wei et al. (2013) also obtained similar results in this area.
Subduction and collision tectonics may generate local topography on the Moho which may survive for a long time after cessation of the collision and subduction (Cook et al., 2000; Balling, 2000). Stable continental structures can exist over long periods of time (>1.5 Ga) (e.g. de Smet et al., 1998). The dipping Moho topography is considered as an indication of the remnants of collision and deep subduction (Svenningsen et al., 2007). In the Late Mesozoic, only the Kula Plate was rapidly moving north-northwest and was subducting beneath the Eurasian continent (e.g. Hilde et al., 1977; Lee et al., 2005; Hou et al., 2009) with a shallow dipping Benioff zone (Menzies et al., 2007). Therefore, we regard that our results provide a robust image of the fossil architecture of the Kula Plate subducting beneath the NCC.

The bulk Vp/Vs ratio identified in this study shows higher values for the regions in the northern part of the eastern NCC and the Trans-North China Orogen (>1.76) (Fig. 5), as well as in the southern part of the western NCC, suggesting an intermediate to mafic/ultra-mafic lower crust in these areas (Zandt and Ammon, 1995; Thompson et al., 2010; He et al., 2013b). Compared to the northern part, the bulk Vp/Vs ratio is lower (mostly between 1.76 and 1.74 or <1.74) at the central and southern parts of the eastern NCC (Fig. 5), which imply an intermediate to felsic lower crust in this area (Zandt and Ammon, 1995; Chang and Baag, 2007; He et al., 2013a).

4. 410 AND 660 km UPPER MANTLE DISCONTINUITIES

Our results show a significant deepening of the 410 km discontinuity beneath the northern part of the Trans-North China Orogen and the eastern NCC (410 km discontinuity >400 km) (Fig. 6). A similar feature is also observed for the 660 km discontinuity (Fig. 7) (660 km discontinuity >655 km) in these regions. The average values for the depth of the 410 and 660 km discontinuities in this area are around ~406 and ~651 km respectively, both of which are lower than the global average values.

Investigations on the deepening of both the 410 and 660 km discontinuities have correlated the feature with a phase transition from majorite garnet to perovskite at 660 km depth (e.g. Deuss et al., 2006; Huerta et al., 2009), characterized by positive pressure–temperature gradients (the Clapeyron slope is positive). Therefore, when influenced by a mantle plume (or upwelling mantle), both the 410 and 660 km discontinuities would display deepening. A similar 660 km discontinuity feature has been observed in other regions, such as beneath Sri Lanka, western North America, West Yunnan and Northeast China (Pathak et al., 2006; Houser and Williams, 2010; He, 2010; He et al., 2013b).

Elevated temperature is predicted to deepen the 410 km discontinuity from its global average value by ~8 km/100 °C. For a plume with a 200–300 °C temperature anomaly, a downward deflection of ~15–25 km is expected (Foulger, 2012). Our results indicate a significant deepening of both the 410 and 660 km discontinuities by around 15 km. We regard this feature as an indication of the vestige of an upwelling mantle plume. Upwelling of the mantle provides a reasonable explanation for this topography of the upper mantle discontinuities in this area.

The mantle plume has a large diameter of around 500 km or more (Albers and Christensen, 1996). Seismic tomography shows that a possible mantle upwelling exists between longitude 110–120°E and latitude 34–44°N (Liu and Chang, 2001; Zhao and Zheng, 2005). In another study, Liang et al. (2004) suggested a thermal mantle ‘dome’ in the NCC based on the results for Pn velocity inversion. This location is consistent with our proposed region for the upwelling mantle plume. We consider that these geophysical images record the state of the Mesozoic mantle beneath this region (Zhai et al., 2007).

5. DISCUSSION

From west to east in the NCC, the thickness of continental lithosphere varies from 200–250 km in the Ordos Basin to 100–150 km in the Taihang Mountains to 60–100 km in the...
northern part of the North China Platform (Q.L. Yang et al., 2012). The thickness is >60 km in the Shandong Peninsula and Bohai Basin (Q.L. Yang et al., 2012). Some workers argue that the process of thinning of the cratonic lithospheric mantle beneath the NCC may be associated with the low-angle subduction of the Kula or Pacific plates beneath the eastern part of the NCC (Q.L. Yang et al., 2012; Li et al., 2012; Zhai et al., 2007). However, our studies show that the Kula Plate subducted far into the NCC (Fig. 4, arrow a), and in this case, there is no reason why only the eastern part of the NCC was affected, preserving the keel beneath the western NCC. We therefore exclude the model of low-angle subduction of the Kula or Pacific plates as a major factor for the lithospheric thinning and destruction of the NCC.

Because of the smaller size of the craton, as compared to the other large cratons on the globe, the NCC may have been more easily affected by subduction and collision of the surrounding blocks (Zheng et al., 2007). The Cenozoic tectonic evolution of East China is generally correlated to the collision between the Indian and Eurasian plates (J.Z. Liu et al., 2004; M. Liu et al., 2004), as well as the subduction of the Pacific Plate beneath the Eurasian Plate (Deng et al., 1996; Allen et al., 1997). The culmination of the decratonization of the NCC has also been related to an eastward jump of Cenozoic subduction of the Pacific Plate and the far-field effect of eastward extrusion of Cenozoic subduction of the Indian Plate (Li et al., 2012).

After the cessation of the Kula Plate subduction, the Pacific Plate moved northward and subducted beneath the Eurasian Plate since 53 Ma, with an E to W trend (e.g. Zhang et al., 2003; Parés and Moore, 2005). The shear wave splitting measurements also show a fossil architecture with an E–W trending deformation in the NCC (Zhao and Zheng, 2005). Our results demonstrate that the westward crustal thickening in the western part of the area (outside the NCC) (Fig 4, arrow b), might have been directly influenced by the east to west compression, possibly related to the Pacific Plate

Figure 4. Distribution of crustal thickness in North China (see Supplementary Table S2). Arrow a: the gradual increase in crustal thickness in a northwestward direction in the NCC. Arrow b shows the gradual increase in crustal thickness in a westward direction beneath the western region of this area (outside the NCC).

Central and southern parts of the eastern NCC show a flat Moho interface. This figure is available in colour online at wileyonlinelibrary.com/journal/gj

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subduction. Therefore, the eastward extrusion of Cenozoic subduction of the Indian Plate and westward compression of the Pacific Plate might have led to lower crustal delamination (Kay and Kay, 1993) in this area.

The central and southern parts of the eastern NCC with the flat Moho interface and the felsic-intermediate lower crust is markedly different to the other regions in the eastern NCC (Figs. 4 and 5), which suggest that this area underwent lower crustal delamination (Christensen, 1996; Zandt and Ammon, 1995; He et al., 2013a). The delamination resulted in the flat Moho interface following the low-angle subduction of the Kula Plate. This process also led to the upper lithospheric delamination (Kay and Kay, 1993). When lower crustal delamination occurs, the asthenospheric mantle would rise into and above the level of the lithosphere. Once this happens, the lithosphere will peel away and sink (Stern, 2004). Eventually, the lower crustal and (or) lithospheric delamination (Z.J. Zhang et al., 2012) would result in lithospheric thinning and craton destruction (Zhang et al., 2011).

However, it is difficult for the delamination process to act on the whole eastern NCC and remove a domain as thick as 80–120 km of the lithosphere. Lower crustal xenoliths in Mesozoic and Cenozoic basalts within the NCC are of two types (Zhai et al., 2007), suggesting that a hot and fertile lithosphere has replaced the earlier cratonic keel. The regional synthesis suggests that Mesozoic–Cenozoic lithospheric thinning and mantle replacement was heterogeneously distributed across the NCC in space and time (Zhang et al., 2007). Moreover, it has been generally assumed that delamination is a large-scale process that occurs rapidly (Zhang et al., 2011). Evidence presented in previous studies suggests that destruction of the eastern NCC is probably diachronous (Xu, 2007; Yang et al., 2010).

It has been inferred that westward subduction of the Pacific Plate has played the first-order role in thinning the lithosphere of the NCC (Zhang et al., 2009). It is possible that both the mechanical delamination and thermo-chemical erosion served only as the second-order mechanisms for the lithospheric thinning (Zheng and Wu, 2009).

Figure 5. Distribution of Vp/Vs ratio in North China (see Supplementary Table S2). Central and southern parts of the eastern NCC are characterized by a felsic and intermediate lower crust, whereas the northern part of the Trans-North China Orogen and the eastern NCC have an intermediate to mafic/ultra-mafic lower crust. This figure is available in colour online at wileyonlinelibrary.com/journal/gj

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The upwelling mantle plume can lead to the lower crust underplating and the formation of a mafic/ultramafic lower crust (Pirajno, 2007; Zandt and Ammon, 1995; He et al., 2013b). The mafic and ultra-mafic lower crust partially overlaps with the deepened region of 410 and 660 km discontinuities, as identified by this study in the northern part of the Trans-North China Orogen and the eastern NCC, confirming an upwelling mantle plume and magma underplating. The P-wave velocity and density in the lowermost crust beneath this area are significantly higher than the surrounding region, suggesting a deep process of lower crustal underplating (Z.J. Zhang et al., 2012, 2013). A comprehensive synthesis of the U–Pb geochronology and Hf isotopes of Phanerozoic zircons reveal plume-induced widespread and episodic magma underplating into the ancient lower crust of the NCC (H.F. Zhang et al., 2013). The basalt-borne xenoliths and geophysical observations reveal a higher heat flow value (~65 mW/m²) in the eastern NCC from the Cenozoic to the present-day (e.g. Chen et al., 1991; Menzies et al., 1993; Griffin et al., 1998; Fan et al., 2000; Xu, 2001; Zhu et al., 2002; Huang et al., 2003; Wu et al., 2005; Chen et al., 2006, 2008; Chen, 2010). These data also support deep mantle upwelling and lower crustal underplating in this region (Stel et al., 1993).

Recent studies on the sedimentation history of major basins in the NCC have revealed that the western Shandong–Bohai Bay basins, the western Liaoning basins, and the Xishan Basin to the west of Beijing received some detritus from the southeastern Central Asian Orogenic Belt (CAOB) in the Late Triassic–Jurassic (Yang et al., 2006; Meng et al., 2010; Li et al., 2013). These results suggest that the eastern NCC must have witnessed a regional subsidence rather than uplift in the Jurassic–Early Cretaceous interval (Li et al., 2013; Li, 2013). The subsidence might be attributed to thermo-chemical erosion of the lithosphere by the underlying convective mantle (e.g. Menzies et al., 1993; Griffin et al., 1998; Xu, 2001; Li et al., 2013).
Widespread intraplate magmatism occurred during the Mesozoic in the NCC (D.B. Yang et al., 2012). Menzies and Xu (1998) and Xu (2001) emphasized the importance of thermo-mechanical erosion from the base of the lithosphere and subsequent chemical erosion resulting from asthenosphere upwelling. Deng et al. (2004) correlated the thermal erosion to the mantle plume activity (Zhang et al., 2007). Associated with lithospheric thinning is upwelling of the convective asthenosphere and modification of the thermal structure of the lithosphere (Xu et al., 2009).

Destruction of the eastern and northern parts of the NCC likely started during the Early Mesozoic (Han et al., 2004; Yang and Wu, 2009; Yang et al., 2007, 2010; Zhang et al., 2009), with the lithospheric destruction initiated at the northern and eastern margins (Zhang et al., 2009; S.H. Zhang et al., 2012). This inference is consistent with the location of the proposed upwelling mantle plume. Therefore, we suggest that the lithospheric thinning in the eastern NCC is also related to thermal erosion caused by an upwelling mantle, or plume in this area.

6. CONCLUSIONS

The Kula Plate subduction beneath the NCC with a low-angle Benioff zone is excluded as a major factor for the lithospheric thinning of the eastern NCC. An upwelling mantle or plume might have existed beneath the northern part of the Trans-North China Orogen and the eastern NCC, which resulted in magmatic underplating beneath the lower crust in this area. The westward subduction of the Pacific Plate and resultant compression led to lower crustal and (or) lithospheric delamination in the central and southern parts of the eastern NCC. Eventually, both upwelling mantle plume and lower crust and (or) lithospheric delamination resulted in lithospheric thinning and craton destruction in the eastern NCC.

ACKNOWLEDGEMENTS

We thank Editor Prof. Ian D. Somerville and two anonymous referees for their constructive comments which
greatly helped us in preparing the revised version of this manuscript for resubmission. Financial support is provided by National Nature Science Foundation of China (41174081) and SinoProbe-Deep Exploration in China (SinoProbe-08). This study also contributes to the 1000 Talent Award to M. Santosh from the Chinese Government. Waveform data for this study are provided by Data Management Centre of China National Seismic Network at the Institute of Geophysics, China Earthquake Administration.

REFERENCES

Albers, M., Christensen, U.R. 1996. The excess temperature of plumes rising from the core-mantle boundary. Geophysical Research Letters 23, 3567–3570.

Allen, M.B., Macdonald, D.I.M., Zhao, X., Vincent, S.J., Brunet-Menzies, C. 1997. Early Cenozoic two-phase extension and late Cenozoic thermal subsidence and inversion of the Bohai Basin, North China. Marine Petroleum Geology 14, 951–972.

Balling, N. 2000. Deep seismic reflection evidence for ancient subduction and collision zones within the continental lithosphere of northwestern Europe. Tectonophysics 329, 269–300.

Chang, S.J., Baag, C.E. 2007. Moho depth and crustal Vp/Vs variation in Southern Korea from teleseismic receiver functions: implication for tectonic affinity. Bulletin of Seismological Society America 97, 1621–1631.

Chen, L. 2009. Lithospheric structure variations between the eastern and central North China Craton from S- and P-receiver function migration. Physics of the Earth and Planetary Interiors 173, 216–227.

Chen, L. 2010. Concordant structural variations from the surface to the base of the upper mantle in the North China Craton and its tectonic implications. Lithos 120, 96–115.

Chen, L., Ai, Y.S. 2009. Discontinuity structure of the mantle transition zone beneath the North China Craton from receiver function migration. Journal of Geophysical Research 114, B06307. DOI: 10.1029/2008JB006221.

Chen, G.Y., Song, Z.H., An, C.Q., Cheng, L.H., Zhuang, Z., Fu, Z.W., Lu, Z.L., Hu, J.F. 1991. Three dimensional crust and upper mantle structure of the North China region. Acta Geophysical Sinica 34, 172–181 (in Chinese with English abstract).

Chen, L., Zheng, T.Y., Xu, W.W. 2006. A thinned lithospheric image of the Tanlu Fault Zone, eastern China: constructed from wave equation based receiver function migration. Journal of Geophysical Research 111, B09312. DOI: 10.1029/2005JB003974.

Chen, L., Wang, T., Zhao, L., Zheng, T.Y. 2008. Distinct lateral variation of lithospheric thickness in the Northeastern North China Craton. Earth and Planetary Science Letters 267, 56–68.

Christensen, N. 1996. Poisson’s ratio and crustal seismicity. Journal of Geophysical Research 101, 3139–3156.

Cook, F.A., Velden, A., Hall, K.W., Reberts, B.J. 2000. Frozen subduction in Canada’s Northwest Territories: lithoprobe deep lithospheric reflection profiling of the western Canadian Shield. Tectonics 18, 1–24.

Cope, T.D., Graham, S.A. 2007. A upper crustal response to Mesozoic tectonism in the western Liaoning, North China, and implication for lithospheric delamination. In: Mesozoic Sub-Continental Lithospheric Thinning Under Eastern Asia, Zhai, M.G., Windley, B.F., Kusky, T.M., Meng, Q.R. (eds). Geological Society, London, Special Publications, 280, 201–222.

Deng, J.F., Mo, X.X., Zhao, H.L., Luo, Z.H., Du, Y.S. 1994. Lithospheric root/derooting and activation of the East China continent. Geoscience-Journal of Graduate School, China University of Geosciences 8, 349–356 (in Chinese with English abstract).

Deng, J.F., Zhao, H.L., Mo, X.X., Luo, Z.H. 1996. Continental Roots-Plume Tectonics of China-Key to the Continental Dynamics. Geological Publishing House: Beijing; 1–96.

Deng, J.F., Mo, X.X., Zhao, H.L., Wu, Z.X., Luo, Z.H., Su, S.G. 2004. A new model for the dynamic evolution of Chinese lithosphere: “continental roots–plume tectonics”. Earth-Science Reviews 65, 223–275.

Deuss, A., Redfern, S.A.T., Chambers, K., Woodhouse, J.H. 2006. The nature of the 660-kilometer discontinuity in Earth’s mantle from global seismic observations of PP precursors. Science 311, 198–201.

Fan, W.M., Zhang, H.F., Baker, J., Jarvis, K.E., Mason, P.R.D., Muenzies, M.A. 2000. On and off the North China Craton: where is the Archaean keel?. Journal of Petrology 41, 933–950.

Foulger, G.R. 2012. Are ‘hot spots’ hot spots?. Journal of Geodynamics 58, 1–28.

Gao, S., Zhang, B.R., Jin, Z.M., Kern, H., Luo, T.C., Zhao, Z.D. 1998. How mafic is the lower continental crust?. Earth and Planetary Science Letters 161, 101–117.

Gao, S., Rudnick, R.L., Xu, W.L., Yuan, H.L., Liu, Y.S., Walker, R.J., Puchtel, I.S., Liu, X.M., Huang, H., Wang, X.R., Yang, J. 2008. Recycling deep cratonic lithosphere and generation of intraplate magmatism in the North China Craton. Earth and Planetary Science Letters 270, 41–53.

Griffin, W.L., Zhang, A.D., O’Reilly, S.Y., Ryan, G. 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean Craton. In: Mantle Dynamics and Plate Interactions in East Asia, Flower, M., Chung, S. L., Lo, C.H., Lee, T.Y. (eds). American Geophysics Union Geodynamics Series 27, 107–126.

Han, B.F., Kagami, H. Li, H.M. 2004. Age and Nd-Sr isotopic geochemistry of the Guangtoushan alkaline granite, Hebei Province, China: implications for early Mesozoic crust–mantle interaction in North China Block. Acta Petrologica Sinica 20, 1375–1388 (in Chinese with English abstract).

He, C.S. 2010. Seismic evidence for plume and subducting slab in West Yunnan, Southwestern China. Acta Petrologica Sinica (English Edition) 85, 801–840.

He, C.S., Dong, S.W., Santosh, M., Chen, X.H. 2013a. Seismic evidence for a geosuture between the Yangtze and Cathaysia Blocks, South China. Scientific Reports 3. DOI: 10.1038/srep02200.

He, C.S., Dong, S.W., Chen, X.H., Santosh, M., Li, Q.S. 2013b. Seismic evidence for plume-induced rifting in the Songliao basin of Northeast China. Tectonophysics, http://dx.doi.org/10.1016/j.tecto.2013.07.015.

Hilde, T.W.C., Uyeda, S., Kroenke, L. 1977. Evolution of the western Pacific and its margin. Tectonophysics 38, 145–165.

Hou, G., Yang, M., Yao, W. 2009. Destruction of the North China Craton: evidence from the Bohai Bay Basin. In: Hou, G., Rosenbaum, G. (eds) General Contributions. Journal of the Virtual Explorer, Electronic Edition, ISSN 1441–8142 31, paper 2. DOI: 10.3809/virtex.2009.00243.

House, C., Williams, Q. 2010. Reconciling Pacific 410 and 660km discontinuity topography, transition zone shear velocity patterns, and mantle phase transitions. Earth and Planetary Science Letters 296, 255–266.

Huang, Z., Su, W., Peng, Y., Zheng, Y., Li, H. 2003. Rayleigh wave tomography of China and adjacent regions. Journal of Geophysical Research 108(B2), 2073. DOI: 10.1029/2001JB001696.

Huerta, A.D., Nyblade, A.A., Reusch, A.M. 2009. Mantle transition zone structure beneath Kenya and Tanzania: more evidence for a deep-seated thermal upwelling in the mantle. Geophysical Journal International 177, 1249–1255.

Kay, R.W., Kay, S.M. 1993. Delamination and deformation magnetism. Tectonophysics 219, 177–189.

Kemett, B.L.N., Engdahl, E.R. 1991. Travel times for global earthquake location and phase identification. Geophysical Journal International 105, 429–465.

Langston, C.A. 1979. Structure under Mount Rainier, Washington, inferred from teleseismic body waves. Journal of Geophysical Research 84, 4749–4762.

Lee, Y.L., Sur, K.H., Hisada, K. 2005. Asymmetric diagenetic changes in a half-graben basin: the Kannon Group (Lower Cretaceous), SW Japan. Cretaceous Research 26, 73–84.

Li, H.Y. 2013. Destruction of North China Craton: insights from temporal and spatial evolution of the proto-basins and magmatism. Science in China Series D. http://dx.doi.org/10.1007/s11430-012-4534-9.
Santosh, M., Somerville, I.D. 2013. Tectonic evolution of the North China Craton: introduction. Geological Journal 48, 403–405. DOI: 10.1002/gj.2518.

de Smet, J.H., van den Berg, A.P., Vlaar, N.J. 1998. Stability and growth of continental shields in mantle convection models including recurrent melt production. Tectonophysics 296, 15–29.

Stel, H., Cloetingh, S., Heeremans, M., van der Beek, P. 1993. Anorogenic granites, magmatic underplating and the origin of intracratonic basins in a non-extensional setting. Tectonophysics 226, 285–299.

Stern, R.J. 2004. Subduction initiation: spontaneous and induced. Earth and Planetary Science Letters 226, 275–292.

Svenningsson, L., Balling, N., Jacobsen, B.H., Kind, R., Wylegalla, K., Schweitzer, J. 2007. Crustal root beneath the highlands of southern Norway resolved by teleseismic receiver functions. Geophysical Journal International 170, 1129–1138.

Thompson, D.A., Bastow, I.D., Helfrich, G., Kendall, J.-M., Wookey, J., Snyder, D.B., Eaton, D.W. 2010. Precambrian crustal evolution: seismic constraints from the Canadian Shield. Earth and Planetary Science Letters 297(3–4), 655–666. DOI: 10.1016/j.epsl.2010.07.021.

Wei, Z., Chen, L., Wang, B. 2013. Regional variations in crustal thickness and Vp/Vs ratio beneath the central–western North China Craton and adjacent regions. Geological Journal 48, 531–542. DOI: 10.1002/gj.2473.

Wu, Y.B., Zheng, Y.F. 2013. Tectonic evolution of a composite collision Orogen; an overview on the Qinling–Tongbai–Hang an–Dabiesu–Sulu Orogenic Belt in central China. Gondwana Research 23, 1402–1428.

Wu, F.Y., Lin, J.Q., Simon, A.W., Zhang, X.O., Yang, J.H. 2005. Nature and significance of the Early Cretaceous giant igneous event in eastern China. Earth and Planetary Science Letters 233, 103–119.

Wu, F.Y., Xu, Y.G., Gao, S., Zhang, J.P. 2008. Lithospheric thinning and destruction of the North China Craton. Acta Petrologica Sinica 24, 1145–1174.

Xiao, W.J., Windley, B.F., Allen, M.B., Han, C. 2013. Palaeozoic multiple accretionary and collisional tectonics of the Chinese Tianshan oрогenic collage. Gondwana Research 23, 1316–1341.

Xu, Y.G. 2001. Thermotectonic destruction of the Archean lithospheric keel beneath eastern China: evidence, timing, and mechanism. Physics and Chemistry of the Earth A 26, 747–757.

Xu, Y.G. 2007. Diachronous lithospheric thinning of the North China Craton and formation of the Daxin’anling–Taihangshan gravity lineament. Lithos 96, 281–298.

Xu, P.F., Zhao, D.P. 2009. Upper-mantle velocity structure beneath the North China Craton: implications for lithospheric thinning. Geophysical Journal International 177, 1279–1283.

Xu, J.F., Shinjo, R., Dufant, M.C., Wang, Q., Rapp, R.P. 2002. Origin of Mesozoic adakitic intrusive rocks in the Ningzhen area of east China: partial melting of delaminated lower continental crust?. Geology 30, 1111–1114.

Xu, Y.G., Li, H.Y., Pang, C.J., He, B. 2009. On the timing and duration of the destruction of the North China Craton. Chinese Science Bulletin 54, 1379–1396.

Yang, D.B., Xu, W.L., Pei, F.P., Yang, C.H., Wang, Q.H. 2012. Spatial extent of the influence of the deeply subducted South China Block on the southeastern North China Craton: constraints from Sr–Nd–Pb isotopes in Mesozoic mafic igneous rocks. Lithos 136–139, 246–260.

Yang, J.H., Wu, F.Y. 2009. Triassic magmatism and its relation to deformation in the eastern North China Craton. Science in China Series D: Earth Sciences 52, 1319–1330.

Yang, J.H., Wu, F.Y., Wilde, S.A. 2003. A review of the geodynamic setting of large-scale Late Mesozoic gold mineralization in the North China Craton: an association with lithospheric thinning. Ore Geology Reviews 23, 125–152.

Yang, J.H., Wu, F.Y., Shao, J.A., Wilde, S.A., Xie, L.W., Liu, X.M. 2006. Constraints on the timing of uplift of the Yanan Fold and Thrust Belt, North China. Earth and Planetary Science Letters 246, 336–352.

Yang, J.H., Wu, F.Y., Wilde, S.A., Liu, X.M. 2007. Petrogenesis of Late Triassic granitoids and their enclaves with implications for post-
collisional lithospheric thinning of the Liaodong Peninsula, North China Craton. Chemical Geology 242, 155–175.

Yang, J.H., O’Reilly, S., Walker, R.J., Griffin, W., Wu, F.Y., Zhang, M., Pearson, N. 2010. Diachronous decratonization of the Sino-Korean Craton: geochemistry of mantle xenoliths from North Korea. Geology 38, 799–802.

Yang, Q.L., Zhao, Z.F., Zheng, Y.F. 2012. Slab–mantle interaction for thinning of cratonic lithospheric mantle in North China: geochemical evidence from Cenozoic continental basaits in central Shandong. Lithos 155, 442–460.

Yuan, X., Ni, J., Kind, R., Sandvol, E., Mechie, J. 1997. Lithospheric and upper mantle structure of southern Tibet from a seismonological passive source experiment. Journal of Geophysical Research 102, 27491–27500.

Zandt, G., Ammon, C.J. 1995. Continental crust composition constrained by measurements of crustal Poisson’s ratio. Nature 374, 152–154.

Zhai, M.G., Santosh, M. 2011. The Early Precambrian odyssey of the North China Craton: a synoptic overview. Gondwana Research 20, 6–25.

Zhai, M.G., Fan, Q.C., Zhang, H.F., Sui, J.L., Shao, J.A. 2007. Lower crustal processes leading to Mesozoic lithospheric thinning beneath eastern North China: underplating, replacement and delamination. Lithos 96, 36–54.

Zhang, H.F. 1993. Geochemistry and genesis of kimberlite in the Tieling area, Liaoning Province. Geoscience 7, 458–464.

Zhang, H.F. 2007. Temporal and spatial distribution of Mesozoic mafic magmatism in the North China Craton and implication for secular lithospheric evolution. In: Mesozoic Sub-Continental Lithospheric Thinning under Eastern Asia, Zhai, M.G., Windley, B.F., Kusky, T. M., Meng, Q.R. (eds). Geological Society, London, Special Publications 280, 35–54.

Zhang, H.F., Zhu, R.X., Santosh, M., Ying, J.F., Su, B.X., Hu, Y. 2013. Episodic widespread magma underplating beneath the North China Craton in the Phanerzoic: implications for craton destruction. Gondwana Research 23, 95–107.

Zhang, H.F., Ying, J.F., Shimoda, G., Kita, N.T., Morishita, Y., Shao, J.A., Tang, Y.J. 2007. Importance of melt circulation and crust–mantle interaction in the lithospheric evolution beneath the North China Craton: evidence from Mesozoic basalt-borne clinopyroxene xenocrysts and pyroxenite xenoliths. Lithos 96, 67–89.

Zhang, J.F., Wang, C., Wang, Y.F. 2012. Experimental constraints on the destruction mechanism of the North China Craton. Lithos 149, 91–99.

Zhang, S.H., Zhao, Y., Liu, X.C., Liu, D.Y., Chen, F., Xie, L.W., Chen, H.H. 2009. Late Paleozoic to Early Mesozoic mafic–ultramafic complexes from the northern North China Block: constraints on the composition and evolution of the lithospheric mantle. Lithos 110, 229–246.

Zhang, S.H., Zhao, Y., He, H., Hou K.L., Li, C.F. 2012. Early Mesozoic alkaline complexes in the northern North China Craton: implications for cratonic lithospheric destruction. Lithos 155, 1–18.

Zhang, Y.Q., Ma, Y.S., Yang, N., Shi, W., Dong, S.W. 2003. Cenozoic extensional stress evolution in North China. Journal of Geodynamics 36, 591–613.

Zhang, Z.J., Chen, Q.F., Bai, Z.M., Chen, Y., Badal, J. 2011. Crustal structure and extensional deformation of thinned lithosphere in Northern China. Tectonophysics 508, 62–72.

Zhang, Z.J., Wu, J., Deng, Y.F., Peng, J.W., Zhang, X., Chen, Y. 2012. Giuliano Panza. Lateral variation of the strength of lithosphere across the eastern North China Craton: new constraints on lithospheric disruption. Gondwana Research 22, 1047–1059.

Zhang, Z.J., Wang, Y.H., Deng, Y.F., Chen, L., Wu, J., Teng, J.W., Chen, Y., Fan, W.M., Panza, G. 2013. Geophysical constraints on Mesozoic disruption of North China Craton by underplating-triggered lower-crust flow of the Archean lithosphere. Terra Nova 25, 245–251.

Zhao, G.C., Zhai, M.G. 2013. Lithotectonic elements of Precambrian basement in the North China Craton: review and tectonic implications. Gondwana Research 23, 1207–1240.

Zhao, L., Zheng, T.Y. 2005. Using shear wave splitting measurement to investigate the upper mantle anisotropy beneath the North China Craton: distinct variation from east to west. Geophysical Research Letters 32, L1039. DOI: 10.1029/2005GL022585.

Zhao, G.C., Wilde, S.A., Cawood, P.A., Sun, M. 2001. Archean blocks and their boundaries in the North China Craton: lithological, geochemical, structural and P–T path constraints and tectonic evolution. Precambrian Research 107, 45–73.

Zhao, G.C., Sun, M., Wilde, S.A., Li, S.Z. 2005. Late Archean to Paleoproterozoic evolution of the North China Craton: key issues revisited. Precambrian Research 136, 177–202.

Zhao, G.C., Cawood, P.A., Li, S.Z., Wilde, S.A., Sun, M., Zhang, J., He, Y.H., Yin, C.Q. 2012. Amalgamation of the North China Craton: key issues and discussion. Precambrian Research 222–223, 55–76.

Zheng, Y.F., Wu, F.Y. 2009. Growth and reworking of cratonic lithosphere. Chinese Science Bulletin 54, 3347–3353.

Zheng, J.P., O’Reilly, S.Y., Griffin, W.L., Lu, F.X., Zhang, M. 1998. Nature and evolution of Cenozoic lithospheric mantle beneath Shandong peninsula, Sino-Korean craton, eastern China. International Geology Review 40, 471–499.

Zheng, J.P., Griffin, W.L., O’Reilly, S.Y., Yu, C.M., Zhang, H.F., Pearson, N., Zhang, M. 2007. Mechanism and timing of lithospheric modification and replacement beneath the eastern North China Craton: peridotitic xenoliths from the 100 Ma Fuxin basalts and a regional synthesis. Geochimica et Cosmochimica Acta 71, 5203–5223.

Zheng, Y.F., Chen, R.X., Zhao, Z.F. 2009. Chemical geodynamics of continental subduction-zone metamorphism: insights from studies of the Chinese Continental Scientific Drilling (CCSD) core samples. Tectonophysics 475, 327–358.

Zheng, X.F., Yao, Z.X., Liang, J.H., Zheng, J. 2010. The role played and opportunities provided by IGP DMC of China National Seismic Network in Wenchuan earthquake disaster relief and researches. Bulletin of Geosociology Society America 100(5B), 2866–2872.

Zheng, Y.F., Xiao, W.J., Zhao, G.C. 2013. Introduction to tectonics of China. Gondwana Research 23, 1189–1206.

Zhu, L. 2000. Crustal structure across the San Andreas Fault, southern California from teleseismic converted waves. Earth Planetary and Space Science Letters 179, 183–190.

Zhu, L., Kanamori, H. 2000. Moho depth variation in southern California from teleseismic receiver functions. Journal of Geophysical Research 105, 2069–2980.

Zhu, J., Cao, J., Cai, X., Yan, Z., Cao, X. 2002. High resolution surface wave tomography in east Asia and west Pacific marginal seas. Chinese Journal of Geophysics 45, 646–664 (in Chinese with English abstract).

Zorin, Y.A., Zorina, L.D., Spiridonov, A.M., Rutshtein, I.G. 2001. Geodynamic setting of gold deposits in Eastern and Central Trans-Baikal (Chita Region, Russia). Ore Geology Reviews 17, 215–232.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher’s web site:

Table S1. Earthquake catalogues used by this study.
Table S2. Results of h–k stacking (valid seismic station).
Table S3. Results of upper mantle discontinuity.
Figure S1. H–k stacks from stations JS and NIC.
Figure S2. Average receiver function.