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Catastrophic craton destruction via wholesale lithosphere delamination

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ABSTRACT

The nuclei of continents, manifested as cratons, are the most long-lived parts of Earth's lithosphere. However, ancient cratons in some areas can be substantially destroyed through mechanisms that are not fully understood. We used experimentally calibrated geobarometers to calculate the equilibrium pressures of mafic magmas in the North China craton, which directly constrain the evolving depth of the lithosphere-asthenosphere boundary beneath the craton through time. We show that the lithospheric thickness of the eastern part of the craton decreased from ~200 km to ~35 km in the Early Cretaceous. This intense destruction took place within a short time interval of ~10 m.y., at least locally. Following this destruction, the lithosphere gradually rethickened and stabilized as the upwelling asthenosphere cooled and formed a juvenile lithosphere. We suggest that this catastrophic lithosphere thinning resulted from wholesale lithosphere delamination. As a consequence of this catastrophic loss of thick mantle roots, the eastern part of the North China craton may have undergone rapid crustal rebound and surface uplift, as recorded by the regional unconformities formed between 130 and 120 Ma in the destructed area.

INTRODUCTION

Delamination has long been considered as an efficient mechanism for recycling the lower crust and mantle portions of the continental lithosphere into the convective mantle (Lee et al., 2000; Jagoutz and Behn, 2013). However, almost all evidence for lithosphere delamination comes from geodynamic modeling predictions (Johnson et al., 2013; Stein et al., 2022) and the chemical imbalances between the continental crust and its building blocks (Rudnick, 1995; Gao et al., 1998), most of which is circumstantial. Part of this dilemma is due to the scarcity of direct records of lithosphere delamination processes, especially for cratons, where in some areas the continental lithosphere had remained stable for billions of years before destruction took place. One such place is the North China craton.

The North China craton is one of the oldest cratons in the world and preserves rock records as old as 3.8 Ga (Liu et al., 1992). Since its western and eastern blocks amalgamated in the Paleoproterozoic (Zhao et al., 2012), the North China craton remained stable until the Mesozoic, when the lithosphere was reactivated and massively destroyed (Menzies et al., 2007). As a consequence of this destruction, the preexisting ~200-km-thick Archean lithospheric mantle was completely replaced by a < 100 km thin juvenile mantle beneath the eastern part of the craton (Menzies et al., 1993; Griffin et al., 1998). The destruction of the North China craton is generally believed to have been related to paleo-Pacific plate subduction (Liu et al., 2019; Sun et al., 2021), but exactly how the thick lithospheric mantle was removed is highly debated. Delamination, thermal erosion, and chemical erosion have all been proposed as potential mechanisms for the thinning of the lithospheric mantle beneath the North China craton (Xu, 2001; Zhu et al., 2011; Wu et al., 2019).

To resolve the destruction process, one critical yet missing piece of information is the time scale of lithosphere thinning of the North China craton. In this study, we used experimentally calibrated geobarometers for mafic magmas to reconstruct the evolution of lithosphere thickness for the North China craton. These results in conjunction with Nd isotopic data provide direct constraints on the catastrophic lithosphere delamination process beneath the North China craton.

METHODS

Mafic magmas are derived from mantle melting, and their compositions are dictated by the source lithologies, melting conditions, and subsequent differentiation processes (Niu, 2005). Melting occurs when the geothermal gradient (change in temperature [dT]/change in pressure [dP]) intersects the solidus of mantle rocks. The upper mantle geothermal gradient consists of two parts: a high dT/dP conductive geotherm in the lithosphere and a low dT/dP convective geotherm in the asthenosphere. Because most mantle rocks have solidi with positive dT/dP at $P > 2.5$ GPa (Fig. 1A), the kinked geotherm intersects the solidi near the lithosphere-asthenosphere boundary, and initial melting primarily occurs at the top of the asthenosphere (Fig. 1B; Elkins-Tanton, 2005; Niu, 2021). Therefore, the generation depth of primary mafic magma can be used to constrain the maximum bound on lithospheric thickness.

One complexity with this approach is that primary magmas may partially reequilibrate with mantle rocks at shallower depths during their transit through the lithosphere, especially when the overlying lithosphere is thick. As a result of this reequilibration, the final equilibrium pressures recorded by the evolving magmas can be reset and highly scattered and should be taken as a minimum bound on lithospheric thickness. To evaluate the extent of reequilibration with the lithosphere, we examined the Nd radiogenic isotopes of these mafic magmas. Protracted metasomatism by fluids/melts sourced from low Sm/Nd enriched reservoirs leads to highly unradiogenic Nd isotopic compositions in the continental lithosphere ($\varepsilon Nd(t) < 0$; Foley, 2008). In contrast, the asthenosphere is characterized by radiogenic Nd isotopic compositions ($\varepsilon Nd(t) > 0$) due to secular melt extraction

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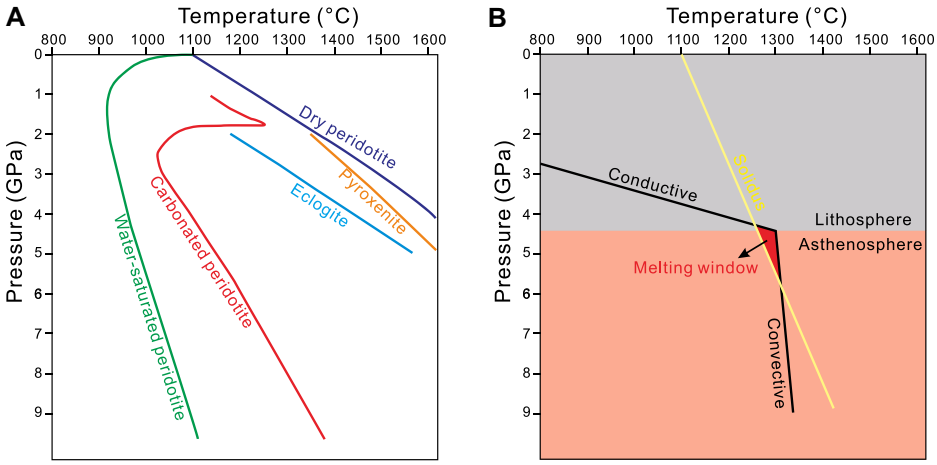


Figure 1. Conceptual diagrams showing lithospheric thickness control on mantle melting. (A) Solidi of dry peridotite, carbonated peridotite, water-saturated peridotite, pyroxenite, and eclogite (modified from Xu et al., 2020). (B) Mantle rocks melt when geotherm intersects solidus, so the melting window will concentrate at the inflection of the geotherm, the depth of which corresponds to the lithosphere-asthenosphere boundary. Different mantle lithologies have different solidi, some of which have complex, nonmonotonic pressure-temperature (*P-T*) relationships. In this case, the geotherm may not intersect the solidi near the lithosphere-asthenosphere boundary. Nevertheless, the solidi of all mantle lithologies show positive *dT/dP* at >2.5 GPa; i.e., a pressure range that is more relevant to our discussions.

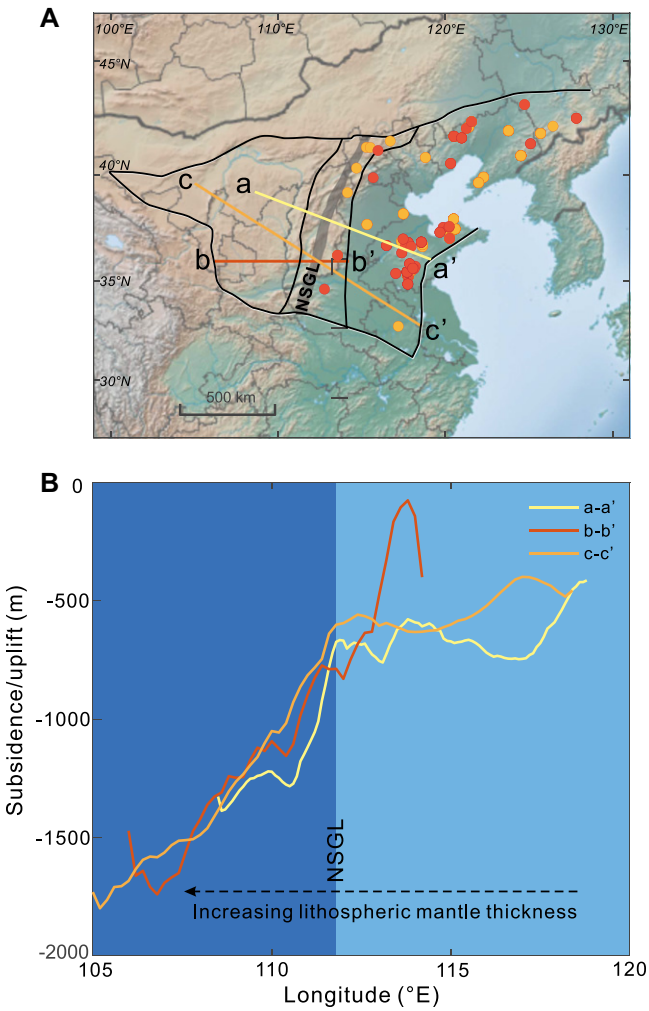


Figure 2. Westward continental subsidence/uplift of the North China craton. (A) Bold colored lines a-a′, b-b′, and c-c′ represent three west-to-east profiles of elevation, crustal thickness, and crustal density that were used to evaluate surface subsidence/uplift. Filled circles denote our compiled samples used in equilibrium pressure calculations. NSGL—North-South Gravity Lineation. Surface subsidence/uplift refers to the deviation of actual elevation from the calculated elevation based on Airy isostasy (see the Supplemental Material [see footnote 1]). (B) Magnitude of surface subsidence/uplift along profiles a-a′, b-b′, and c-c′ correlated with increased lithospheric mantle thickness, suggesting that the cratonic lithospheric mantle of the North China craton is denser than the ambient mantle.

(Hofmann, 1997). The contrasting Nd isotopic signatures of the ancient continental lithosphere and the asthenosphere are thus useful for assessing the source compositions and equilibration depths of mafic magmas.

We used two major-element–based geobarometers to calculate the equilibrium pressures of mafic magmas from the North China craton. One geobarometer was calibrated against SiO_2 activity of the melts buffered by olivine and orthopyroxene (Lee et al., 2009); the other one was parameterized based on the pressure-dependent Al_2O_3 activity variation of melts saturated with garnet (Sun and Dasgupta, 2020). These two geobarometers can be applied to silica-saturated and silica-undersaturated mafic magmas, respectively. We compiled whole-rock composition data for Mesozoic to Cenozoic mafic magmas and Ordovician kimberlites of the North China craton. All the samples were taken from locations to the east of the North-South Gravity Lineation, a boundary that constrains the area of destruction of the North China craton (Fig. 2A; Zhu et al., 2012). Before calculating the equilibrium pressures, we applied a series of filters to the data set to remove samples that did not meet the criteria for using the geobarometers (see the Supplemental Material[1]).

RESULTS

Studies on the xenoliths entrained in Ordovician diamondiferous kimberlites suggest that the old, refractory, and thick mantle keel remained intact beneath the North China craton in the Paleozoic (Gao et al., 2002; Menzies et al., 2007). Our calculated pressures for these kimberlites are in the range of ~5–9 GPa, with a mean of 6.3 GPa, consistent with a > 200-km-thick cratonic lithosphere. However, the present-day lithospheric thickness of the eastern North China craton ranges between 60 and 100 km based on geophysical observations, indicating significant thinning during this period (Chen et al., 2008; Wu et al., 2019).

The calculated equilibrium pressure results fill in the gap between the Mesozoic and present day. Samples older than ca. 120 Ma exhibit highly scattered equilibrium pressures, ranging between 1 and 7 GPa. Younger samples show more restricted equilibrium pressures. The equilibrium pressures of the youngest Cenozoic samples are 3–5 GPa, corresponding to a depth range of 90–150 km. This depth range is slightly higher than the modern lithosphere-asthenosphere boundary depth, suggesting that these Cenozoic basalts were primarily generated

[1]Supplemental Material. Brief review of basaltic samples from the North China craton used in calculations, data filter procedure, and detailed calculation processes. Please visit https://doi.org/10.1130/GEOL.S.22151891 to access the supplemental material, and contact editing@geosociety.org with any questions.

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in the asthenosphere with little reequilibration with the lithospheric mantle.

DISCUSSION

One intriguing observation from our reconstruction is the sharp decline in maximum equilibrium pressures from >6 GPa to near 1 GPa between 130 and 120 Ma (Fig. 3B). This large pressure change is also reflected in the $(La/Yb)_N$ ratios, which could also be used to infer the melting depth, and which are most sensitive when melting transitions from garnet- to spinel-peridotite. Because most of the samples fall in the garnet-peridotite field (>2–3 GPa), the $(La/Yb)_N$ ratio is not an ideal indicator of the changing source depth. Nevertheless, the $(La/Yb)_N$ also shows a sharp decrease at 130–120 Ma, a trend broadly consistent with that of our calculated equilibrium pressures (Fig. S4). The highly scattered pressure values seen in samples older than ca. 120 Ma may be a consequence of various extents of reequilibration with the ancient lithospheric mantle. This is supported by the highly negative εNd(t) values seen in the pre–120 Ma samples (Fig. 3C). In this regard, the maximum equilibrium pressure may best represent the original lithospheric thickness as discussed above. High-pressure mafic magmas (e.g., > 6 GPa) with negative εNd(t) occurred until 130–120 Ma, indicating the existence of a thick lithospheric mantle root until the Early Cretaceous. The rapid disappearance of high-pressure mafic magmas between 130 and 120 Ma suggests that the thick Archean mantle roots were removed within 10 m.y. to the east of the North-South Gravity Lineation, at least locally.

After the catastrophic thinning of the mantle lithosphere, the equilibrium pressures of these mafic magmas appear to have gradually increased from near 1 GPa to >3 GPa between 120 and 60 Ma. The increased pressure may reflect lithosphere regrowth owing to conductive cooling of passively upwelling asthenosphere. The time scale of thermal relaxation of an upwelling asthenosphere can be estimated by $t \approx x^2/\kappa$, where x is the thickness of the thermal boundary layer, and κ is the thermal diffusivity (Lee, 2014). The formation of a new 50-km-thick thermal boundary layer would take ~80 m.y. or less if cooling were assisted by melt extraction. This time scale is consistent with that of the lithosphere regrowth indicated by our data. The formation of this new thermal boundary layer may have shielded the overlying crust from the hot asthenosphere, which accounts for the rapidly vanishing felsic magmatism after ca. 110 Ma (Fig. 3E).

The extremely short time scale of lithosphere thinning provides key evidence for the destruction mechanism of the North China craton. Although convectional removal driven by Rayleigh-Taylor instability can cause lithosphere thinning under continuous thermal perturbation or fluid/melt metasomatism, these "bottom-up" destruction processes generally take place over tens of million years or longer because the entire lithospheric mantle needs to be thoroughly transformed either thermally or chemically (Menzies et al., 2007; Wang et al., 2015). These slow destruction mechanisms are incompatible with our findings.

By contrast, "top-down" destruction caused by delamination occurs on much shorter time

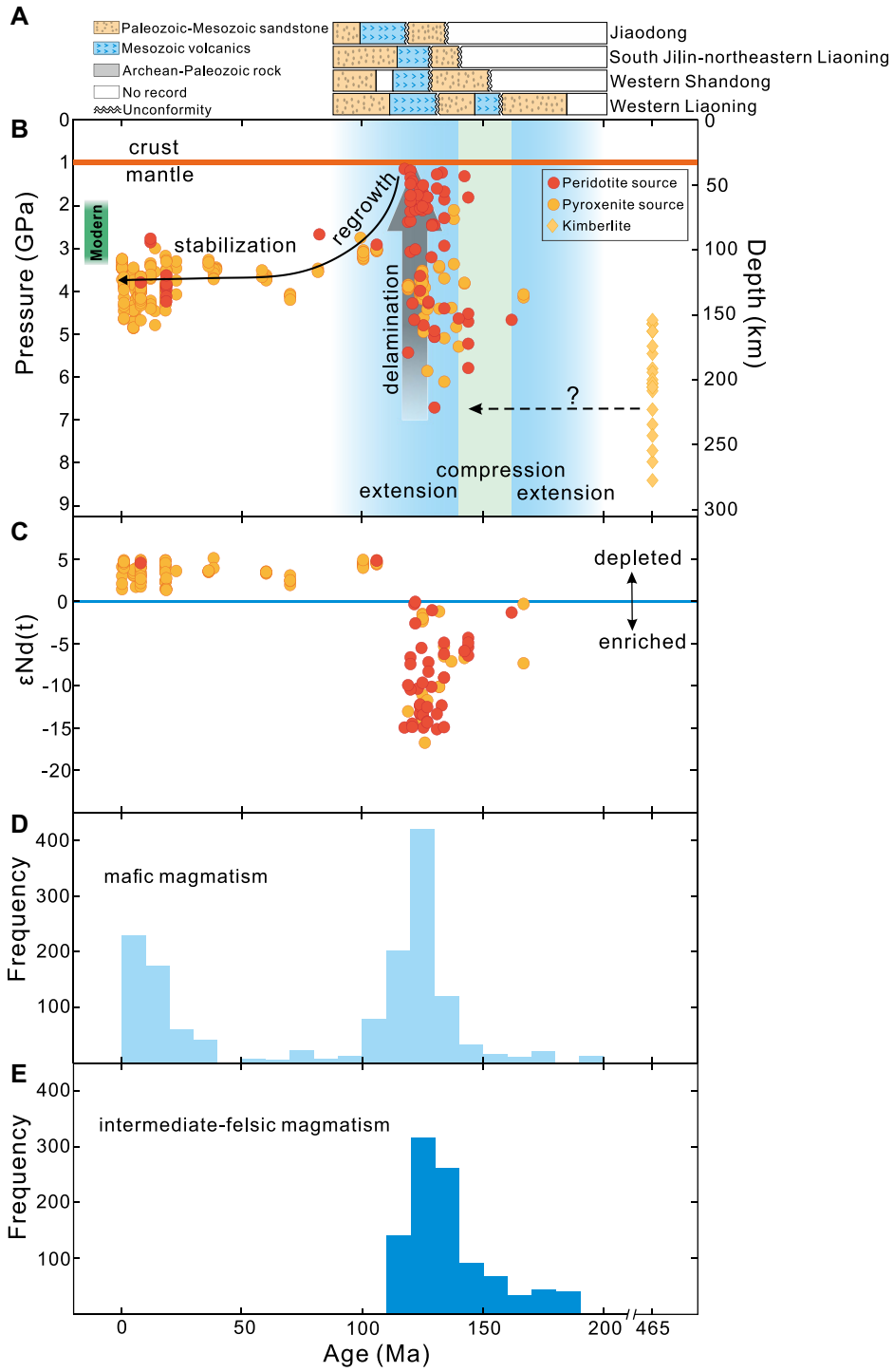


Figure 3. Reconstructed lithospheric thickness evolution of the North China craton. (A) Stratigraphic columns in the eastern North China craton show regional unconformities (modified from Wu et al., 2019). (B) Calculated equilibrium pressures and corresponding lithosphere-asthenosphere boundary depth versus age of mafic magmas and kimberlites from the North China craton. Shading shows extensional or compressional tectonic regimes. (C) Nd isotopic characteristics of mafic magmas used in the pressure calculations. Values transitioned from enriched Nd isotopic composition to depleted at ca. 120 Ma. (D) Mafic magmatism frequency. (E) Intermediate-felsic magmatism frequency.

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scales (Menzies et al., 2007; Lee, 2014). In addition, the large pressure reduction recorded by samples between 130 and 120 Ma suggests that the delamination was wholesale. That is, almost the entire lithospheric mantle was detached from the remaining portion in the eastern part of the craton. The wholesale delamination scenario is also supported by the lack of Archean-age peridotite xenoliths in the Cenozoic basalts found across the eastern North China craton (Wu et al., 2003).

The lithospheric mantle must be denser than the underlying asthenosphere to delaminate (Bird, 1979). Composition and temperature are the two main factors controlling the lithospheric density. Mantle xenoliths from the North China craton suggest that the lithospheric mantle was depleted prior to extensive destruction (Menzies et al., 2007). Because melt depletion decreases the density of the lithospheric mantle, strongly depleted cratonic mantle is widely thought to be positively buoyant with respect to the asthenospheric mantle (Pearson et al., 2021). However, the lithospheric mantle is also cold compared with the asthenospheric mantle, which would increase the density of the lithospheric mantle due to thermal contraction. Therefore, the density of the lithospheric mantle relative to that of the asthenospheric mantle represents the outcome of two competing components—chemical depletion and thermal contraction. Today, most cratonic areas show lower elevations relative to active continental margins with similar crustal thicknesses (Lee et al., 2015), suggesting that the lithospheric mantle beneath ancient cratons may be negatively buoyant. To further evaluate the buoyancy of the lithospheric mantle beneath the North China craton, we calculated the subsidence/uplift of the surface along three west-to-east crustal profiles (Fig. 2A; see the Supplemental Material). Here, the subsidence/uplift represents the difference between the elevation predicted by isostasy calculations and the observed elevation. Although the elevation calculated from the isostasy model is sensitive to parameters such as seawater depth, the west-to-east trends of subsidence/uplift reflect the relative change in elevation difference and are thus robust. Our calculation showed that the North China craton displays systematic westward continental subsidence, the magnitude of which positively correlates with the thickness of the remaining lithospheric mantle (Fig. 2B). This prominent relationship indicates that the lithospheric mantle beneath the North China craton is denser than the ambient mantle and drags the crust downward.

Once the dense lithospheric mantle falls off, underlying asthenosphere would upwell and undergo partial melting under decompression, generating intense syn-delamination mafic magmatism (Fig. 3D). As the dense lithospheric mantle detaches from the crust, the crust would rebound under isostatic adjustment, causing the surface to uplift rapidly (Levander et al., 2011; Bao et al., 2014). This uplift is probably ephemeral because the hot topmost asthenospheric mantle would rapidly transform to cold juvenile lithospheric mantle upon cooling. Between 130 and 120 Ma, the sedimentary strata record a widespread unconformity across the eastern North China craton, including western Liaoning, south Jilin–northeastern Liaoning, western Shandong, and Jiaodong (Fig. 3A). This widely occurring hiatus in the sedimentary successions appears to be peculiar because it formed within an extensional tectonic regime. Therefore, these regional stratigraphic unconformities cannot be explained by orogenic uplift induced by compression but instead reflect a short-lived topography change driven by crustal rebound in response to massive lithosphere delamination.

A final question pertains to the trigger of the catastrophic wholesale lithosphere delamination beneath the North China craton. Delamination requires the formation of a rheologically weak zone in the lithosphere, and for wholescale delamination, this weak zone would need to form at a shallow depth. Beginning in the Early Jurassic, continuous subduction and slab rollback of the paleo-Pacific plate may have generated large amounts of mafic magmas, which subsequently ascended and stalled at shallow depths in the lithosphere, perhaps near the Moho. This is reflected by the cluster of equilibrium pressures at 1–2 GPa in the Early Cretaceous (Fig. 3B). Large amounts of magma may have modified the lithosphere intensely and rheologically weakened the shallow lithosphere by lowering its viscosity. Ultimately, the underlying dense lithospheric mantle might have detached from the buoyant crust along these magmatically activated weak zones.

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