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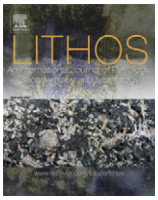

Petrogenetic evaluation of the Laohutai basalts from North China Craton: Melting of a two-component source during lithospheric thinning in the late Cretaceous–early Cenozoic

Y.S. Kuang [a,b], X. Wei [a,b], L.B. Hong [a,b], J.L. Ma [a], C.J. Pang [a], Y.T. Zhong [a], J.-X. Zhao [c], Y.-G. Xu [a,]*

[a] State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, 510640, PR China
[b] Graduate University of Chinese Academy of Sciences, Beijing, 100049, PR China
[c] School of Earth Sciences, The University of Queensland, Brisbane, QLD 4072, Australia

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ABSTRACT

While the consensus has been reached as to the lithospheric thinning beneath the North China Craton, the timing of this event remains controversial. Whether it took place during the Early Cretaceous or it extended over a period from late Triassic to early Cenozoic is a matter of hot debate. With aims of contributing to this issue, we performed geochronological and geochemical analyses on basalts of the Laohutai Formation which were emplaced in the Fushun basin at 60–70 Ma. The Laohutai Formation consists of Ne- or Hy-normative alkali basalts in the lower part and Q-normative tholeiitic basalts in the upper part. The tholeiites are characterized by positive Eu and Sr anomalies and show higher $\varepsilon_{Nd}(t)$ (3.2–5.3) than the co-existing alkali basalts (1.8–2.4), opposite to the common observation made in other occurrences. Depletion of highly incompatible elements, positive Nb–Ta and negative Pb anomalies in the Laohutai basalts are indicative of oceanic crustal components (likely in form of pyroxenite/eclogite) in their magma source. Since Eu and Sr anomalies are not related to magmatic differentiation, the negative correlation between $^{87}Sr/^{86}Sr_i$ and Eu/Eu* suggests that the melting process and sampling of source heterogeneity are intrinsically related. We propose a differential melting of a two-component source in association with lithospheric thinning to account for the temporal variation of the Laohutai basalts. Specifically, earlier alkali basalts were formed by low degree of melting of a source at a greater depth, modified by melts derived from a hydrothermally altered, upper oceanic crust; whereas the later tholeiitic basalts were generated by high degree of melting of a gabbroic lower oceanic crust and minor peridotite at a shallower depth. When the lithospheric lid effect is applied, this petrogenetic model suggests the late Cretaceous–early Cenozoic as an important period of lithospheric thinning, therefore leaning support to the idea of the protracted destruction process beneath the North China Craton.

1. Introduction

Consensus has been reached in recent years that the North China Craton (NCC) represents the best case for removal of old lithospheric mantle (>100 km) beneath a cratonic region (Carlson et al., 2005; Griffin et al., 1998; Menzies et al., 1993; Xu, 2001). However, the timing of the lithospheric thinning in this area remains controversial (e.g., Wu et al., 2008; Xu et al., 2009; Zhu et al., 2011), which is pivotal to understanding the destruction mechanism and its geodynamic controlling factors (Menzies et al., 2007). The current knowledge about the timing and duration of the cratonic destruction mainly stems from studies on magmatism. Unfortunately, different researchers arrive at completely different conclusions. For instance, on the basis of positive $\varepsilon_{Nd}(t)$ values associated with some late Triassic and Early Cretaceous mafic rocks in the Liaodong Peninsula, Yang et al. (2007, 2008) constrained the decratonization timing of this region to be Triassic and Early Cretaceous. Gao et al. (2004) interpreted Jurassic high-Mg adakitic rocks from western Liaoning being derived by partial melting of delaminated crust, implying that the destruction of the NCC took place in the middle Jurassic. However, Wu et al. (2006) related Jurassic magmatism to the subduction of Paleo-Pacific plate underneath the Asian continent, and suggested that only early Cretaceous (135–115 Ma) magmatism was related to lithospheric thinning during the cratonic destruction (Wu et al., 2005). Consequently, the destruction of the NCC was suggested to be accomplished over a relatively short period during the early Cretaceous. However, on the basis of shift from late Mesozoic isotopically enriched basalts to Cenozoic depleted lavas, Xu et al. (2004a, 2009) suggested a protracted (>100 Ma) lithospheric thinning process, probably starting from late Triassic–Early Jurassic to late Cretaceous–early Cenozoic. Clearly, while the early Cretaceous must represent an important period, most likely the climax of

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* Corresponding author at: Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, 510640 Wushan, Guangzhou, PR China. Tel.: +86 20 85290109; fax: +86 20 85290261.
E-mail address: yigangxu@gig.ac.cn (Y.-G. Xu).

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lithospheric thinning in the NCC, issue remains as to whether it continued into the late Cretaceous–early Cenozoic.

This debate likely stemmed from different studied targets. For instance, Wu et al. (2006) drew their conclusions on the basis of granitic magmas. But felsic rocks can only yield information regarding melting behavior of the crust. Their inference on lithospheric thinning is therefore not straightforward. A more rigorous constraint on the timing of the destruction of the NCC is expected from studies of mantle-derived rocks. However existing studies are heavily concentrated on early Cretaceous (Gao et al., 2008; Guo et al., 2001; Xu et al., 2004b; Yang and Li, 2008; Zhang et al., 2002) and late Cenozoic basalts (Chen et al., 2007; Fan and Hooper, 1991; Song et al., 1990; Tang et al., 2006; Xu et al., 2004a, 2005, 2012; Zeng et al., 2011; Zhang et al., 2009; Zhi et al., 1990; Zhou and Armstrong, 1982), whereas investigation into the basalts emplaced during the latest Mesozoic and earliest Cenozoic are comparatively rare. To mitigate this shortcoming, geochronologcial and geochemical analyses have been undertaken on a suite of basalts from Fushun, North China, for which previous stratigraphic and K – Ar dating suggest a Paleogene age (Liu et al., 1992; Song and Cao, 1976; Wang et al., 1988). The aim of this study was to constrain the source of magmas emplaced during this particular period, and by inference the change in lithospheric architecture underneath the NCC. Using the concept of melting column (Fram and Lesher, 1993; Langmuir et al., 1992; Niu and Batiza, 1991), the data presented in this study indicate a continuation of lithospheric thinning towards late Cretaceous–early Cenozoic, thereby shedding new light on the debate as to the timing of cratonic destruction in the NCC.

2. Previous studies on magmatism in North China and samples for this study

The NCC is one of the oldest continental nuclei in the world (3.8 Ga, Jahn et al., 1987; Liu et al., 1992). Sedimentary records suggest that it is stable from the early Proterozoic to late Paleozoic. The decratonization is manifested by the occurrence of widespread Mesozoic–Cenozoic magmatism that has attracted intensive studies (e.g., Liu et al., 1992; Wu et al., 2005). Geochronological studies delineate a strong magmatic pulse at ~125 Ma (Wu et al., 2005; Xu et al., 2004a; Yang et al., 2003, 2008), forming the basis of the idea that the destruction of the NCC took place during the Early Cretaceous. However, the majority of the early Cretaceous basalts show a "crust-like" signature, such as enriched Sr – Nd isotopes and pronounced Nb – Ta depletions in the primitive mantle normalized spidergram, which is consistent with a derivation from an enriched lithospheric mantle source (Guo et al., 2001; Xu et al., 2004b; Zhang et al., 2002). This suggests that the lithosphere during the early Cretaceous was not thin enough for asthenosphere-derived melts to erupt (Xu et al., 2009). Moreover, to ensure melting of enriched components in a cratonic lithosphere, the lithosphere may have already been thinned to some extent in order to facilitate/enhance heat transfer from convective mantle to lithosphere. Pre-Cretaceous lithospheric thinning is supported by some late Triassic and Early Cretaceous mafic rocks in the Liaodong Peninsula which display positive $\varepsilon_{Nd}(t)$ values (Yang et al., 2007).

In terms of ε_{Nd} variation with time, the evolution of the Mesozoic–Cenozoic mafic magmatism in Shandong is divided into three stages (Xu, 2001; Xu et al., 2004b). The magmas in the first stage (180–95 Ma), characterized by negative $\varepsilon_{Nd}(t)$, were largely derived from the enriched lithospheric mantle (e.g., Guo et al., 2001; Xu et al., 2004b; Zhang et al., 2002), whereas those produced during the latest stage (younger than 80 Ma), characterized by positive $\varepsilon_{Nd}(t)$, were largely derived from the asthenospheric mantle (Yan et al., 2003; Zeng et al., 2011; Zhang et al., 2009). These two stages are separated by a magmatic hiatus between 95 and 80 Ma. A similar scenario is noted for western Liaoning, with the magmatic hiatus occurring between 117 and 106 Ma (Shao et al., 2005). Such a temporal compositional variation in mafic magmas is most likely accompanied by a lithospheric thinning process (Xu, 2001). The melting of the lithospheric mantle in the first stage was induced by the addition of volatiles and/or recycling of crustal components that led to a decrease in the melting temperature. The magmatic hiatus corresponded to exhaustion of fusible enriched components in the lithospheric mantle, which resulted in a termination of melting, until the time where lithospheric thinning had progressed far enough to produce partial melts of the peridotitic mantle, i.e. the depleted component. Thus only when the lithosphere was sufficiently thinned to make the thermal gradient cross the solidus of dry peridotites (McKenzie and Bickle, 1988), the melting of the upwelling asthenosphere generated the magmas of the third stage.

Compared to the intensive studies conducted on the Early Cretaceous and late Cenozoic basalts, investigation into late Cretaceous and early Cenozoic magmas is rare due to limited exposure, making the lithospheric evolution during this period poorly characterized. To fill this gap, a basaltic lava succession at Fushun is targeted in this study.

As the northern extension of the Tan-Lu fault (Fig. 1a), the Fushun–Mishan graben consists of Fushun, Laohutai and Lizigou Formations (Fig. 1). The Fushun Formation is a coal-bearing strata of 385–1979 m thick and was likely formed during the Paleogene time. The Laohutai Formation is composed of volcanic successions and subordinate amounts of coal, gray to black shales, sandstones and tuffs, with a total thickness of up to 501 m. It unconformably sits on the Archean Anshan Formation, and is in turn covered by Lizigou Formation (E_1lz) (Fig. 1b). It has been suggested that the Laohutai basalts are tholeiitic in composition (Liu et al., 1992; Wang and Wang, 1982). However, systematic sampling from bottom to top of the lava succession performed in this study reveals the presence of both tholeiitic and alkalic basalts. The Laohutai lava succession comprises three volcanic units, which are separated by coal-bearing shale and/or sandstone units (Fig. 1b). Each unit ended with amygdaloidal basalts. The lowermost of these units is alkali basalts, while the middle and upper units are tholeiitic basalts.

Alkali basalts are black massive and have olivine (<2%) and augite (5–10%) as phenocrysts, with a groundmass of plagioclase (20–40%), pyroxene (30–40%), and minor olivine and magnetite. Tholeiitic basalts exhibit similar petrographic characteristics, with relatively bigger phenocrysts compared to alkali basalts. Towards the top of the lava succession, the rocks are typically amygdaloidal.

3. Analytical methods

The samples were sawed into slabs and the central and most fresh parts were selected. The slabs were then crushed into small chips (<5 mm) which were hand-picked under a binocular microscope to remove those with surface alteration features and amygdaloidal vesicles. The purified rock chips were then leached with 1 N HCl in ultrasonic bath for 1–2 h, before being ground in a steel mill or in an agate mill. Major and trace elements, Ar – Ar and Sr – Nd isotopes were analyzed at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS) while Pb isotopes were analyzed at School of Earth Sciences, Queensland University, Australia. All errors are reported as 2σ.

Bulk rock major element abundances were determined using an X-ray fluorescence spectrometer (XRF, Rigaku ZSX100e) on glass disks following analytical procedures described by Goto and Tatsumi (1996). A pre-ignition was used to determine the loss on ignition (LOI) prior to major element analyses. Analytical uncertainties for majority of major elements were estimated at smaller than 1% from repeatedly analyzed U.S.G.S. standards AGV-1 and BHVO-2. The measured values of international standards are in satisfactory agreement with the recommended values (Table 1).

Trace elements were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS), using a Perkin-Elmer Sciex ELAN 6000 instrument, following the analytical procedures described by Xu (2002). The powders (~50 mg) were dissolved in distilled HF-HNO_3 in Savillex screwtop Telfon breakers at 150 °C for >4 days. Rh was used as an