Chemical Geology 470 (2017) 93–106

Contents lists available at ScienceDirect

Chemical Geology

journal homepage: www.elsevier.com/locate/chemgeo

Major transition of continental basalts in the Early Cretaceous: Implications for the destruction of the North China Craton

Kai Wu[a,f], Ming-Xing Ling[b,e,*], Weidong Sun[c,d,e,**], Jia Guo[a,f], Chan-Chan Zhang[a,f]

[a] CAS Key Laboratory of Mineralogy and Metallogeny, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[b] State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[c] Center of Deep Sea Research, Institute of Oceanography, Chinese Academy of Sciences, Qingdao 266071, China
[d] Laboratory for Marine Mineral Resources, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266237, China
[e] CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China
[f] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Editor: K. Mezger

Keywords:
Ridge subduction
Alkali basalt
The Pacific plate
North China Craton
Lithosphere thinning

ABSTRACT

Geochemical compositions of continental basalts are generally considered as the best proxy record of the chemical and isotopic evolution of subcontinental lithosphere and convective mantle. There are voluminous Cretaceous continental basalts in the North China Craton (NCC), which are mainly composed of alkali basalts with minor sub-alkali basalts. Abrupt changes in chemical and isotopic compositions of these basalts were often ascribed to subcontinental lithosphere thinning of the NCC. However, processes responsible for such changes and its implications for subcontinental lithosphere evolution remain obscure. Here we report major geochemical changes at ~108 Ma in the north part of the NCC. The > 108 Ma alkali basalts are characterized by negative $\varepsilon_{Nd}(t)$ and declining "island arc-like" geochemical characteristics from the east to the west, implying decreasing slab-derived components from westward subducting slabs in their metasomatized lithospheric mantle sources. In contrast, the < 108 Ma Cretaceous alkali basalts have depleted Sr-Nd isotopic compositions and "OIB-like" geochemical features. These observations suggest that westward subduction of the Paleo-Pacific plate was responsible for the Cretaceous basaltic activities in the NCC. Combined with plate reconstructions and geophysical observations, we propose that flat subduction of the "extinct" ridge between the Izanagi and the Pacific plates controlled this major transition as well as the destruction of the NCC. The transition from a supra-subduction zone environment to a within-plate extensional environment around 108 Ma is probably due to the eastward slab rollback and the northward shift of the spreading ridge.

1. Introduction

There is increasing evidence that the subcontinental lithospheric mantle is dynamic, as indicated by changes in its thickness and containing components with varying geochemical and isotopic compositions through time (Farmer, 2014 and references therein). Continental basalts provide direct clues for the evolution of continental lithosphere and the underlying convective mantle. Previous studies recognized two types of continental basalts, namely basalts with similar geochemical compositions to ocean island basalts (OIB-like) and those resembling island arc basalts (Crow et al., 2010; Farmer, 2014; Fitton, 2007; Kempton et al., 2011). These two types of continental basalts, in some cases, erupted in the same region, e.g., the North China Craton (NCC) (Liu et al., 2008; Meng et al., 2015; Xu, 2001; Yang and Li, 2008). Origin and spatial-temporal changes of these basalts are crucial to decipher the evolution of continental lithosphere.

The NCC experienced the replacement of an ancient, thick and refractory lithospheric mantle by a young and fertile one through lithosphere thinning during the Mesozoic (Fan et al., 2000; Gao et al., 2008; Griffin et al., 1998; Ma et al., 2016; Menzies et al., 2007; Xu, 2001, 2014; H.F. Zhang et al., 2003), and the peak period of lithosphere thinning occurred at 130–110 Ma (Meng et al., 2015; Xu et al., 2004, 2009). Meanwhile, Cretaceous basalts in the NCC have also experienced a geochemical transition from "island arc-like" to "OIB-like" (Liu et al., 2008; Meng et al., 2015; Xu, 2001; Yang and Li, 2008; H.F. Zhang et al., 2003). It, however, still remains obscure that when and how such a transition happened beneath the NCC, and what implications for lithosphere evolution can be obtained. Liu et al. (2008) proposed a major

---

* Correspondence to: M.-X. Ling, State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China.
** Correspondence to: W. Sun, Center of Deep Sea Research, Institute of Oceanography, Chinese Academy of Sciences, Qingdao 266071, China.
E-mail addresses: mxling@gig.ac.cn (M.-X. Ling), weidongsun@gig.ac.cn (W. Sun).

http://dx.doi.org/10.1016/j.chemgeo.2017.08.025
Received 31 May 2017; Received in revised form 11 August 2017; Accepted 29 August 2017

geochemical transition from "island arc-like" to "OIB-like" in the NCC at ~110 Ma. This study and subsequent researches by Yang et al. (2012) and Meng et al. (2015), however, comprised alkali basalts from Fangcheng (124.9 Ma), Feixian (119 Ma), Sihetun (125–124 Ma), Fuxin (107–94 Ma), Qujiatun (81.6 Ma) and Daxizhuang (73 Ma) and sub-alkali basalts from Yixian (125–122 Ma). No basalts erupted between 120 Ma and 107 Ma were discussed in these studies. The geochemical transition of Cretaceous basalts is ascribed to changes in their magma sources from the metasomatized lithospheric mantle to the asthenosphere (Meng et al., 2015; Ma et al., 2014; Xu, 2001). The occurrence of asthenosphere-dominated melts was generally considered as a mark of accomplishment of the lithosphere destruction, because decompression melting of asthenosphere beneath ancient cratons can only occur when the lithosphere is thin enough (Ma et al., 2016; Mckenzie and Bickle, 1988; Xu, 2014). Therefore, some studies proposed that this change indicated that the lithosphere thinning has completed at ~110 Ma through a "rapid" delamination process (e.g. Gao et al., 2004; Meng et al., 2015; Wu et al., 2002). Such a lithosphere delamination process was also adopted to explain the recently discovered small amounts of ~121 Ma lamprophyres with OIB-like geochemical characteristics in Shandong peninsula (Ma et al., 2014; Ma et al., 2016). It has been suggested that these lamprophyres were derived from the asthenosphere, indicating that the ancient lithospheric mantle would have already been replaced by a juvenile one at ~121 Ma in the eastern margin of the NCC (Dai et al., 2016; Ma et al., 2014, 2016). In contrast, this geochemical transition was considered as a part of a prolonged thermal erosion process, because the long-lasting continental lithosphere-derived magmatism (180–90 Ma) was replaced by asthenosphere-derived basaltic rocks in the Late Cretaceous (Menzies et al., 2007; Xu, 2001; Xu et al., 2004), and the enriched components observed in the Early Cretaceous basalts were essentially absent in the Tertiary basalts due to decratonization (Lu et al., 2006; Xu, 2014).

In addition, processes associated with the subduction of the Paleo-Pacific plate (Ling et al., 2013; Sun et al., 2007), e.g., "basal hydration weakening" to transform the lithosphere into convective asthenosphere (Guo et al., 2014; Niu, 2005; Niu et al., 2015), perturbing the hydrous mantle transition zone by the subducting Izanagi plate to release water for hydroweakening the lithospheric mantle (Kusky et al., 2007; Wang et al., 2016), slab rollback-induced unstable mantle flows (Sun, 2015; Wang et al., 2016; Zhang et al., 2014; Zhu et al., 2011, 2015; Zhu et al., 2012a, 2012b; Zhu and Zheng, 2009) or ridge subduction in the Early Cretaceous (Li et al., 2014; Ling et al., 2009, 2013; Sun et al., 2007), have also been proposed to explain the lithosphere destruction of the NCC. If subduction of the Pacific plate was the controlling factor, the question is what kind of signatures of plate subduction can be seen from those Cretaceous basalts?

Here we use a more complete geochemical dataset to explore spatial and temporal evolution of Cretaceous basalts in the NCC, as well as their relationship to the westward subduction of the Paleo-Pacific plate. Combined with plate reconstructions, geophysical observations and geological records of surrounding tectonic units, we also provide new insights into the petrogenesis of continental basalts, the evolution of the lithospheric mantle and the tectonics at the eastern Asian continental margin in the Cretaceous.

2. Geological background

The NCC is comprised of the east and the west blocks separated by the Proterozoic Trans-North China Orogen, which geographically corresponds to the Taihang Mountains (Guo et al., 2014; H.F. Zhang et al., 2003; Zhao et al., 2001). The Tan-Lu fault cut across the east part of the NCC (Xu, 2001) (Fig. 1). After collision between the east and the west blocks at ~1.8 Ga, the NCC remained stable until the Mesozoic (Gao et al., 2004; Griffin et al., 1998; Xu, 2001; Zhu et al., 2012a). Late Ordovician diamondiferous kimberlite reveals a cold, thick lithosphere of ~200 km (Fan and Menzies, 1992; Gao et al., 2002; Griffin et al., 1998; Menzies et al., 2007; Wu et al., 2006; Xu et al., 2004). However, studies on Late Cretaceous and Cenozoic basalts and mantle xenoliths indicate that the lithosphere has been thinned to ~60 km (Ma et al., 2016; Menzies et al., 2007; Wu et al., 2005; Xu, 2001, 2014; Zhang and Zheng, 2003). Therefore, > 100 km lithospheric mantle is inferred to have been removed during the Mesozoic (Fan and Menzies, 1992; Gao et al., 2008; Griffin et al., 1998; Wu et al., 2005; Xu, 2001; Zhu et al., 2012a).

Although the timing for lithosphere destruction of the NCC still remains controversial, it is generally accepted that the most intense period for lithospheric thinning was the Early Cretaceous, as suggested by occurrence of voluminous magmatic activities and significant mineralization (Gao et al., 2008; Menzies et al., 2007; Wu et al., 2005; Xu et al., 2004). Cretaceous basalts spread throughout the east block of the NCC. These basalts are mainly composed of alkali basalts with minor sub-alkali basalts (Fig. 1 and Table S1). Sub-alkali basalts are only outcropped in regions adjacent to the Tan-Lu Fault (Fig. 1). In contrast, alkali basalts are distributed even in the interior of the NCC (Fig. 1). Jining is the westernmost site that has > 108 Ma alkali basalts in the NCC reported so far, which is located at the western block of the NCC (Guo et al., 2014). In this contribution, a more complete dataset for Cretaceous basalts from the NCC including those formed between 120 and 107 Ma are used for the following discussion. Accurate intruding ages for these basalts are well constrained by various means, and all chemical data are from literatures without any artificial selection. More details about the geochronological and geochemical dataset are available in the "Supplementary materials". Crustal assimilation for each basaltic intrusion is precluded in corresponding data source, which has also been summarized in the "Supplementary materials". In addition, since experiments have shown that alkali basalts was produced at higher pressures than sub-alkali basalts (DePaolo and Daley, 2000; Falloon et al., 1988), variations in basalt compositions may partly result from vertical mantle heterogeneity. In order to minimize these disturbances, alkali and sub-alkali basalts are treated separately in the following sections.

3. Major transitions in Cretaceous basalts

Previous studies indicate that the isotopic and geochemical change of the Cretaceous basalts in the NCC occurred at the end of the Early Cretaceous (Liu et al., 2008; Meng et al., 2015; Xu, 2001; Yang and Li, 2008; Yang et al., 2012). The Cretaceous basalts in the NCC can be divided into two groups according to their Nd isotopic compositions: basalts formed before 108 Ma with negative $\varepsilon_{Nd}(t)$ and those formed after 108 Ma with positive $\varepsilon_{Nd}(t)$ (Fig. 2). Basalts formed before 108 Ma in the NCC exhibit enriched and generally variable Sr-Nd isotopic compositions. The Fangcheng basalts and the Feixian basalts have the lowest $\varepsilon_{Nd}(t)$ and the highest $(^{87}Sr/^{86}Sr)_i$ among these basalts. Chengde basalts and Xiaoling basalts show similar ε_{Nd} (t) with Fangcheng and Feixian basalts, but lower $(^{87}Sr/^{86}Sr)_i$. The rest of the > 108 Ma basalts have relatively high $\varepsilon_{Nd}(t)$ and moderate $(^{87}Sr/^{86}Sr)_i$, most of which lies within the field defined by Paleozoic kimberlite and peridotite. In contrast, the < 108 Ma Cretaceous basalts display depleted Sr-Nd isotopic composition, which are mostly plotted in the field defined by Cenozoic basalts in the NCC (Fig. 2).

The transition in geochemical compositions is illustrated in Fig. 3. The > 108 Ma alkali basalts are characterized by lower high field strength elements (HFSE), but generally higher and variable large ion lithophile elements (LILE) and LILE/HFSE, which overlaps the fields of arc magmas (Fig. 3). With the exception of the Jining basalts, all the > 108 Ma alkali basalts and all Cretaceous sub-alkali basalts have lower Nb contents (< 25 ppm). In contrast, the < 108 Ma Cretaceous alkali basalts have higher and variable HFSE (e.g. Nb > 25 ppm), but lower LILE concentrations and LILE/HFSE ratios. Interestingly, HFSE contents and Nb/Zr ratios of those < 108 Ma alkali basalts are positively correlated with Ba, Th, Pb/Zr and Ba/Zr (Fig. 3), which suggests