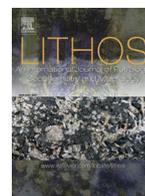




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## Research Article

# Petrogenesis of the early Cretaceous intra-plate basalts from the Western North China Craton: Implications for the origin of the metasomatized cratonic lithospheric mantle

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## ABSTRACT

We present new bulk-rock  $^{40}\text{Ar}/^{39}\text{Ar}$  age, major and trace elements and Sr-Nd-Hf isotopic data on the early Cretaceous intra-plate alkali basalts from the Western North China Craton (WNCC) to study the origin of the metasomatized cratonic lithosphere mantle. The age of these basalts is ~116 Ma. These basalts have elevated incompatible element abundance with high  $[\text{La}/\text{Sm}]_{\text{N}}$  (2.80–4.56) and enriched Sr-Nd-Hf isotopic compositions ( $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7062\text{--}0.7075$ ,  $\varepsilon_{\text{Nd}}(t) = -6.0$  to  $-13.0$  and  $\varepsilon_{\text{Hf}}(t) = -8.3$  to  $-17.4$ ), being similar to the contemporary analogues from the Western North China Craton and Paleozoic kimberlites and mantle xenoliths. The WNCC basalts also show good correlations between  $\varepsilon_{\text{Nd}}(t)$  and  $\varepsilon_{\text{Hf}}(t)$ , and high  $[\text{La}/\text{Sm}]_{\text{N}}$ . All these geochemical observations are consistent with the interpretation that these basalts originated from partial melting of the lithospheric mantle that experienced melt metasomatism. Two types metasomatism melts are required to explain the geochemical characteristics of these rocks. The obvious negative Nb-Ta (compared with K)-Ti and positive Ba-Pb anomalies observed in these basalts further constrain that one of the metasomatic melts was derived from the subducted terrigenous sediment. Furthermore, the overall higher P/Nd, Nb/La and Nb/Th and lower Lu/Hf of basalts in the WNCC suggest that there is also contribution of low-F melts from asthenosphere mantle. Collectively, we suggest that the formation of the metasomatized lithosphere mantle beneath the WNCC is the process of metasomatic reaction between mantle peridotite and the melts of different origin to generate metasomatic veins containing amphibole/phlogopite. Partial melting of the metasomatic lithospheric mantle at 106–120 Ma in the WNCC was considered to be induced by thermal perturbation that was ultimately related to the breakoff of the subducted oceanic slab following the closure of the Mongolia-Okhotsk ocean.

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## 1. Introduction

Cratonic lithospheric mantle is physically thick, cold, buoyant and rigid and geochemically depleted in incompatible element with high MgO and low FeO, which is thought to be the residue of the upper mantle after high extent of melt extraction in early history of the earth (e.g., Abbott et al., 1997; Jordan, 1988; Ringwood, 1975). For this reason, the overlying continental crust can survive for a long time. However, the processes of lateral subduction (e.g., Hawkesworth et al., 1993) and vertical upwelling of melts/fluids from the asthenospheric mantle (e.g., Niu, 2005, 2014) could potentially change the mineralogy and

geochemistry of the cratonic lithosphere mantle, resulting in varying extents of lithosphere modification/re-fertilization and increasing the susceptibility of the craton destruction/lithosphere thinning. Therefore, the melts or xenoliths derived from such ancient metasomatized cratonic lithosphere mantle, for example, the North China Craton (NCC), would contain important information on the cratonic lithosphere re-fertilization history.

Previous studies, mostly based on >110 Ma mafic igneous rocks in the Eastern North China Craton (ENCC), showed that the partial melts derived from the metasomatized NCC lithospheric mantle share the similar continental crust-like signatures of being enriched in large ion lithosphere elements (LILE; e.g., Rb, Ba, K), depleted in high field strength elements (HFSE; e.g., Nb, Ta, Ti) and with enriched Sr-Nd-Hf isotope compositions (radiogenic Sr and unradiogenic Nd-Hf) (e.g., Dai et al., 2016; Liu et al., 2008; Meng et al., 2015), implying that

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the whole NCC lithospheric mantle experienced re-fertilization before partial melting. Formation of the enriched lithosphere mantle of NCC has been ascribed to: (1) the delamination of the lower continental crust (e.g., Gao et al., 2004, 2008; Liu et al., 2008); (2) the subduction of continental crust of South China Block (e.g., Dai et al., 2016; Yang et al., 2012; Zhang et al., 2002; Zhao et al., 2018); (3) the subduction of the Paleo-Pacific plate (e.g., Ma et al., 2014). The “delamination of lower crust” model deciphers the scenario that the lithosphere mantle was enriched/metamorphosed by the melts derived from foundered lower crust (Gao et al., 2004, 2008; Liu et al., 2008). While this model is attractive, it is physically not straightforward how the lower continental crust of the NCC together with buoyant lithospheric mantle foundered into the asthenosphere mantle in scale of the whole North China (Niu, 2014). Furthermore, the thickening of the lower crust is the prerequisite for the crust delamination. But except for some areas (e.g., Xuhuai), there is not enough evidence to show that this process occurred in the whole North China Craton (Wu et al., 2008 and references therein). The “continent-continent subduction/collision” model means the lithosphere mantle enriched through interaction with melt generated from melting of the subducted crust of South China Block (Dai et al., 2016; Yang et al., 2012; Zhang et al., 2002; Zhao et al., 2018). This model cannot explain the origin of the enriched lithospheric mantle beneath the north margin and interior of the NCC, but only works restricted to the areas close to the Dabie–Sulu Orogenic Belt. Some studies suggest the lithosphere mantle was modified by subduction-related fluids from Paleo-Pacific plate (e.g., Ma et al., 2014). Similarly, the subduction of the Paleo-Pacific plate cannot explain the origin of the enriched lithospheric mantle beneath the area far from the Pacific subduction zone, for example, the Western North China Craton (WNCC).

There is growing evidence that the lithosphere under WNCC has also been thinning in the Mesozoic (Chen et al., 2009; Guo et al., 2014) as evidenced by the widespread late Cretaceous volcanic rocks along north margin of WNCC (Fig. 1a; Guo et al., 2014, 2018; He et al., 2013; Zhang, 2013; Zhong et al., 2014, 2015; Zou et al., 2008). These early Cretaceous basalts have high incompatible element abundances and highly enriched Sr–Nd–Hf isotopic compositions (e.g., Guo et al., 2014, 2018; Zhong et al., 2014, 2015), implying they also originated from an ancient metasomatized lithosphere mantle (Guo et al., 2014, 2018). However, the mechanism of the enriched mantle formation was unclear in details. The study of lithosphere mantle enrichment beneath northern margin of WNCC could help us to understand the mantle re-fertilization beneath the area far from Dabie–Sulu Orogenic Belt and Pacific subduction zone and have a significant meaning in the exploration of the evolution of whole NCC.

Here we present new bulk-rock  $^{40}\text{Ar}/^{39}\text{Ar}$  dating, major element, trace element and Sr–Nd–Hf isotopic data on the early Cretaceous basalts from Wulate Zhongqi and Heishitougou, Western North China Craton (WNCC; Fig. 1) to study the origin of the metasomatized lithospheric mantle beneath WNCC. The data suggest that the enriched lithospheric mantle beneath the WNCC was formed through metasomatism by silicate melts derived from terrigenous sediments and low-F melts from asthenosphere mantle. These processes could lead to the formation of metasomatic dikes/veins containing amphibolite/phlogopite. Integrated with the regional geology, we suggest that the sediments were recycled into the mantle depth together with the subducted Paleo-Asia ocean slab in early Paleozoic, while subsequent melting of the metasomatized lithospheric mantle materials in early Cretaceous produced the WNCC intra-plate alkali basalts.

## 2. Geological setting and samples

The North China Craton is one of the oldest cratons on the earth with the history in excess of 3.8 Gyrs (e.g., Liu et al., 1992). It is bounded by the Central Asian Orogenic Belt (CAOB) to the north and the Qinling–Dabie–Sulu high-ultrahigh pressure metamorphic belt to the south

(Fig. 1a). It can be divided into Eastern North China Craton (ENCC) and Western North China Craton (WNCC) based on the studies of the basement rocks (Fig. 1a; e.g., Zhao et al., 2001). The WNCC is further divided into the Yinshan block in the north and the Ordos block in the south by the nearly E–W trending, ca. 2.0 to 1.9 Ga Khondalite Belt (Zhao et al., 2005). After the amalgamation of the eastern and western blocks, the North China Craton remained tectono-thermally quiescent until the Mesozoic. Previous studies showed that the ENCC experienced extensive destruction/lithosphere thinning in the Mesozoic ( $> 110$  Ma) (Niu, 2005, 2014; Zhu et al., 2011), while the lithosphere thinning in the WNCC was limited in the northern margin (Chen et al., 2009; Guo et al., 2014).

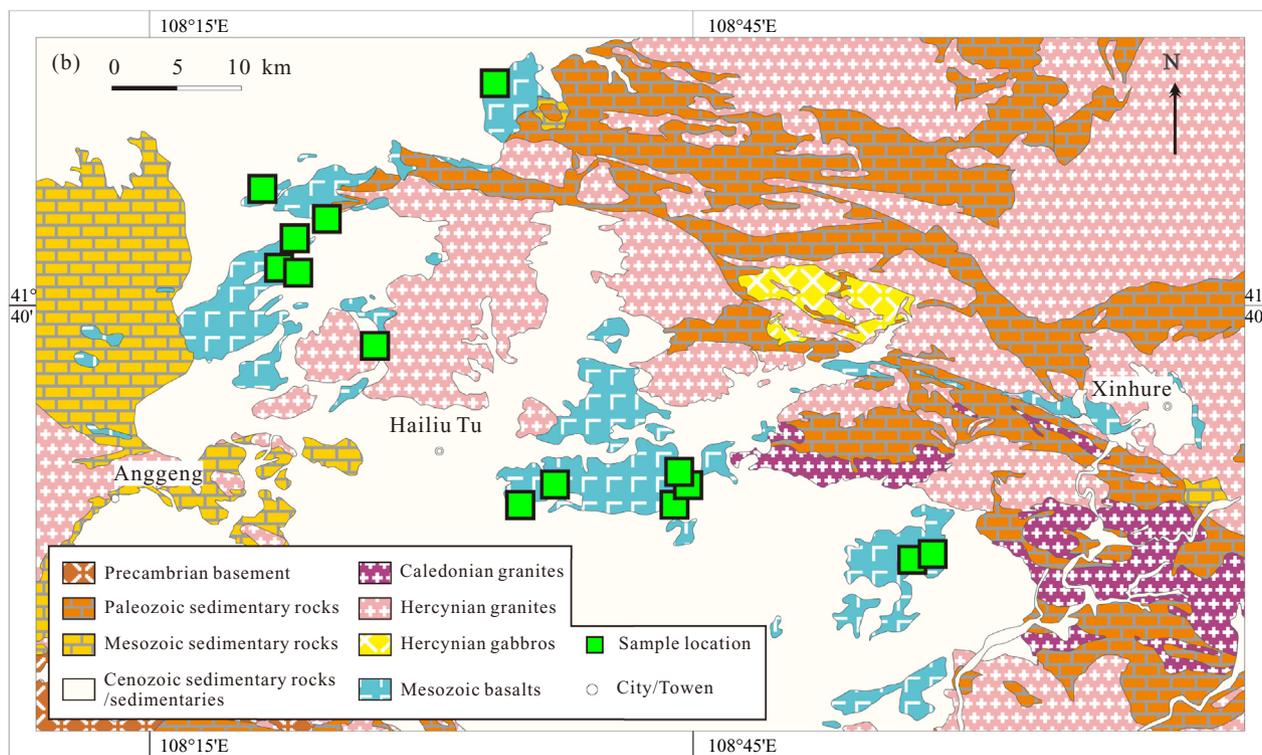
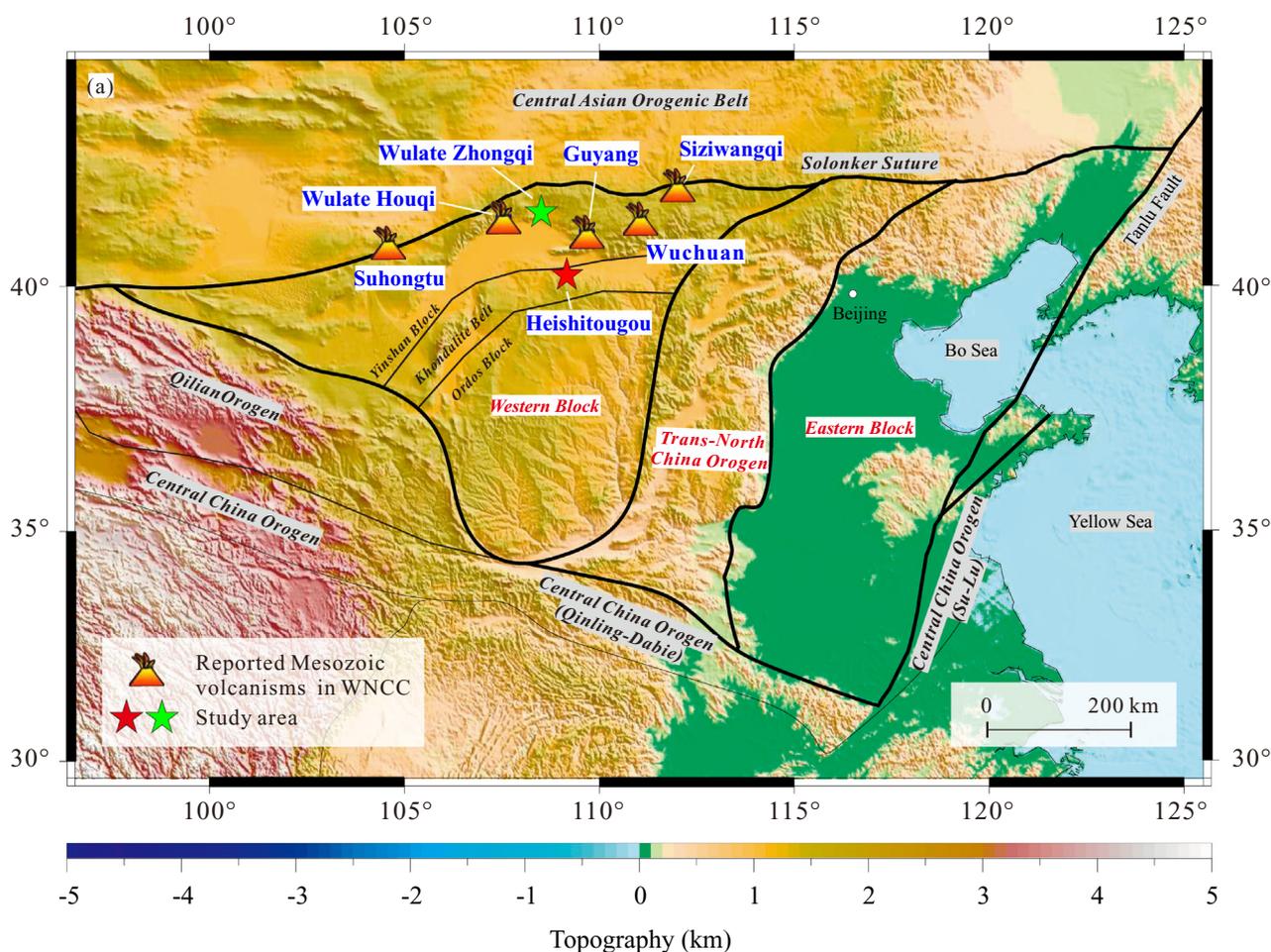
The northern margin of the WNCC was an active continental margin during Paleozoic to Early Triassic with the Paleo-Asian slab subducting southward (Li, 2006; Xiao et al., 2003; Zhang et al., 2009). The Paleo-Asian ocean closed in early Triassic when the North China Craton collided with the southern Mongolian composite terrane along the Solonker Suture (SLS; Wilde, 2015). Following the closure of the Paleo-Asian ocean, the northern margin of the NCC became active continental margin again with the Mongolia–Okhotsk Ocean subducting southward. The Mongolia–Okhotsk Ocean was ultimately closed in Jurassic to the earliest Cretaceous (Donskaya et al., 2013; Tomurtogoo et al., 2005), and the region came into intra-plate tectonic setting in early Cretaceous. So far, only several outcrops of Early Cretaceous volcanic rocks have been reported in the WNCC, i.e., Siziwang Qi, Wuchuan Basin, Guyang Basin, Wulate Houqi and Suhongtu, dominated by mafic-intermediate compositions with minor felsic volcanic assemblages (Fig. 1a; Guo et al., 2014, 2018; He et al., 2013; Zhang, 2013; Zhong et al., 2014, 2015; Zou et al., 2008). These volcanic rocks were erupted during 135–105 Ma and are spatially distributed along the northern margin of the WNCC (Table 1 and Fig. 1a), forming an E–W trending volcanic rock belt.

Wulate Zhongqi is a newly identified Mesozoic volcanism outcrop that is located on the north margin of the WNCC (Fig. 1). These basalts, erupted on the Cretaceous red sedimentary layer (Fig. 2a), covers a large area of  $\sim 240$  km<sup>2</sup> (Fig. 1b). Heishitougou is located  $\sim 150$  km south of the Wulate Zhongqi in Khondalite Belt (Fig. 1). Heishitougou volcanic rocks are covered under the Quaternary sediments with very limited outcrops of 2–3 m thick (Fig. 2b) and their eruption age is 126.2 Ma (Zou et al., 2008). The samples in this study include Wulate Zhongqi basalts and andesitic basalts and Heishitougou basalts. Most basalt and andesitic basalt samples are massive with intergranular texture, being made up of microlites of plagioclase, olivine, clinopyroxene and magnetite (Fig. 2c, d, f). Several Wulate Zhongqi samples have porphyritic texture with olivine ( $\sim 5$ – $10\%$ ) and plagioclase ( $\sim 5\%$ ) as phenocrysts, and most of olivine phenocrysts were altered into iddingsite (Fig. 2e). Their groundmass, with intergranular texture, is made up of microlites of plagioclase, clinopyroxene and olivine (Fig. 2e).

## 3. Sample preparation and analytical procedure

### 3.1. $^{40}\text{Ar}$ – $^{39}\text{Ar}$ Geochronology

We selected the freshest basaltic sample (ZQ14-47; Fig. 2f) for  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  dating. The sample grains were irradiated for 14 h in the Cadmium-lined B-1 CLICIT facility, a TRIGA-type reactor, in Oregon State University, USA. After a decay period of irradiation, samples were analysed by laser  $^{40}\text{Ar}/^{39}\text{Ar}$  heating following procedures detailed in Vasconcelos et al. (2002). Before analysis, the rock grains and fluence monitors were baked-out under vacuum at  $\sim 200$  °C for  $\sim 12$  h. The sample was heated incrementally with a continuous-wave Verdi Diode laser (532 nm) with a 2 mm wide defocused beam. The fraction of gas released was cleaned through a cryocooled cold-trap ( $T = -125$  °C) and two C-50 SAES Zr–V–Fe getters and analysed for Ar isotopes in a MAP215-50 mass spectrometer equipped with a third C-50 SAES Zr–V–Fe getter. Analytical procedures followed are described in Deino and



**Fig. 1.** (a) Sketch map of major tectonic divisions of the North China Craton (modified from Shi et al. (2020) and Zhao et al. (2001)). Also shown are the early Cretaceous volcanism in the WNCC. (b) The distribution and sample locations of the Wulate Zhongqi basalts.

**Table 1**  
Statistics of age data of early Cretaceous volcanics from the WNCC

Location	Rock type	Age(Ma)	Dating method	Data source
Siziwang Qi	Shoshonite	127 ± 2	Whole rock Ar-Ar	He et al., 2013
	Shoshonite	119.6 ± 1.4	Whole rock K-Ar	Zhang et al., 2005
	Shoshonite	128.4 ± 1.8	Whole rock K-Ar	
	Shoshonite	108.6 ± 1.4	Whole rock K-Ar	
Guyang	Basalt	133.13 ± 0.91	Whole rock Ar-Ar	Guo et al., 2018
	Basalt	123.47 ± 0.62	Whole rock Ar-Ar	
	Rhyolite	126.5 ± 1.3	SHRIMP zircon U-Pb	
	Rhyolite	126.1 ± 3.0	SHRIMP zircon U-Pb	
Wulate Zhongqi	Trachyte	122 ± 2	LA-ICP-MS Zircon U-Pb	Zhang, 2013
	Rhyolite	135 ± 2	LA-ICP-MS Zircon U-Pb	
	Basalt	116.35 ± 0.75	Whole rock Ar-Ar	This study
Wuchuan	Tuff	130 ± 3	LA-ICP-MS Zircon U-Pb	Zhang, 2013
Heishitougou	Basalt	126.2 ± 0.4	Whole rock Ar-Ar	Zou et al., 2008
Wulate Houqi	Basalt	114.42 ± 0.58	Whole rock Ar-Ar	Guo et al., 2018
	Basalt	107.30 ± 0.54	Whole rock Ar-Ar	
Suhongtu	Andesite to basalt	114.1 ± 0.3	Whole rock Ar-Ar	Zhu et al., 2008
	Andesite to basalt	113.8 ± 0.7	Whole rock Ar-Ar	
	Andesite to basalt	109.3 ± 2.8	Whole rock Ar-Ar	
	Andesite to basalt	110.8 ± 1.3	Whole rock Ar-Ar	
	Andesite to basalt	110.7 ± 1.6	Whole rock Ar-Ar	
	Andesite to basalt	110.3 ± 1.6	Whole rock Ar-Ar	
	Andesite to basalt	110.4 ± 1.2	Whole rock Ar-Ar	
	Andesite to basalt	110.9 ± 1.9	Whole rock Ar-Ar	
	Andesite to basalt	110.6 ± 1.5	Whole rock Ar-Ar	
	Andesite to basalt	111.1 ± 1.2	Whole rock Ar-Ar	
	Andesite to basalt	110.9 ± 2.3	Whole rock Ar-Ar	
	Alkali basalt	110.62 ± 1.40	Whole rock Ar-Ar	Zhong et al., 2015
	Alkali basalt	112.71 ± 2.06	Whole rock Ar-Ar	
	Alkali basalt	106.64 ± 1.38	Whole rock Ar-Ar	
	Alkali basalt	106.48 ± 1.32	Whole rock Ar-Ar	
Alkali basalt	108.93 ± 1.68	Whole rock Ar-Ar		
Alkali basalt	109.51 ± 1.76	Whole rock Ar-Ar		

Potts (1990) and Vasconcelos et al. (2002). A  $^{40}\text{Ar}/^{36}\text{Ar}$  value of  $298.56 \pm 0.31$  for atmospheric argon was used for the calculation of the mass spectrometer discrimination (Renne et al., 2009). The irradiation correction factor (J) for each Al-disk were determined by the laser total fusion analyses of 15 individual aliquots of neutron fluence monitor.

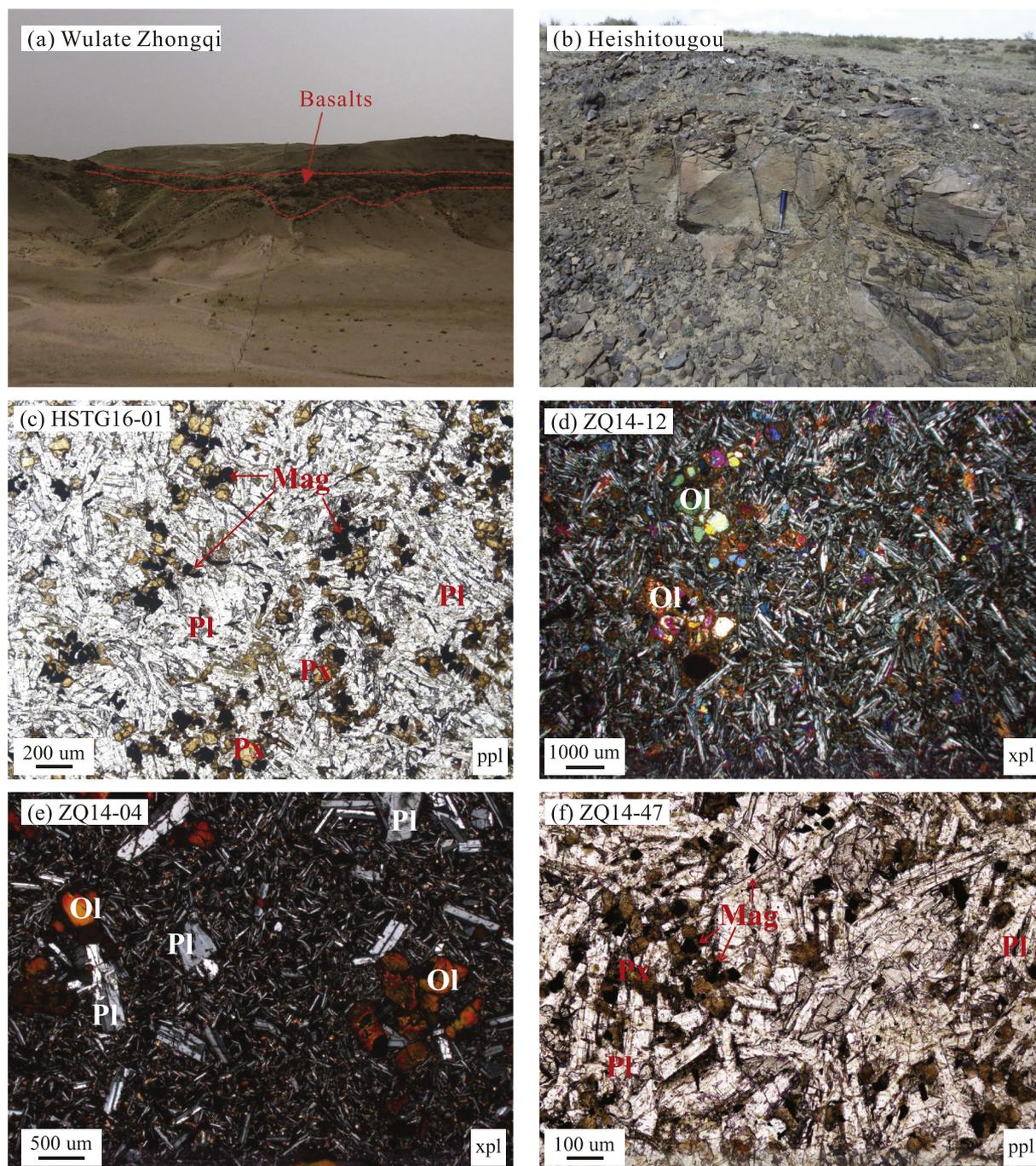
### 3.2. Geochemistry

Eighteen samples were chosen for geochemical analyses. We removed weathered surfaces, pen marks and saw marks first. All samples were crushed into grains of ~0.5–1.0 mm size to painstakingly remove phenocrysts under a binocular. The sample grains were then ultrasonically-cleaned with Milli-Q water and dried in a clean environment before analyses.

All the bulk-rock geochemical analyses were done at the Laboratory of Ocean Lithosphere and Mantle Geodynamic, Institute of Oceanology, Chinese Academy of Sciences. Major elements were analysed using an Agilent 5100 inductively coupled plasma-optical emission spectroscopy (ICP-OES) following Kong et al. (2019). After dried at 105 °C for ~2 h in the oven, about ~50 mg rock powders were weighted in platinum crucibles together with ~250 mg lithium metaborate. The platinum crucibles were heated in the muffle furnace at 1050 °C for 2 h until the mixture completely molten. The crucible was further heated over a Bunsen burner (Dragon series) at 1000 °C and stirred to ensure all sample materials forming a single coherent melt drop that was finally poured/quenched and resolved in 5%  $\text{HNO}_3$  at room temperature. USGS standards materials BCR-2 and AGV-2 were used to monitor the analytical accuracy and precision. For loss on ignition (LOI) analysis, ~500 mg samples were weighed and heated in a muffle furnace at 1000 °C for 30 min, cooled in a desiccator, and then weighed again to calculate the weight loss as the LOI (see Supplementary Table 1).

Trace elements were analysed using an Agilent-7900 inductively coupled plasma mass spectrometer (ICP-MS) following Chen et al. (2017). About 50 mg rock powders were dissolved with distilled  $\text{HNO}_3 + \text{HCl} + \text{HF}$  in a high-pressure jacket equipped Teflon beaker at 190 °C for 15 h. The sample solutions are then evaporated to incipient dryness at 100 °C, refluxed with 2 ml of concentrated  $\text{HNO}_3$  before being heated again to incipient dryness to remove all the residual HF, and then re-dissolved with distilled 20%  $\text{HNO}_3$  for 2 h till complete digestion/dissolution. USGS standards materials BCR-2 and AGV-2 were used to monitor the analytical accuracy and precision (see Supplementary Table 1).

The Sr-Nd-Hf isotope ratios were measured using a Nu Plasma II Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC ICP-MS) following the procedures of Sun et al. (2019). The sample dissolving process was similar to that for trace elements analysis, and the final solution was re-dissolved in 2 ml 3 N  $\text{HNO}_3$ . The final sample solution was first loaded onto Sr-spec resin columns to separate Sr with the eluted sample solution collected and then loaded onto AG 50 W-X8 resin columns to separate REE. The eluted sample solution from AG 50 W-X8 resin columns was collected and then loaded onto Ln-spec resin columns to collect Hf. The separated REE solution was dried and re-dissolved with 0.25 N HCl before being loaded onto Ln-spec resin columns to collect Nd. The measured  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$ , and  $^{176}\text{Hf}/^{177}\text{Hf}$  isotope ratios were normalized for instrumental mass fraction using the exponential law to  $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ ,  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$  and  $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ , respectively. Standards of NBS-987, JNdi-1 and Alfa Hf were analysed every three to five samples to monitor the instrument drift for Sr, Nd and Hf isotopes, respectively. Repeated analysis for NBS-987 gave an average  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710251 \pm 0.000020$  ( $n = 8, 2\sigma$ ), for JNdi-1 gave an average  $^{143}\text{Nd}/^{144}\text{Nd} = 0.512111 \pm 0.000003$ , ( $n = 6, 2\sigma$ ), and for Alfa Hf gave an average  $^{176}\text{Hf}/^{177}\text{Hf} = 0.282196 \pm 0.000007$  ( $n = 8, 2\sigma$ ). The analysis results of USGS reference materials AGV-2, BCR-2 and BHVO-2 run with our



**Fig. 2.** Representative field photographs and petrography. (a) Volcanic rock outcrop in Wulate Zhongqi. (b) Volcanic rock outcrop in Heishitougou. (c)–(f) Petrography of the basalts and andesitic basalts from Wulate Zhongqi and Heishitougou. Pl- plagioclase; Mag- magnetite; Px- pyroxene; Ol- olivine.

samples are given in Table 2, which are all consistent with the reported reference values (GeoREM, <http://georem.mpch-mainz.gwdg.de/>).

## 4. Results

### 4.1. $^{40}\text{Ar}$ – $^{39}\text{Ar}$ geochronological data

The  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  age data for sample ZQ14-47 from Wulate Zhongqi is reported in Supplementary Table 2 and shown in Fig. 3. The sample was analysed twice, and the two incremental heating spectra of sample ZQ14-47 define similar plateau-like segments, containing ~40 and 50%

of the total  $^{39}\text{Ar}$  released, and these plateau-like segments yield compatible ages of  $119.65 \pm 0.40$  and  $119.54 \pm 0.53$  Ma (Fig. 3a). An integrated apparent age obtained by combining the results from all steps analysed is also shown (Fig. 3b). Inverse isochron was gotten by plotting all results on a  $^{39}\text{Ar}/^{40}\text{Ar}$  vs.  $^{36}\text{Ar}/^{40}\text{Ar}$  diagram and the inverse age was calculated from the  $^{39}\text{Ar}/^{40}\text{Ar}$  intercept of isochron on the diagram. However, the inverse isochron suggests significant excess argon in the sample ( $^{40}\text{Ar}/^{36}\text{Ar}$  intercept =  $857 \pm 72$ ). In this case, the inverse isochron is more reliable here and the calculated inverse isochron age is  $116.35 \pm 0.75$  Ma. Therefore, the age of these basalts is ~116 Ma.

**Table 2**

Bulk rock Sr-Nd-Hf isotope analysis result for the early Cretaceous basalts from Wulate Zhongqi and Heishitougou and the USGS standard materials.

Sample	$^{87}\text{Rb}/^{86}\text{Sr}^a$	$^{87}\text{Sr}/^{86}\text{Sr} \pm 1\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}_i^b$	$^{147}\text{Sm}/^{144}\text{Nd}^a$	$^{143}\text{Nd}/^{144}\text{Nd} \pm 1\sigma$	$^{143}\text{Nd}/^{144}\text{Nd}_i^b$	$^{176}\text{Lu}/^{177}\text{Hf}^a$	$^{176}\text{Hf}/^{177}\text{Hf} \pm 1\sigma$	$^{176}\text{Hf}/^{177}\text{Hf}_i^b$	$\epsilon_{\text{Nd}(t)}$	$\epsilon_{\text{Hf}(t)}$
ZQ14-04	0.284658	0.708013 ± 8	0.707543	0.116999	0.512054 ± 2	0.511965	0.009202	0.282452 ± 4	0.282431	-10.22	-9.58
ZQ14-06	0.278009	0.707603 ± 7	0.707143	0.113846	0.512042 ± 4	0.511955	0.008238	0.282425 ± 2	0.282407	-10.40	-10.44
ZQ14-09	0.191951	0.706930 ± 3	0.706613	0.101585	0.511952 ± 6	0.511875	0.005541	0.282325 ± 1	0.282312	-11.97	-13.79
ZQ14-12	0.236677	0.707432 ± 6	0.707040	0.116473	0.512043 ± 3	0.511955	0.008261	0.282428 ± 2	0.282410	-10.41	-10.34
ZQ14-26	0.164826	0.707251 ± 5	0.706978	0.100089	0.511901 ± 3	0.511825	0.005393	0.282231 ± 1	0.282220	-12.94	-17.08
ZQ14-29	0.132837	0.707000 ± 6	0.706780	0.106168	0.512261 ± 6	0.512180	0.006623	0.282425 ± 2	0.282410	-6.01	-10.33
ZQ14-37	0.300084	0.706725 ± 4	0.706229	0.109955	0.512109 ± 2	0.512025	0.007035	0.282466 ± 1	0.282451	-9.04	-8.89
ZQ14-40	0.322481	0.706985 ± 4	0.706452	0.109773	0.512130 ± 2	0.512046	0.006978	0.282483 ± 1	0.282468	-8.62	-8.30
ZQ14-44	0.341646	0.707099 ± 5	0.706534	0.108778	0.512128 ± 2	0.512045	0.007145	0.282480 ± 1	0.282465	-8.64	-8.41
ZQ14-47	0.273976	0.707038 ± 7	0.706585	0.110126	0.512036 ± 3	0.511952	0.006982	0.282417 ± 1	0.282402	-10.47	-10.62
ZQ14-52	0.299392	0.707984 ± 5	0.707488	0.097399	0.511895 ± 2	0.511821	0.005268	0.282223 ± 2	0.282211	-13.02	-17.38
ZQ19-08	0.265713	0.707303 ± 6	0.706864	0.105005	0.511984 ± 2	0.511904	0.006247	0.282364 ± 2	0.282351	-11.40	-12.43
ZQ19-12	0.218088	0.707262 ± 5	0.706901	0.109203	0.512032 ± 3	0.511948	0.007274	0.282430 ± 2	0.282414	-10.53	-10.20
HSTG16-01	0.122298	0.706551 ± 6	0.706331	0.121700	0.512108 ± 4	0.512008	0.008737	0.282490 ± 3	0.282455	-9.13	-8.53
HSTG16-02	0.123237	0.706641 ± 8	0.706420	0.121044	0.512099 ± 5	0.511999	0.008463	0.282482 ± 3	0.282462	-9.31	-8.29
HSTG16-04	0.117542	0.706525 ± 8	0.706314	0.121502	0.512098 ± 4	0.511998	0.008607	0.282481 ± 3	0.282461	-9.33	-8.33
HSTG16-09	0.119337	0.706525 ± 8	0.706310	0.121104	0.512096 ± 4	0.511996	0.008571	0.282476 ± 3	0.282456	-9.35	-8.50
BHVO-2		0.703524 ± 4			0.513012 ± 3			0.283085 ± 1			
BCR-2		0.705113 ± 5			0.512655 ± 4			0.282859 ± 2			
AGV-2		0.704016 ± 5			0.512797 ± 4			0.282979 ± 3			

#### 4.2. Geochemical data

Major and trace element data on our WNCC basalt samples are given in Supplementary Table 1. These samples have high alkali content ( $\text{Na}_2\text{O} + \text{K}_2\text{O} = 4.81\text{--}7.78\text{ wt}\%$ ), and they are trachybasalts, basaltic trachyte-andesite and trachyandesite according to Le Bas et al. (1986) (Fig. S1a) and belong to shoshonite and high-K series according to Le Maitre et al. (1989) (Fig. S1b). For simplicity, these samples are hereafter referred to as basalt. Volcanic rocks from Wulate Zhongqi display a relative larger compositional variation (Fig. 4 & S1). Samples from Wulate Zhongqi show increasing  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$  and decreasing  $^{\text{T}}\text{Fe}_2\text{O}_3$ ,  $\text{CaO}/\text{Al}_2\text{O}_3$ , Cr and Ni with decreasing MgO (Fig. 4). The Heishitougou samples have a uniform composition with higher  $\text{TiO}_2$ ,  $^{\text{T}}\text{Fe}_2\text{O}_3$ , and lower  $\text{SiO}_2$  at a given MgO when compared with the Wulate Zhongqi samples (Fig. 4).

In chondrite-normalized rare earth element (REE) diagram (Fig. 5a), the WNCC samples show consistent enrichment in light rare earth elements (LREEs) and depletion in heavy rare earth elements (HREEs) ( $[\text{La}/\text{Sm}]_N = 2.80\text{--}4.56$ ) without obvious Eu negative anomaly, being similar to the >110 Ma basaltic rocks in ENCC (Dai et al., 2016; Liu et al., 2008). In primitive mantle normalized multi-element spidergram (Fig. 5b), these samples display positive Ba and Pb anomalies and negative Ti anomalies. Different from the analogues in the ENCC (Dai et al., 2016; Liu et al., 2008), basalts from WNCC have higher Nb-Ta-Ti

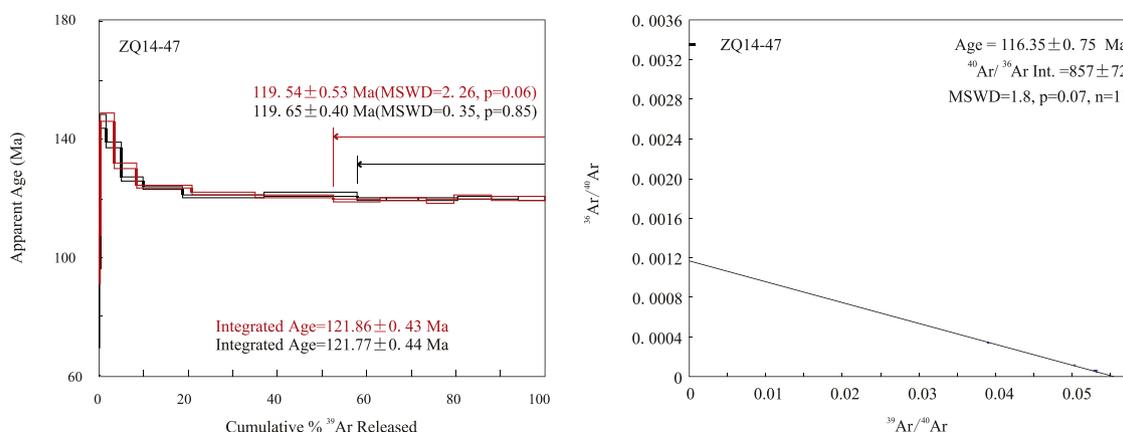
abundances and thus show less obvious Nb-Ta trough, implying somewhat different mantle source or source history.

Bulk-rock Sr, Nd and Hf isotopic data of our WNCC samples are given in Table 2. The initial Sr-Nd-Hf isotope ratios were calculated using the age of 116.35 Ma (this study) and 126.2 Ma (Zou et al., 2008) for samples from Wulate Zhongqi and Heishitougou, respectively. Generally, these samples show enriched isotopic compositions with a large range of  $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7062\text{--}0.7075$ ,  $\epsilon_{\text{Nd}(t)} = -6.0$  to  $-13.0$  and  $\epsilon_{\text{Hf}(t)} = -8.3$  to  $-17.4$ , plotting in the field defined by the >110 Ma basaltic rocks from the ENCC in both Sr-Nd and Hf-Nd isotopes spaces (Fig. 6).

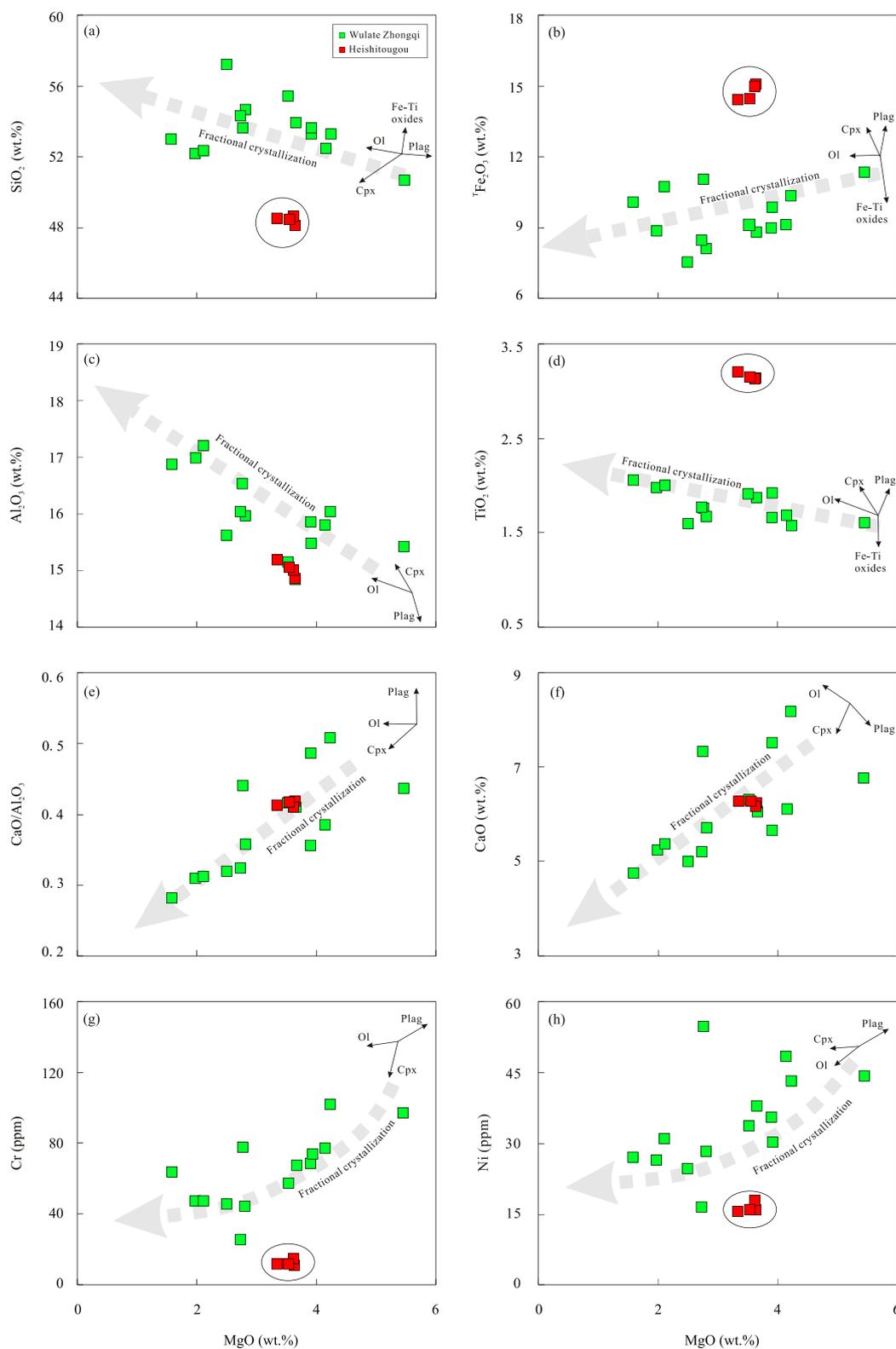
## 5. Discussions

### 5.1. Evaluation of post-magmatic processes

The samples in this study have been altered to some extent based on the petrographic observation (Fig. 2c–e) and high LOI (>2.5%) in 8 samples (Supplementary Table 1). However, our samples show good correlations between “alteration immobile” elements (e.g., Zr) and most other elements (e.g., Ba, Pb, La, Hf) (Fig. S2), implying that most elements are not influenced by such slight alteration and only Rb was affected in some samples. For these reasons, the following discussion will not involve the elements affected by alteration (e.g., Rb), but use those more immobile elements such as Th, REE, HFSE.



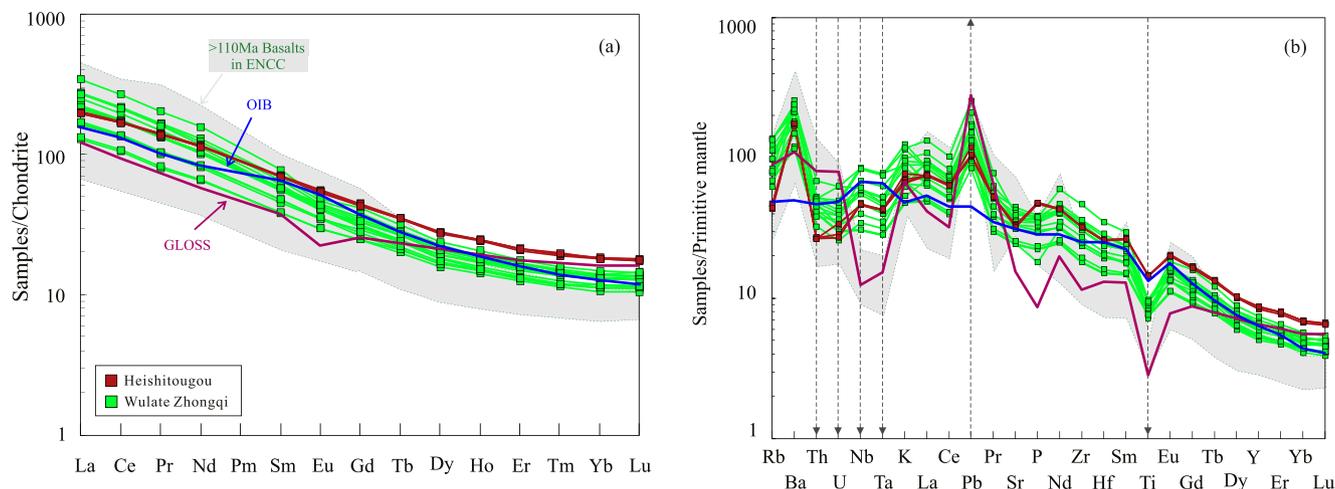
**Fig. 3.** Ar-Ar age spectra and  $^{39}\text{Ar}/^{40}\text{Ar}$  vs.  $^{36}\text{Ar}/^{40}\text{Ar}$  correlation of the whole rock sample ZQ14-47 from Wulate Zhongqi.



**Fig. 4.** MgO-variation diagrams showing major element oxides, CaO/Al<sub>2</sub>O<sub>3</sub>, Cr and Ni for basalts from Wulate Zhongqi and Heishitougou. Arrows decreasing MgO approximate first-order trends dominated by fractional crystallization. The arrows in the right represent the effect of fractional crystallization of different minerals. Plag- plagioclase; Cpx- clinopyroxene; Ol- olivine.

The Wulate Zhongqi samples have relatively large SiO<sub>2</sub> variation (50.71–57.32 wt%) with low MgO (1.58–5.45 wt%), Ni (16–55 ppm) and Cr (26–102 ppm) concentration, indicating their evolved nature

from mantle-derived parental melts through fractional crystallization. The correlated variations between <sup>1</sup>Fe<sub>2</sub>O<sub>3</sub>, CaO/Al<sub>2</sub>O<sub>3</sub>, Ni, Cr and MgO (Fig. 4) indicate the olivine and clinopyroxene as the dominant



**Fig. 5.** Chondrite-normalized rare earth element and primitive mantle normalized incompatible element patterns for basalts from Wulate Zhongqi and Heishitougou. Chondrite and primitive mantle values are from Sun and McDonough (1989). For comparison, plotted also are average composition of present-day oceanic island basalts (OIB; Sun and McDonough, 1989), global subducted sediment (GLOSS, Plank and Langmuir, 1998), average crust of NCC (Gao et al., 1998) and the range of >110 Ma Basalts from the ENCC (Dai et al., 2016; Liu et al., 2008).

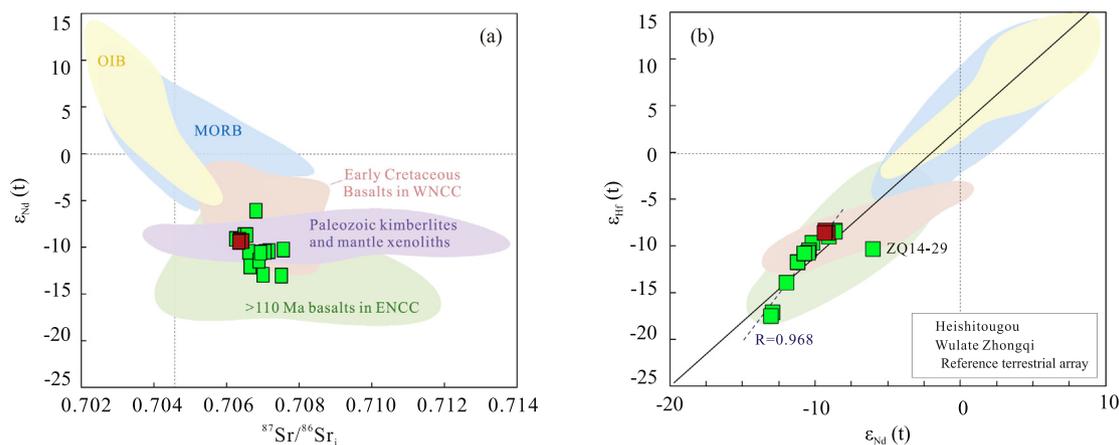
fractional crystallization phases, being consistent with the petrographic observation. Furthermore, the negative correlation between  $\text{Al}_2\text{O}_3$  and  $\text{MgO}$  (Fig. 4c) and no obvious Eu negative anomalies (Fig. 5a) suggest that plagioclase was not the dominant fractional crystallization phase.

Crustal contamination is inevitable for mantle-derived melts during their ascent through the thick continental crust. Thus, it is necessary to evaluate the effect of crustal contamination before using the geochemical data to discuss their source characters and mantle melting processes. The continental crust is characterized by elevated abundances of  $\text{SiO}_2$  and LILEs and depletion in HFSEs with low  $^{143}\text{Nd}/^{144}\text{Nd}$  (Gao et al., 1998; Liu et al., 2004). If a significant volume of crustal materials was involved, there must be an obvious positive relationship between  $\text{SiO}_2/\text{MgO}$ ,  $\text{Nb}/\text{La}$  and  $\epsilon_{\text{Hf}}(t)$  (or  $\epsilon_{\text{Nd}}(t)$ ). The rough correlations between  $\epsilon_{\text{Hf}}(t)$  and these element ratios are found in four samples (ZQ14-09, ZQ14-26, ZQ14-52, ZQ19-08), indicating that they had undergone various levels of crustal assimilation (Fig. 7). However, for most samples, crustal contamination is limited (Fig. 7). Thus, the characteristics of these samples, excluding ZQ14-09, ZQ14-26, ZQ14-52 and ZQ19-08,

could reflect those of the magma source, and the four samples potentially contaminated by the crustal materials would not be covered in the following discussion.

## 5.2. Melt metasomatized lithospheric mantle source of the WNCC basalts

Previous studies explain the widespread >110 Ma intra-plate alkali basalt with high  $^{87}\text{Sr}/^{86}\text{Sr}$ , low  $^{143}\text{Nd}/^{144}\text{Nd}$  and low  $^{176}\text{Hf}/^{177}\text{Hf}$  in the ENCC (Fig. 6; Dai et al., 2016; Meng et al., 2015) as the partial melts of the metasomatized cratonic lithosphere (e.g., Meng et al., 2015; Niu, 2005, 2014). This is easily understood. As the cratonic lithospheric mantle is isolated from the underlying convective mantle, it tends to inherit the enriched isotopic compositions of metasomatic agents once the mantle was metasomatized by isotopically enriched melts or tends to accumulate radiogenic isotopes with time if the mantle was metasomatized by melts with high parent/daughter ratios. The basalts from the Wulate Zhongqi and Heishitougou show significantly radiogenic Sr and un-radiogenic Nd-Hf isotopic compositions, being



**Fig. 6.** Sr, Nd and Hf isotope compositions of basalts from Wulate Zhongqi and Heishitougou. Plotted also are the literature data of >110 Ma Mesozoic basalts from the ENCC (Dai et al., 2016; Gao et al., 2008; Guo et al., 2003; Guo et al., 2013; Ling et al., 2009; Meng et al., 2015; Yang et al., 2006; Yang et al., 2012; Zhang et al., 2002, 2003), Early Cretaceous basalts from WNCC (Guo et al., 2014, 2018) and Paleozoic kimberlite and mantle xenoliths (Wu et al., 2006 and references therein). Reference Terrestrial Array ( $\epsilon_{\text{Hf}} = 1.36\epsilon_{\text{Nd}} + 2.95$ ) is after Vervoort and Blichert-Toft (1999). Also shown are the present-day compositions of oceanic island basalts (OIB) and mid-ocean ridge basalts (MORB) (Stracke et al., 2003; Stracke et al., 2005). R value (correlation coefficient) of WNCC basalts was calculated excluding ZQ14-29.

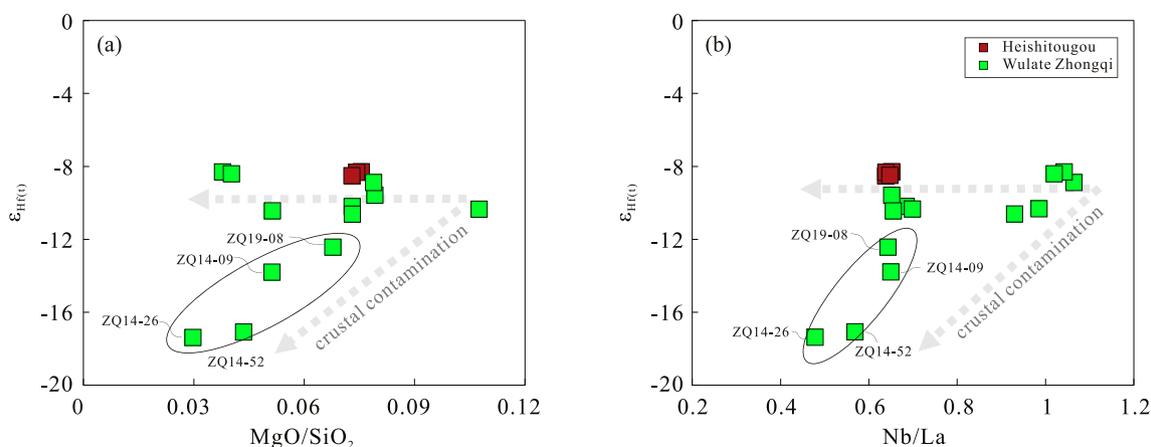


Fig. 7.  $\epsilon_{\text{Hf}}(t)$  vs.  $\text{MgO}/\text{SiO}_2$  and  $\text{Nb}/\text{La}$  diagrams to show crustal materials contamination play negligible role in the most WNCC basalts, except for ZQ14-09, ZQ14-26, ZQ14-52 and ZQ19-08.

distinctly different from the asthenospheric mantle derived mid-ocean ridge basalts (MORB) but plotted in the region defined by the >110 Ma basalts from ENCC and basalts with similar age from WNCC in Sr-Nd and Nd-Hf isotopes spaces (Fig. 6). This implies that basalts from Wulate Zhongqi and Heishitougou shared similar origin from partial melting of the lithospheric mantle with these ENCC and WNCC basalts. Importantly, in Sr-Nd isotope space, these basalts also plot in the field of NCC ancient lithosphere mantle represented by Paleozoic kimberlites and mantle xenoliths from NCC (Fig. 6a), providing evidence that the source of these basalts is lithosphere mantle.

Theoretically, the craton lithospheric mantle is the partial melting residues, refractory and highly depleted in incompatible elements (Abbott et al., 1997; Jordan, 1988; Ringwood, 1975). However, this is inconsistent with the basic observation that the occurrence of large scale of the Mesozoic volcanism (Zhu et al., 2011) and incompatible elements highly enriched magmas derived from such a craton lithospheric mantle (e.g., Dai et al., 2016; Liu et al., 2008). This implies that the enrichment or re-fertilization process/processes occurred at the lithosphere mantle before its melting. The WNCC basalts display remarkably enrichment in incompatible elements with high  $[\text{La}/\text{Sm}]_N = 2.80\text{--}4.56$  (Fig. 5), indicating that their mantle source was enriched by melts. Specifically, the significantly correlated  $\epsilon_{\text{Nd}}(t)$  with  $\epsilon_{\text{Hf}}(t)$  ( $R = 0.968$ ) in these samples (excluding the sample ZQ14-29) is consistent with that the mantle source isotopic variation is largely controlled by simple magmatic processes. All these geochemical observations imply that the mantle source of the WNCC basalts was the craton lithospheric mantle that was metasomatized by melts.

### 5.3. The origin of the metasomatic melt and the formation of enriched lithosphere mantle

WNCC basalts display obviously different incompatible element distribution pattern from present-day average OIB with negative Nb-Ta (compared with K) -Ti and positive Ba-Pb anomalies (Fig. 5). Several processes can be responsible for the negative Nb-Ta (compared with K) and Ti anomalies in these samples (Fig. 5): (1) the involvement of the continental crust materials during the magma ascent; (2) Ti-rich mineral (e.g., amphibole, rutile) crystallization during the magma evolution or being as a residual phase in the source region (e.g., Tiepolo et al., 2001; Xiong et al., 2005); (3) Contribution of crustal component in the mantle source (e.g., Cheng et al., 2018; Dai et al., 2016; Liu et al., 2008). First, as discussed above, continental crustal contamination was negligible in the petrogenesis of our samples. Second,  $\text{TiO}_2$  increases with the decreasing MgO in our samples (Fig. 4d), arguing against the Ti-bearing minerals crystal fractionation. Furthermore, the fractional crystallization of Ti-bearing minerals or their being as a residual phase

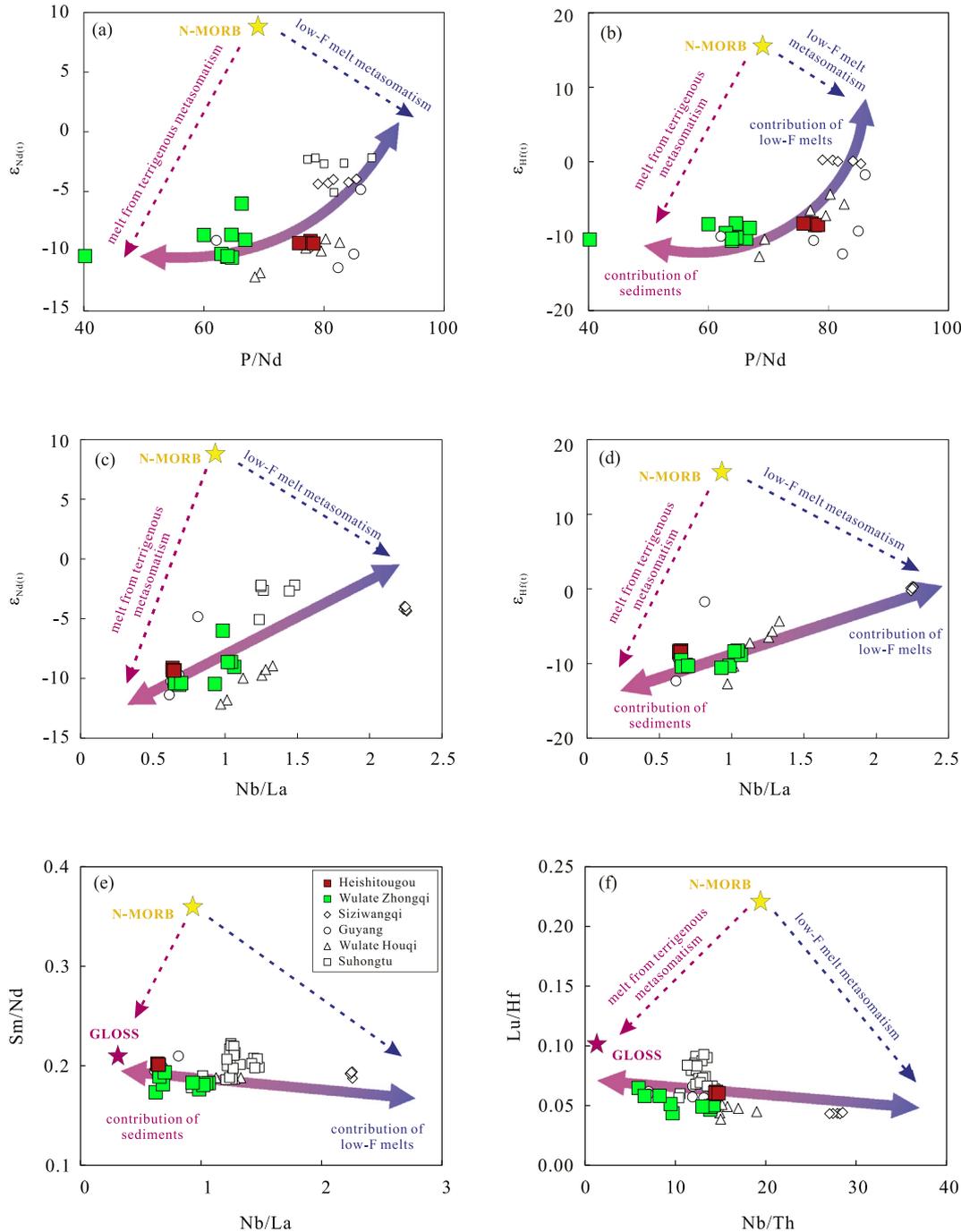
in the source region could not produce the Pb anomaly as observed in our samples (Fig. 5b). Therefore, the involvement of crustal materials was the most probable cause to the Nb-Ta-Ti and positive Pb-Ba anomalies in the mantle source of these basalts (Fig. 5b).

Three mechanisms have been proposed to produce continental crustal material recycling into mantle: (1) lower crustal delamination (e.g., Gao et al., 2004, 2008; Liu et al., 2008); (2) continental crust subduction (e.g., Dai et al., 2016; Yang et al., 2012; Zhang et al., 2002; Zhao et al., 2018); (3) sediments recycling by oceanic subduction (e.g., Cheng et al., 2018; Sun et al., 2019). Zhang et al. (2012) suggested that the lithosphere mantle beneath WNCC was not newly-accreted in the Phanerozoic but was transformed from the Archean-Proterozoic lithospheric mantle. Considering the existence of ancient lithospheric relicts in the lithosphere mantle beneath the WNCC, the possibility of lower crust with lithosphere mantle foundering (delamination) into the denser asthenosphere could be excluded. Furthermore, there is no evidence of continental crust subduction in the study area just as the case of South China block subduction underneath the southern margin of the NCC. We therefore suggest the continental crust materials presenting in the mantle source region was most likely originated from subducted sediments. This inference is also consistent with the research of Tertiary basalts-hosted xenoliths from north margin NCC (Wang et al., 2019). Subduction sediments consist of terrigenous sediments and pelagic sediments. Considering that most trace elements (e.g., alkali elements, HFSEs, REEs) of subduction sediments are mainly linked to terrigenous sediments (Plank and Langmuir, 1998), we suggest the crust-like geochemical characters of basalts in this study are the results of involvement of terrigenous sediments in the mantle source. Because the subducted terrigenous sediments is characterized by depletion in HFSEs and P and enriched Sr-Nd-Hf isotope composition (Plank and Langmuir, 1998), the contribution of terrigenous sediment material into the mantle source would decrease P/Nd, Nb/La,  $\epsilon_{\text{Nd}}(t)$  and  $\epsilon_{\text{Hf}}(t)$  in the erupting magma. This is indeed the case for the WNCC basalts, with both  $\epsilon_{\text{Nd}}(t)$  and  $\epsilon_{\text{Hf}}(t)$  showing positive correlation with P/Nd and Nb/La (Fig. 8a–d). Therefore, the silica-rich melts derived from subducted terrigenous sediments is an important metasomatism agent beneath WNCC.

However, the mantle source only metasomatized by silica-rich melts derived from subducted sediment is not consistent with the geochemical trends of WNCC basalts (Fig. 8), which requires another enriched component in the mantle source. This component must have higher Nb/La and P/Nd, lower Sm/Nd and Lu/Hf than N-MORB and moderately low  $\epsilon_{\text{Nd}}(t)$  and  $\epsilon_{\text{Hf}}(t)$  (Fig. 8), which implies that this component is characterized by enrichment of incompatible elements and more enrichment in the progressively more incompatible elements. The most likely candidate for this enriched component is the low mass fraction

(low-F) melts (Niu et al., 2012; Niu and O'Hara, 2003). Niu and coauthors suggest such low-F melts may develop within asthenosphere/LVZ and is enriched in volatiles, alkalis and incompatible elements, and it will develop low  $\epsilon_{\text{Nd}}(t)$  and  $\epsilon_{\text{Hf}}(t)$  after long-term accumulation of radioisotopes, because of its low Sm/Nd and Lu/Hf (Niu et al., 2012; Niu and O'Hara, 2003). They also proposed that OIB was originated from such low-F melts metasomatized mantle (Niu et al., 2012; Niu and O'Hara, 2003). The occurrence of the Early Cretaceous basalts with OIB-like trace elements patterns from Suhongtu and Siziwangqi in the

WNCC (Guo et al., 2014; Hui et al., 2020) suggests that low-F melts metasomatism process is common in the lithosphere mantle beneath the region. Note that the WNCC lavas display a contrasting difference from the contemporary analogues in ENCC with obvious Th-U negative anomalies relative to Nb-Ta (Fig. 5b). We explain this observation as the result of the involvement of phlogopite/amphibole metasomes during magma event that produce WNCC lavas. This is because reaction between low-F melts from asthenosphere and Si-poor peridotites could produce phlogopite/amphibole metasomes (Niu, 2008; Pilet et al.,



**Fig. 8.** (a) and (c) are P/Nd and Nb/La vs.  $\epsilon_{\text{Nd}}(t)$  diagrams; (b) and (d) are P/Nd and Nb/La vs.  $\epsilon_{\text{Hf}}(t)$  diagrams; (e) Nb/La vs. Sm/Nd diagrams and (f) Nb/Th vs. Lu/Hf diagrams to show both the terrigenous sediments and low-F melts contribution in the formation of the enriched mantle source of the WNCC basalts. We select N-MORB (Sun and McDonough, 1989; Workman and Hart, 2005), represented by yellow star, as the magma from partial melting of depleted mantle source and red star represents global subducted sediment (GLOSS, Plank and Langmuir, 1998). The Double-headed arrows represent the variation trends of the incompatible element ratios caused by the contribution of different metasomatism agents. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2011; Soder et al., 2016) and partial melts derived from the phlogopite/amphibole-bearing mantle could inherit their mantle source low Th-U and elevated Nb-Ta characters (Pilet et al., 2008).

To illustrate the two metasomatic melts roles in the formation of the metasomatic lithospheric mantle source of the WNCC Mesozoic basalts, we approximate basalts from Siziwangqi as the result of partial melts derived from low-F melts metasomatized mantle (Guo et al., 2014) and choose global subducted sediments (GLOSS, Plank and Langmuir, 1998) as the end-members of subducted terrigenous sediments to model its contribution. The modelling result shows that ~40% terrigenous sediments are required to mix with the Siziwangqi highly enriched basaltic melts to produce the Wulate Zhongqi and Heishitougou lavas (Fig. 9). Not that the modelling result is not unique, which depends on end-members and parameters we chose. However, what we emphasize here is that there are two different metasomatized agents in the WNCC basalts mantle source.

In conclusion, despite the possible varied compositions of the initial metasomatism melts (derived from subducted sediments or asthenosphere) and the complex reaction between the melts and the peridotite matrix, the ultimate result of such a metasomatism is the formation of the metasomes characterized by an assemblage of hydrous and anhydrous metasomatic minerals such as pyroxene, amphibole and/or phlogopite (Förster et al., 2019; Niu, 2008; Pilet et al., 2011; Sekine and Wyllie, 1983; Soder et al., 2016; Wyllie and Sekine, 1982). Partial melting of such metasomatized mantle produced K-enriched and shoshonitic WNCC basalts, and these basalts inherited the geochemical characters of terrigenous sediments and low-F melts from asthenosphere with enrichment in incompatible elements, obvious Nb-Ta (compared with K)-Ti negative anomalies, Ba-Pb positive anomalies and Th-U trough (Fig. 5b).

#### 5.4. A petrogenetic model for the generation of widespread WNCC basalts

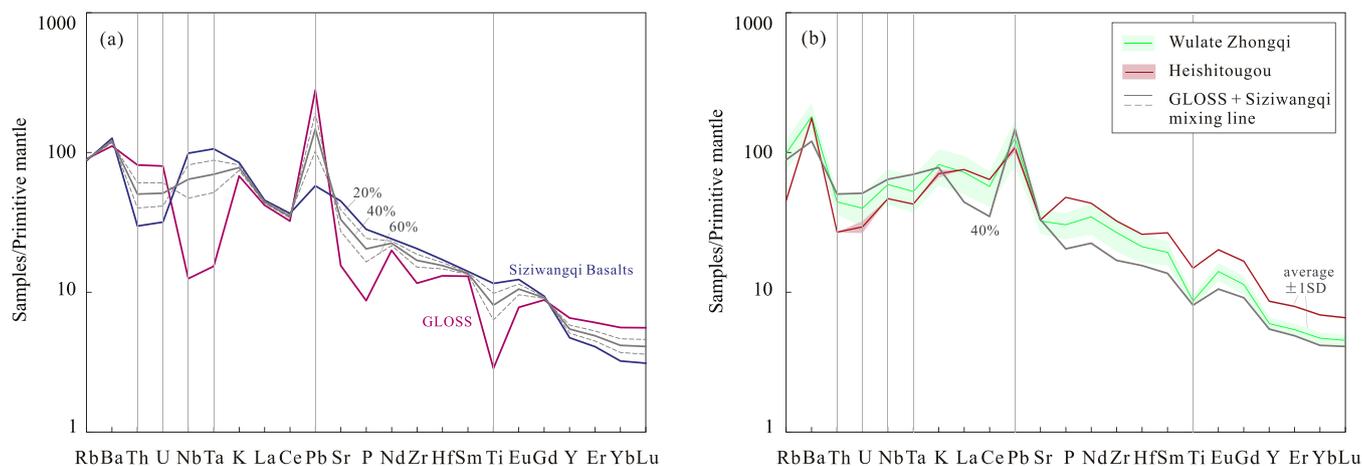
Because the study area is located at the northern margin of the NCC, the first and foremost tectonic background related to these magmatism activities is the closure of the Paleo-Asian ocean. However, the Paleo-Asian ocean was closed in late Permian to early Triassic (Li, 2006; Xiao et al., 2003; Zhang et al., 2009). The temporal span from such an event to the early Cretaceous magmatism is at least ~100 Myrs, which makes it impossible to be related with each other. In addition, as there is no known regional domal uplift nor the presence of volumetrically significant "large igneous province", the WNCC volcanisms are unlikely to have been caused by a hotspot or mantle plume. Third, the addition of fluids, released from the speculated Paleo-Pacific slabs lying in the

transition zone, to the ancient craton lithosphere could well explain the >110 Ma basaltic magmatism in the ENCC (Niu, 2005, 2014). But this mechanism may not apply here because the WNCC is too far (~1500 km) away from the speculated western Pacific subduction zone. Thus, other mechanism is required to explain the petrogenesis of these intra-plate basalts.

Previous studies demonstrate that extensional basins (e.g., Graham et al., 2001) and metamorphic core complexes (e.g., Davis et al., 2002) of early Cretaceous ages are widespread in the northern margin of the WNCC, suggesting an extensional setting at that time in the region. Some authors explained such an extension to be related with the breakoff of subducted oceanic slab after the closure of Mongolia-Okhotsk Ocean in the Middle Jurassic (Li et al., 2018; Ouyang et al., 2015). Our contemporary basaltic volcanism in WNCC supports this model. We also suggest that the early Cretaceous basaltic volcanism in the WNCC in this study and in other recent literature (Table 1; Fig. 1; Guo et al., 2014, 2018; He et al., 2013; Zhang, 2013; Zhong et al., 2014, 2015; Zou et al., 2008) were all the products of the same tectonic-thermal event.

As discussed above, the mantle source of WNCC basalts have undergone metasomatism by melts from subducted terrigenous sediments. The subduction of both Paleo-Asian oceanic slab and Mongolia-Okhotsk seafloor slab could bring the sediments into mantle. However, given that the Tertiary basalt-hosting mantle xenoliths from northern margin of NCC have the character of metasomatism by melts of Paleo-Asian Ocean sediments (Wang et al., 2019) and the north margin of the WNCC is closed to the Solonker suture spatially. We preferred that the Paleo-Asian Ocean subducted sediment is more prior to affect the NCC lithospheric mantle.

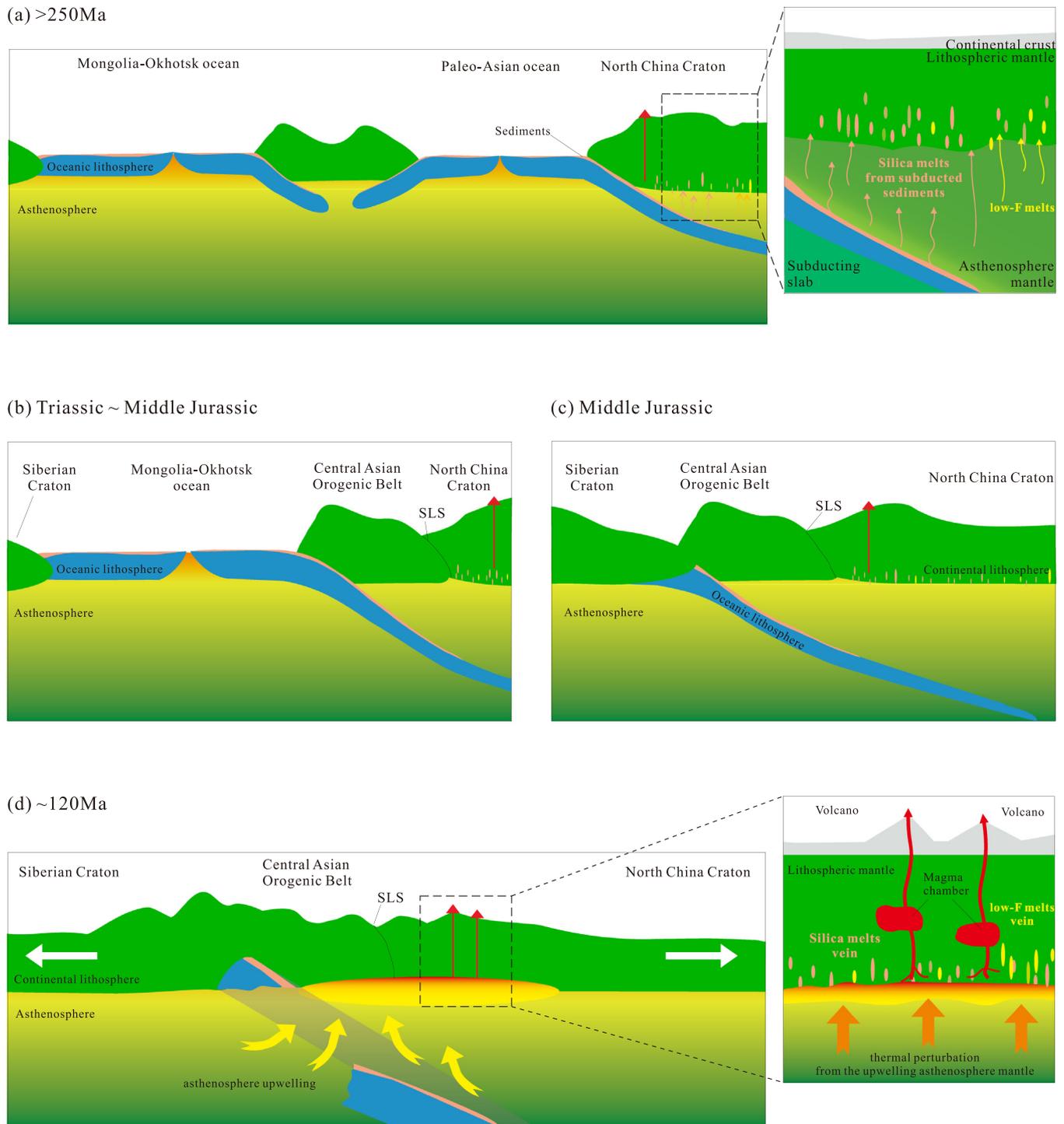
Following this interpretation, we propose a petrogenetic model for the WNCC basalts as follows. In the Paleozoic, the Paleo-Asian oceanic slab subducted underneath the North China Craton (Li, 2006; Xiao et al., 2003; Zhang et al., 2009), carrying continent-derived sediments (Fig. 10a). Melts derived from these subducted sediments metasomatized the base of the lithosphere mantle beneath the northern margin of the WNCC and formed the metasomatic veins (Wang et al., 2019; Fig. 10a). Such a metasomatized mantle was subsequently overprinted by metasomatism of low-F melts that derived from the asthenosphere/LVZ (Fig. 10a). The closure of the Paleo-Asian ocean was followed by the closure of the Mongolia-Okhotsk Ocean and the formation of Central Asian Orogenic Belt (CAOB) during the Jurassic to the earliest Cretaceous (Fig. 10b & c; Donskaya et al., 2013; Tomurtogoo et al., 2005). The following breakoff of subducted Mongolia-Okhotsk seafloor slab led to the CAOB region and nearby area in an extension background



**Fig. 9.** Trace element modelling of the multiple metasomatism melts in the mantle source of the basalts in Wulate Zhongqi and Heishitougou. We approximate basalts from Siziwangqi as the result of partial melts derived from low-F melts metasomatized mantle (Guo et al., 2014) and choose global subducted sediments (GLOSS, Plank and Langmuir, 1998) as the end-members of subducted terrigenous sediments. The percentage in the fig. (20%, 40%, 60%) means proportion of sediment.

(Fig. 10d) as manifested by Cretaceous extensional basins and metamorphic core complexes (Davis et al., 2002; Graham et al., 2001). Also for this reason, slab breakoff induced asthenosphere upwelling could produce thermal perturbation at the base of the continental lithosphere and

heated the earlier formed metasomatized lithospheric mantle to facilitate the fusible component melting, producing magmas parental to basalts in this study (Fig. 10d). This model explains the widespread early Cretaceous magmatism that concentrated along the northern margin of the WNCC.



**Fig. 10.** Graphical description of the petrogenesis of the early Cretaceous basalts in the WNCC. (a) The Paleo-Asian ocean slab subducted southward underneath the North China Craton in the late Paleozoic and contributed terrigenous sediments into the mantle; and the silica-melts derived from the subducted terrigenous sediments and low-F melts from asthenosphere metasomatized the overlying lithospheric mantle, forming metasomatic veins at the base of the lithosphere; (b) The Paleo-Asian ocean was closed in the early Mesozoic, leading to the orogenesis of the Central Asian Orogenic Belt (CAOB); (c) the Mongolia-Okhotsk ocean closed in the Triassic to Middle Jurassic; (d) Breakoff of subducted Mongol-Okhotsk oceanic slabs resulted in an upwelling of the asthenosphere, and such upwelling asthenosphere produced thermal perturbation at the base of the lithosphere and heated the lithospheric mantle. The fusible metasomatized components were, thus, melted and produced the primary magmas parental to the basalts in this study. SLS in the figure indicated Solonker suture zone.

## 6. Conclusion

The widespread 107.3–133.1 Ma basaltic magmatism in the WNCC originated from partial melting of the metasomatized lithospheric mantle. The mantle source of these basalts contains amphibole/phlogopite, which were formed through metasomatism by low-F melts from asthenosphere mantle and silicic melts derived from the subducted terrigenous sediments. The occurrence of magmatism in WNCC was most probably related to the seafloor slab breakoff following the closure of the Mongolia–Okhotsk ocean, in which scenario upwelling asthenosphere produced thermal perturbation at the base of the lithosphere and heated the lithospheric mantle base, resulting in the melting of the early metasomatized lithospheric mantle materials.

## Declaration of Competing Interest

None.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.lithos.2020.105887>.

## References

- Abbott, D., Drury, R., Mooney, W., 1997. Continents as lithological icebergs: the importance of buoyant lithospheric roots. *Earth Planet. Sci. Lett.* 149, 15–27.
- Chen, L., Cheng, C., Wei, Z.G., 2009. Seismic evidence for significant lateral variations in lithospheric thickness beneath the central and western North China Craton. *Earth Planet. Sci. Lett.* 286, 171–183.
- Chen, S., Wang, X.H., Niu, Y.L., Sun, P., Duan, M., Xiao, Y.Y., Guo, P.Y., Gong, H.M., Wang, G.D., Xue, Q.Q., 2017. Simple and cost-effective methods for precise analysis of trace element abundances in geological materials with ICP-MS. *Sci. Bull.* 62, 277–289.
- Cheng, T., Nebel, O., Sossi, P.A., Wu, J., Siebel, W., Chen, F.K., Nebel-Jacobsen, Y.J., 2018. On the Sr–Nd–Pb–Hf isotope code of enriched, Dupal-type sub-continental lithospheric mantle underneath South–Western China. *Chem. Geol.* 489, 46–60.
- Dai, L.Q., Zheng, Y.F., Zhao, Z.F., 2016. Termination time of peak decretionization in North China: Geochemical evidence from mafic igneous rocks. *Lithos* 240–243, 327–336.
- Davis, G.J., Darby, B., Zheng, Y.D., Spell, T., 2002. Geometric and temporal evolution of an extensional detachment fault, Hohhot metamorphic core complex, Inner Mongolia, China. *Geology* 30, 1003–1006.
- Deino, A., Potts, R., 1990. Single-crystal  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of the Olorgesailie Formation, Southern Kenya Rift. *J. Geophys. Res. Solid Earth* 95, 8453–8470.
- Donskaya, T.V., Gladkochub, D.P., Mazukabzov, A.M., Ivanov, A.V., 2013. Late Paleozoic – Mesozoic subduction-related magmatism at the southern margin of the Siberian continent and the 150 million-year history of the Mongol–Okhotsk Ocean. *J. Asian Earth Sci.* 62, 79–97.
- Förster, M.W., Prelević, D., Buhre, S., Mertz-Kraus, R., Foley, S.F., 2019. An experimental study of the role of partial melts of sediments versus mantle melts in the sources of potassic magmatism. *J. Asian Earth Sci.* 177, 76–88.
- Gao, S., Luo, T.C., Zhang, B.R., Zhang, H.F., Han, Y.W., Zhao, Z.D., Hu, Y.K., 1998. Chemical composition of the continental crust as revealed by studies in East China. *Geochim. Cosmochim. Acta* 62, 1959–1975.
- Gao, S., Rudnick, R.L., Yuan, H.L., Liu, X.M., Liu, Y.S., Xu, W.L., Ling, W.L., Ayers, J., Wang, X.C., Wang, Q.H., 2004. Recycling lower continental crust in the North China craton. *Nature* 432, 892–897.
- 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 Planet. Sci. Lett.* 270, 41–53.
- Graham, S.A., Hendrix, M.S., Johnson, C.L., Badamgarav, D., Badarch, G., Amory, J., Porter, M., Barsbold, R., Webb, L., Hacker, B.R., 2001. Sedimentary record and tectonic implications of Mesozoic rifting in Southeast Mongolia. *Geol. Soc. Am. Bull.* 113, 1560–1579.
- Guo, F., Fan, W.M., Wang, Y.J., Lin, G., 2003. Geochemistry of late mesozoic mafic magmatism in West Shandong Province, eastern China: Characterizing the lost lithospheric mantle beneath the North China Block. *Geochim. J.* 37, 63–77.
- Guo, J.T., Guo, F., Yan Wang, C., Li, C.W., 2013. Crustal recycling processes in generating the early cretaceous Fangcheng basalts, North China Craton: New constraints from mineral chemistry, oxygen isotopes of olivine and whole-rock geochemistry. *Lithos* 170–171, 1–16.
- Guo, P.Y., Niu, Y.L., Ye, L., Liu, J.J., Sun, P., Cui, H.X., Zhang, Y., Gao, J.P., Su, L., Zhao, J.X., Feng, Y.X., 2014. Lithosphere thinning beneath west North China Craton: evidence from geochemical and Sr–Nd–Hf isotope compositions of Jining basalts. *Lithos* 202–203, 37–54.
- Guo, P.Y., Niu, Y.L., Sun, P., Wang, X.H., Gong, H.M., Duan, M., Zhang, Y., Kong, J.J., Tian, L.Y., Wu, S.G., 2018. The early cretaceous bimodal volcanic suite from the Yinshan Block, western North China Craton: Origin, process and geological significance. *J. Asian Earth Sci.* 160, 348–364.
- Hawkesworth, C.J., Gallagher, K., Hergt, J.M., McDermott, F., 1993. Mantle and slab contributions in arc magmas. *Annu. Rev. Earth Planet. Sci.* 21 (1), 175–204.
- He, Y.K., Wu, T.R., Jin, X., 2013.  $^{40}\text{Ar}/^{39}\text{Ar}$  Laser Probe Dating of Siziwangqi Shoshonite and its Geological significance. *Geol. Explor.* 49, 1114–1122 (in Chinese with English abstract).
- Hui, J., Cheng, H.Y., Zhang, J., Zhang, K.J., Qu, J.F., Zhang, B.H., 2020. Early Cretaceous continent basalts in the Alxa Block, NW China: geochronology, geochemistry, and tectonic implications. *Int. Geol. Rev.* 1–18.
- Jordan, T., 1988. Structure and Formation of the Continental Tectosphere. *J. Petrol. Special Vol.* 11–37.
- Kong, J.J., Niu, Y.L., Sun, P., Xiao, Y.Y., Guo, P.Y., Hong, D., Zhang, Y., Shao, F.L., Wang, X.H., Duan, M., 2019. The origin and geodynamic significance of the Mesozoic dykes in eastern continental China. *Lithos* 332–333, 328–339.
- Le Bas, M., Maitre, L.L., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on the total alkali–silica diagram. *J. Petrol.* 27, 745–750.
- Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lameyre, J., Le Bas, M.J., Sabine, P.A., Schmid, R., Sorensen, H., Streckeisen, A., Wooley, A.R., Zanettin, B., 1989. A Classification of Igneous Rocks and Glossary of Terms. Blackwell, Oxford.
- Li, J.Y., 2006. Permian geodynamic setting of Northeast China and adjacent regions: closure of the Paleo-Asian Ocean and subduction of the Paleo-Pacific Plate. *J. Asian Earth Sci.* 26, 207–224.
- Li, Y., Xu, W.L., Tang, J., Pei, F.P., Wang, F., Sun, C.Y., 2018. Geochronology and geochemistry of Mesozoic intrusive rocks in the Xing'an Massif of NE China: Implications for the evolution and spatial extent of the Mongol–Okhotsk tectonic regime. *Lithos* 304–307, 57–73.
- Ling, W.L., Duan, R.C., Xie, X.J., Zhang, Y.Q., Zhang, J.B., Cheng, J.P., Liu, X.M., Yang, H.M., 2009. Contrasting geochemistry of the cretaceous volcanic suites in Shandong province and its implications for the Mesozoic lower crust delamination in the eastern North China craton. *Lithos* 113, 640–658.
- Liu, D.Y., Nutman, A.P., Compston, W., Wu, J.S., Shen, Q.H., 1992. Remnants of  $\geq 3800$  Ma crust in the Chinese part of the Sino-Korean craton. *Geology* 20, 339–342.
- Liu, Y.S., Gao, S., Yuan, H.L., Zhou, L., Liu, X.M., Wang, X.C., Hu, Z.C., Wang, L.S., 2004. U–Pb zircon ages and Nd, Sr, and Pb isotopes of lower crustal xenoliths from North China Craton: insights on evolution of lower continental crust. *Chem. Geol.* 211, 87–109.
- Liu, Y.S., Gao, S., Kelemen, P.B., Xu, W.L., 2008. Recycled crust controls contrasting source compositions of Mesozoic and Cenozoic basalts in the North China Craton. *Geochim. Cosmochim. Acta* 72, 2349–2376.
- Ma, L., Jiang, S.-Y., Hofmann, A.W., Dai, B.-Z., Hou, M.-L., Zhao, K.-D., Chen, L.-H., Li, J.-W., Jiang, Y.-H., 2014. Lithospheric and asthenospheric sources of lamprophyres in the Jiaodong Peninsula: a consequence of rapid lithospheric thinning beneath the North China Craton? *Geochim. Cosmochim. Acta* 124, 250–271.
- Meng, F.X., Gao, S., Niu, Y.L., Liu, Y.S., Wang, X.R., 2015. Mesozoic–Cenozoic mantle evolution beneath the North China Craton: a new perspective from Hf–Nd isotopes of basalts. *Gondwana Res.* 27, 1574–1585.
- Niu, Y.L., 2005. Generation and Evolution of Basaltic Magmas: some Basic Concepts and a New View on the Origin of Mesozoic–Cenozoic Basaltic Volcanism in Eastern China. *Geol. J. China Univ.* 11, 9–46.
- Niu, Y.L., 2008. The Origin of Alkaline Lavas. *Science* 320, 883–884.
- Niu, Y.L., 2014. Geological understanding of plate tectonics: basic concepts, illustrations, examples and new perspectives. *Global Tecton. Metal.* 10, 23–46.
- Niu, Y.L., O'Hara, M.J., 2003. Origin of ocean island basalts: a new perspective from petrology, geochemistry, and mineral physics considerations. *J. Geophys. Res. Solid Earth* 108.
- Niu, Y.L., Wilson, M., Humphreys, E.R., O'Hara, M.J., 2012. A trace element perspective on the source of ocean island basalts (OIB) and fate of subducted ocean crust (SOC) and mantle lithosphere (SML). *Episodes* 35, 310–327.
- Ouyang, H., Mao, J., Zhou, Z., Su, H., 2015. Late Mesozoic metallogeny and intracontinental magmatism, southern Great Xing'an Range, northeastern China. *Gondwana Res.* 27, 1153–1172.
- Pilet, S., Baker, M.B., Stolper, E.M., 2008. Metasomatized Lithosphere and the Origin of Alkaline Lavas. *Science* 320, 916–919.
- Pilet, S., Baker, M.B., Müntener, O., Stolper, E.M., 2011. Monte Carlo Simulations of Metasomatic Enrichment in the Lithosphere and Implications for the source of Alkaline Basalts. *J. Petrol.* 52, 1415–1442.
- Plank, T., Langmuir, C.H., 1998. The chemical composition of subducting sediment and its consequences for the crust and mantle. *Chem. Geol.* 145, 325–394.

- Renne, P.R., Cassata, W.S., Morgan, L.E., 2009. The isotopic composition of atmospheric argon and Ar/Ar geochronology: Time for a change? *Quat. Geochronol.* 4, 288–298.
- Ringwood, A.E., 1975. *Composition and Petrology of the Earth's Mantle*. McCraw-Hill, New York, p. 618.
- Sekine, T., Wyllie, P.J., 1983. Experimental simulation of Mantle Hybridization in Subduction zones. *J. Geol.* 91, 511–528.
- Shi, Y.N., Niu, F.L., Li, Z.H., Huangfu, P., 2020. Craton destruction links to the interaction between subduction and mid-lithospheric discontinuity: Implications for the eastern North China Craton. *Gondwana Res.* 83, 49–62.
- Soder, C., Altherr, R., Romer, R.L., 2016. Mantle Metasomatism at the Edge of a Retreating Subduction Zone: late Neogene Lamprophyres from the Island of Kos, Greece. *J. Petrol.* 57, 1705–1728.
- Stracke, A., Bizimis, M., Salters, V.J.M., 2003. Recycling oceanic crust: Quantitative constraints. *Geochem. Geophys. Geosyst.* 4, 1–33.
- Stracke, A., Hofmann, A., Hart, S., 2005. FOZO, HIMU, and the rest of the mantle zoo. *Geochem. Geophys. Geosyst.* 6 (5), 1–20.
- Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *Geol. Soc. Lond. Spec. Publ.* 42, 313–345.
- Sun, P., Niu, Y.L., Guo, P.Y., Chen, S., Duan, M., Gong, H.M., Wang, X.H., Xiao, Y.Y., 2019. Multiple mantle metasomatism beneath the Leizhou Peninsula, South China: evidence from elemental and Sr–Nd–Pb–Hf isotope geochemistry of the late Cenozoic volcanic rocks. *Int. Geol. Rev.* 61, 1768–1785.
- Tiepolo, M., Bottazzi, P., Foley, S., Oberti, R., Vannucci, R., Zanetti, A., 2001. Fractionation of Nb and Ta from Zr and Hf at mantle depths: the role of titanite paragasite and kaersutite. *J. Petrol.* 42, 221–232.
- Tomurtogoo, O., Windley, B.F., Kroner, A., Badarch, G., Liu, D.Y., 2005. Zircon age and occurrence of the Adatsag ophiolite and Muron shear zone, Central Mongolia: constraints on the evolution of the Mongol–Okhotsk Ocean, suture and orogen. *J. Geol. Soc. Lond.* 162, 125–134.
- Vasconcelos, P.N., Onoe, A.T., Kawashita, K., Soares, A.J., Teixeira, W., 2002.  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology at the Instituto de Geociencias, USP: instrumentation, analytical procedures, and calibration. *Anais Da Academia Brasileira De Ciencias* 74, 297–342.
- Vervoort, J.D., Blichert-Toft, J., 1999. Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time. *Geochim. Cosmochim. Acta* 63, 533–556.
- Wang, C.Y., Liu, Y.S., Foley, S.F., Zong, K.Q., Hu, Z.C., 2019. Lithospheric transformation of the northern North China Craton by changing subduction style of the Paleo-Asian oceanic plate: Constraints from peridotite and pyroxenite xenoliths in the Yangyuan basalts. *Lithos* 328–329, 58–68.
- Wilde, S.A., 2015. Final amalgamation of the Central Asian Orogenic Belt in NE China: Paleo-Asian Ocean closure versus Paleo-Pacific plate subduction – a review of the evidence. *Tectonophysics* 662, 345–362.
- Workman, R.K., Hart, S.R., 2005. Major and trace element composition of the depleted MORB mantle (DMM). *Earth Planet. Sci. Lett.* 231, 53–72.
- Wu, F.Y., Walker, R.J., Yang, Y.H., Yuan, H.L., Yang, J.H., 2006. The chemical-temporal evolution of lithospheric mantle underlying the North China Craton. *Geochim. Cosmochim. Acta* 70, 5013–5034.
- Wu, F.Y., Xu, Y.G., Gao, S., Zheng, J.P., 2008. Lithospheric thinning and destruction of the North China Craton. *Acta Petrol. Sin.* 24, 1145–1174 (in Chinese with English abstract).
- Wyllie, P.J., Sekine, T., 1982. The formation of mantle phlogopite in subduction zone hybridization. *Contrib. Mineral. Petrol.* 79, 375–380.
- Xiao, W.J., Windley, B., Hao, J.J., Zhai, M.G., 2003. Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the Central Asian Orogenic Belt. *Tectonics* 22.
- Xiong, X.L., Adam, J., Green, T.H., 2005. Rutile stability and rutile/melt HFSE partitioning during partial melting of hydrous basalt: Implications for TTG genesis. *Chem. Geol.* 218, 339–359.
- Yang, Y.H., Zhang, H.F., Xie, L.W., Liu, Y., Qi, C.S., Tu, X.L., 2006. Petrogenesis of typical Mesozoic and Cenozoic volcanic rocks from the North China Craton: new evidence from Hf isotopic studies. *Acta Petrol. Sin.* 22, 1665–1671 (in Chinese with English abstract).
- 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 Block: Constraints from Sr–Nd–Pb isotopes in Mesozoic mafic igneous rocks. *Lithos* 136–139, 246–260.
- Zhang, P.F., 2013. *Geochemical Characteristics and Petrogenesis of the Volcanic Rocks from the Middle of the Yinshan Block*. The University of Chinese Academy of Sciences.
- Zhang, H.F., Sun, M., Zhou, X.H., Fan, W.M., Zhai, M.G., Yin, J.F., 2002. Mesozoic lithosphere destruction beneath the North China Craton: evidence from major-, trace-element and Sr–Nd–Pb isotope studies of Fangcheng basalts. *Contrib. Mineral. Petrol.* 144, 241–254.
- Zhang, H.F., Sun, M., Zhou, X.H., Zhou, M.F., Fan, W.M., Zheng, J.P., 2003. Secular evolution of the lithosphere beneath the eastern North China Craton: evidence from Mesozoic basalts and high-Mg andesites. *Geochim. Cosmochim. Acta* 67, 4373–4387.
- Zhang, S.T., Wu, T.R., Xu, X., Byamba, J., Amarjargal, A., Wang, S.Q., Li, Z.Q., 2005. The Significance of Discovery of early cretaceous Shoshonite in Central Inner Mongolia. *Acta Sci. Nat. Univ. Pekin.* 41, 212–218 (in Chinese with English abstract).
- Zhang, S.H., Zhao, Y., Song, B., Hu, J.M., Liu, S.W., Yang, Y.H., Chen, F.K., Liu, X.M., Liu, J., 2009. Contrasting late Carboniferous and late Permian–Middle Triassic intrusive suites from the northern margin of the North China craton: Geochronology, petrogenesis, and tectonic implications. *GSA Bull.* 121, 181–200.
- Zhang, H.F., Sun, Y.L., Tang, Y.J., Xiao, Y., Zhang, W.H., Zhao, X.M., Santosh, M., Menzies, M.A., 2012. Melt-peridotite interaction in the Pre-Cambrian mantle beneath the western North China Craton: Petrology, geochemistry and Sr, Nd and Re isotopes. *Lithos* 149, 100–114.
- Zhao, G.C., Wilde, S.A., Cawood, P.A., Sun, M., Cruden, A.R., Easton, R.M., 2001. Archean blocks and their boundaries in the North China Craton: lithological, geochemical, structural and P–T path constraints and tectonic evolution. *Precambrian Res.* 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 Res.* 136, 177–202.
- Zhao, Y., Zheng, J.P., Xiong, Q., Zhang, H., 2018. Destruction of the North China Craton triggered by the Triassic Yangtze continental subduction/collision: a review. *J. Asian Earth Sci.* 164, 72–82.
- Zhong, F.P., Zhong, J.H., Wang, Y., Tian, W.F., 2014. Geochemistry Characteristics and Origin of early cretaceous Volcanic Rocks in Suhongtu Depression, Inner Mongolia, China. *Acta Mineral. Sin.* 34, 107–116 (in Chinese with English abstract).
- Zhong, F.P., Zhong, J.H., Abdurahman, A., Wang, Y., You, W.F., Yang, W.L., 2015. Timing and scale of the destruction of the North China craton: Revelation from the early cretaceous volcanic rocks in Suhongtu Depression of Inogen-Ejin Banner Basin. *Geol. China* 42, 435–456 (in Chinese with English abstract).
- Zhu, R.X., Pan, Y.X., He, H.Y., Qin, H.F., Ren, S.M., 2008. Palaeomagnetism and  $^{40}\text{Ar}/^{39}\text{Ar}$  age from a cretaceous volcanic sequence, Inner Mongolia, China: Implications for the field variation during the cretaceous normal superchron. *Phys. Earth Planet. Inter.* 169, 59–75.
- Zhu, R.X., Chen, L., Wu, F.Y., Liu, J.L., 2011. Timing, scale and mechanism of the destruction of the North China Craton. *Sci. China Earth Sci.* 54, 789–797.
- Zou, H.P., Zhang, K., Li, G., 2008. Cretaceous tectono-thermal event in the Ordos Block: an Ar–Ar Chronological evidence from basalt at Hangjin banner, inner Mongolia, North China craton. *Geotecton. Metallog.* 32, 360–364 (in Chinese with English abstract).