

Petrogenesis and Metallogenesis of the Niumaoquan Gabbroic Intrusion Associated with Fe-Ti Oxide Ores in the Eastern Tianshan, NW China

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Abstract: The Niumaoquan layered gabbroic intrusion is in the southern margin of the Central Asian Orogenic Belt in North Xinjiang, China, and hosts a Fe-Ti oxide deposit in its evolved gabbroic phases. In this paper, we report zircon U-Pb age, Sr-Nd-Hf isotopes, plagioclase chemistry, and whole-rock geochemistry of the Niumaoquan layered gabbroic intrusion. Zircon grains separated from an anorthosite sample analyzed by laser ablation inductively coupled plasma mass spectrometry yielded a concordia age of 314.7 ± 0.74 Ma, indicating that the Niumaoquan ore-bearing gabbroic intrusion was emplaced during the Late Carboniferous. The olivine gabbro texture and plagioclase chemistry suggest that plagioclase was an early crystallized silicate phase that crystallized prior to olivine. Fractional crystallization and accumulation of plagioclase significantly controlled the evolution of the Niumaoquan gabbroic intrusion and contributed to the formation of anorthosite layers, causing metallogenic elements to become enriched in the residual melt. The Niumaoquan gabbroic intrusion is characterized by the enrichment of large ion lithophile elements and depletion of high field strength elements, positive zircon $\varepsilon_{\text{Hf}}(t)$ values (+2.1 to +12.2), positive $\varepsilon_{\text{Nd}}(t)$ values (+3.3 to +5.2), and low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7039 to 0.7047), suggesting that the parental magma was produced by interactions between metasomatized lithospheric mantle and depleted asthenospheric melts at an early post-collision stage. The Fe-Ti oxide mineralization of the Niumaoquan intrusion benefited from interactions between depleted asthenospheric melts and lithospheric mantle, and fractional crystallization of abundant plagioclase and magnesian minerals.

Key words: anorthosite, chronology, Fe-Ti oxide, Niumaoquan, Eastern Tianshan

1 Introduction

Magmatic Ni-Cu sulfide, Fe-Ti oxide, Ni-Cu sulfide and Fe-Ti oxide composite, and native copper deposits are the four major types of deposits related to post-collision mantle-derived magma found in North Xinjiang (Wang Jingbin et al., 2008). The formation age, magmatic characteristics, and spatial distribution of deposits associated with mafic-ultramafic intrusions in the Eastern Tianshan are important factors for constructing the metallogenic spectrum associated with mantle-derived magma in a post-collision stage. Compared with typical Ni-Cu sulfide deposits, Ni-Cu sulfide and Fe-Ti oxide composite and native copper deposits in the Eastern Tianshan district, the formation ages of Fe-Ti oxide

deposits are not well constrained. The Niumaoquan layered gabbroic intrusion hosts a typical Fe-Ti oxide deposit in the Eastern Tianshan (Wang Yuwang et al., 2010; Li Dedong et al., 2012; Wang et al., 2014; Shi Yu et al., 2017a). However, this intrusion has not been dated using the zircon U-Pb method, and dating the Niumaoquan using the hornblende Ar-Ar method (Li Dedong et al., 2012) is not reliable for its emplacement age.

The Niumaoquan layered gabbroic intrusion is considered an Early Permian mafic-ultramafic intrusion in the Eastern Tianshan based on a hornblende Ar-Ar age (Li Dedong et al., 2012; Wang et al., 2014). However, the Niumaoquan gabbroic intrusion is significantly different from other typical Early Permian mafic-ultramafic intrusions in petrology assemblages and mineralization style (Wang Yuwang et al., 2010). Typical Early Permian mafic-ultramafic intrusions consist of multiple separate

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intrusive units, not only comprising gabbroic phases, e.g., olivine gabbro, gabbro, and hornblende gabbro, but also ultramafic phases, such as lherzolite and pyroxenite, which are associated with Ni-Cu sulfide mineralization (Mao Jingwen et al., 2003, 2008; Zhou et al., 2004; Tang et al., 2011). The Niumaoquan intrusion is a typical layered gabbroic intrusion composed of interlayered gabbroic rocks (Wang Yuwang et al., 2010; Li Dedong et al., 2012; Wang et al., 2014) and hosting a Fe-Ti oxide deposit. However, anorthosite layers displaying conformable contact with other gabbroic layers is a unique lithology recognized in this study, which distinguishes the Niumaoquan layered gabbroic intrusion from other mafic-ultramafic intrusions that host Ni-Cu sulfide deposits in the Eastern Tianshan district. Anorthosite is an important gabbroic phase in mafic-ultramafic intrusions associated with Fe-Ti oxide deposits (Li et al., 2014; Chen et al., 2015; Li et al., 2015), and possibly plays an important role in understanding the mineralization of the Niumaoquan Fe-Ti oxide deposit. Therefore, the chronology, mineralogy, petrology, and geochemistry of the Niumaoquan gabbroic intrusion are important for addressing Fe-Ti oxide mineralization style and constructing a metallogenic spectrum related to mantle-derived magma in a post-collision stage.

In this paper, we present plagioclase chemistry, zircon U-Pb age, Sr-Nd-Hf isotopes, and whole-rock geochemistry of the Niumaoquan gabbroic intrusion. Using these data, we discuss mantle source characteristics, crustal contamination, and the timing and mechanism of Fe-Ti oxide mineralization in the Niumaoquan layered gabbroic intrusion.

2 Regional Geological Setting

The Central Asian Orogenic Belt (CAOB) is the largest and most complex Phanerozoic orogenic belt in the world (Sengör et al., 1993; Xiao et al., 2008, 2010). At more than 5000 km long, it extends west to east between the Siberian and North China-Tarim cratons (Jahn et al., 2000, 2004). The CAOB was formed by subduction of Paleo-Asian Ocean crust and accretions of oceanic seamounts and plateaus, ophiolites and colliding ancient microcontinents, arc terranes, and successions of passive continental margins (Sengör et al., 1993; Jahn et al., 2000, 2004; Safonova et al., 2004, 2011; Xiao et al., 2008, 2010).

The Eastern Tianshan is on the CAOB's southern margin and consists of three tectonic units: the Bogeda-Harlik Belt in the north, the Jueluotage Belt in the center, and the Middle Tianshan Massif to the south (Fig. 1). The Bogeda-Harlik Belt is composed of well-developed Ordovician–Carboniferous volcanic rocks, granites, and mafic-ultramafic complexes, and is considered to be a Devonian to Late Carboniferous island arc that resulted from the consumption of Kelameili ocean basins (Xiao et al., 2004). The Jueluotage Belt is characterized by Middle Paleozoic volcanic and sedimentary strata, including subaerial volcanics, sandstones, and pelitic slates with interlayered limestones, mudstones, siltstones, and conglomerates. The Jueluotage Belt can be subdivided from north to south into the Dananhu-Tousuquan island arc, the Xiaorequanzi-Wutongwozi intra-arc basin, the Kangguer-Huangshan ductile shear zone, and the Yamansu back-arc basin (Fig. 1; Qin Kezhang et al., 2002). The Middle Tianshan Massif is composed of a

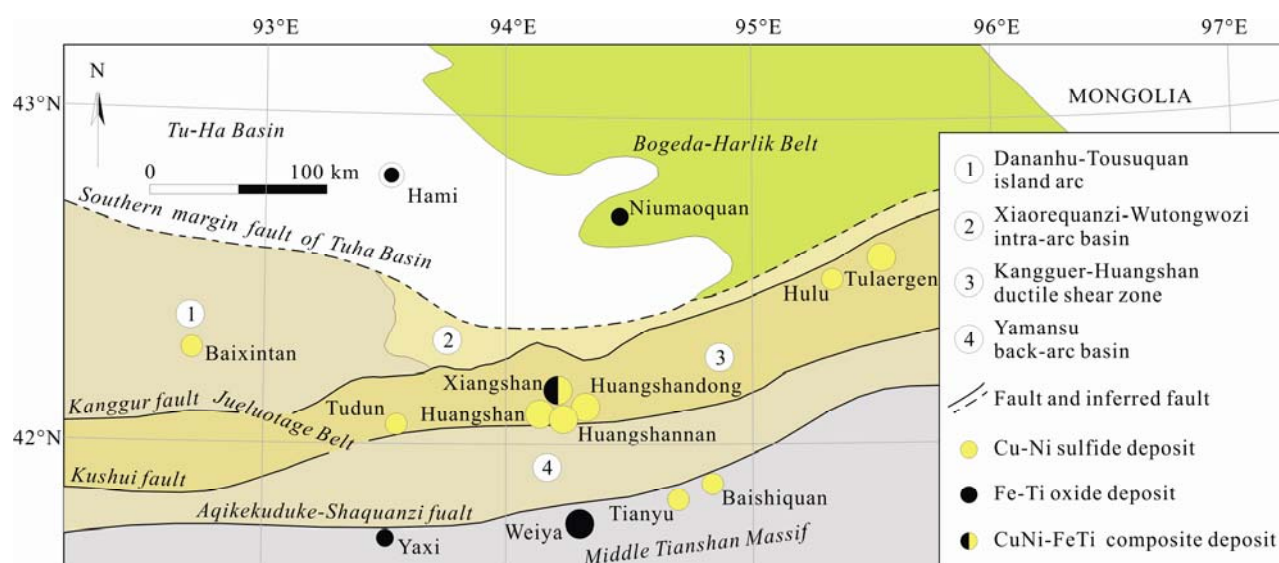


Fig. 1. Geological map of the Eastern Tianshan and distribution of orthomagmatic deposits there (modified from Qin Kezhang et al., 2002).

Precambrian crystalline basement (Qin Kezhang et al., 2002), and is bounded by the Aqikekuduk-Shaquanzi fault in the north (Fig. 1) and the Hongliuhe fault in the south.

Mafic-ultramafic intrusions are widely distributed throughout the Eastern Tianshan, and are emplaced in multiple tectonic units, including the Bogeda-Harlik Belt (Yuan et al., 2010; Lei Wanshan et al., 2016), the Jueluotage Belt (Sun Tao et al., 2013, 2017; Feng Yanqing et al., 2017), and the Middle Tianshan Massif (Chai et al., 2008; Tang et al., 2011). Ni-Cu sulfide, Fe-Ti oxide, and NiCu-FeTi composite deposits are the three major orthomagmatic deposit types in the Eastern Tianshan. Early Permian mafic-ultramafic intrusions were emplaced in the Early to Middle Permian (ca. 289–269 Ma, mainly around ca. 280 Ma; Han Baofu et al., 2004; Zhou et al., 2004; Han et al., 2010; Qin et al., 2011; Tang et al., 2011; Sun et al., 2013; Wang Yalei et al., 2017). These intrusions host many typical Ni-Cu sulfide deposits distributed in multiple tectonic units, such as Baixintan in the Dananhu-Tousuquan island arc (Wang Yalei et al., 2015), Huangshan and Huangshandong in the Jueluotage Belt (Mao Jingwen et al., 2003; Deng Yufeng et al., 2011, 2014, 2015; Mao et al., 2014), and Tianyu and Baishiquan in the Middle Tianshan Massif (Chai et al., 2008; Tang et al., 2011). The Xiangshan intrusion is a unique Early Permian mafic-ultramafic complex characterized by Ni-Cu sulfide and Fe-Ti oxide composite mineralization, and consists of a large-scale ilmenite deposit and a medium-sized Ni-Cu sulfide deposit (Wang Yuwang et al., 2006, 2009; Han et al., 2010; Xiao Qinghua et al., 2010; Tang et al., 2013; Shi Yu et al., 2018). The Fe-Ti oxide deposits in the Eastern Tianshan are mainly associated with layered gabbroic intrusions, which were emplaced from the Early Permian to the Middle Triassic (Zhang Zunzhong et al., 2005, 2007; Wang Yuwang et al., 2008; Xiao Qinghua et al., 2010; Li Dedong et al., 2012). These deposits are also widely distributed in the Eastern Tianshan (Fig. 1), such as the Weiya and Yaxi deposits in the Middle Tianshan Massif (Zhang Zunzhong et al., 2005; Wang Yuwang et al., 2008; Li Dedong et al., 2016; Shi Yu et al., 2016), the Xiangshan deposit in the Jueluotage Belt (Wang Yuwang et al., 2009, 2010; Han et al., 2010; Xiao Qinghua et al., 2010; Shi Yu et al., 2018), and the Niumaoquan deposit in the southern margin of the Bogeda-Harlik Belt (Wang Yuwang et al., 2010; Li Dedong et al., 2012; Wang et al., 2014; Shi Yu et al., 2017a).

3 Petrography and Mineralization of the Niumaoquan Intrusion

The Niumaoquan layered gabbroic intrusion is exposed ca. 81 km southeast of Hami in the southern margin of

the Late Paleozoic Bogeda-Harlik Belt (Fig. 1). The Niumaoquan intrusion was emplaced into Variscan potassic granites (Fig. 2a) and is crosscut by diorite veins (Fig. 2b). This layered intrusion is mainly composed of interlayered gabbroic phases, including olivine gabbro, gabbro, and hornblende gabbro based on textures and mineral assemblages, and is distinctly stratified with rhythmic layering (Figs. 3a and 3b). Anorthosite is a newly recognized lithology in the Niumaoquan gabbroic intrusion, containing >80 modal% plagioclase. Anorthosite occurs as layers in the olivine gabbro and gabbro layers, and shows conformable contact with underlying and overlying gabbroic layers (Fig. 3a). A Fe-Ti oxide ore is hosted by this layered gabbroic intrusion, containing reserves of 351,300 metric tons of Fe at a grade of 25.8wt% Fe (Wang et al., 2014). Fe-Ti oxide ore bodies of the Niumaoquan deposit are mainly hosted in the gabbro and hornblende gabbro layers, both of which overlie the olivine gabbro layers. These oxide ore bodies are also relatively evolved in petrology, mineralogy, and geochemistry (Wang Yuwang et al., 2010; Li Dedong et al., 2012; Wang et al., 2014).

Olivine gabbro is a major gabbroic phase in the Niumaoquan intrusion (Fig. 2a), containing 45vol%–50vol% plagioclase, 25vol%–30vol% clinopyroxene, 10vol%–15vol% hornblende, 5vol%–10vol% olivine, and 1vol%–5vol% orthopyroxene, with minor amounts of sulfide and Fe-Ti oxides (3vol%–8vol%) (Fig. 4a). Plagioclase in olivine gabbro is euhedral and subhedral with a cumulating texture, and some occurs as inclusions enclosed by olivine and clinopyroxene grains (Fig. 4a). Granular clinopyroxene is intergrown with plagioclase, with some having reaction coronae of hornblende. The interstitial Fe-Ti oxides coexist with hornblende in the olivine gabbro.

Anorthosite occurs as conformable layers in olivine gabbro layers (Fig. 3a), and contains approximately 90vol% plagioclase, 0vol%–5vol% clinopyroxene, and 0vol%–5vol% hornblende, with minor amounts of Fe-Ti oxides (Fig. 4b). Plagioclase in anorthosite is euhedral and displays a cumulating texture, whereas clinopyroxene and hornblende are anhedral and grow as interstitial phases (Fig. 4b).

Gabbro is a ubiquitous gabbroic phase in the intrusion (Fig. 2a) and conformably overlies olivine gabbro layers, containing nearly 40vol%–60vol% plagioclase, 25vol%–35vol% clinopyroxene, and approximately 10vol% orthopyroxene, with minor amounts of hornblende and Fe-Ti oxide (Fig. 4c).

Hornblende gabbro mainly occurs in the eastern section of the Niumaoquan intrusion (Fig. 2a) and contains 30vol%–40vol% plagioclase, 10vol%–20vol% clinopyr-

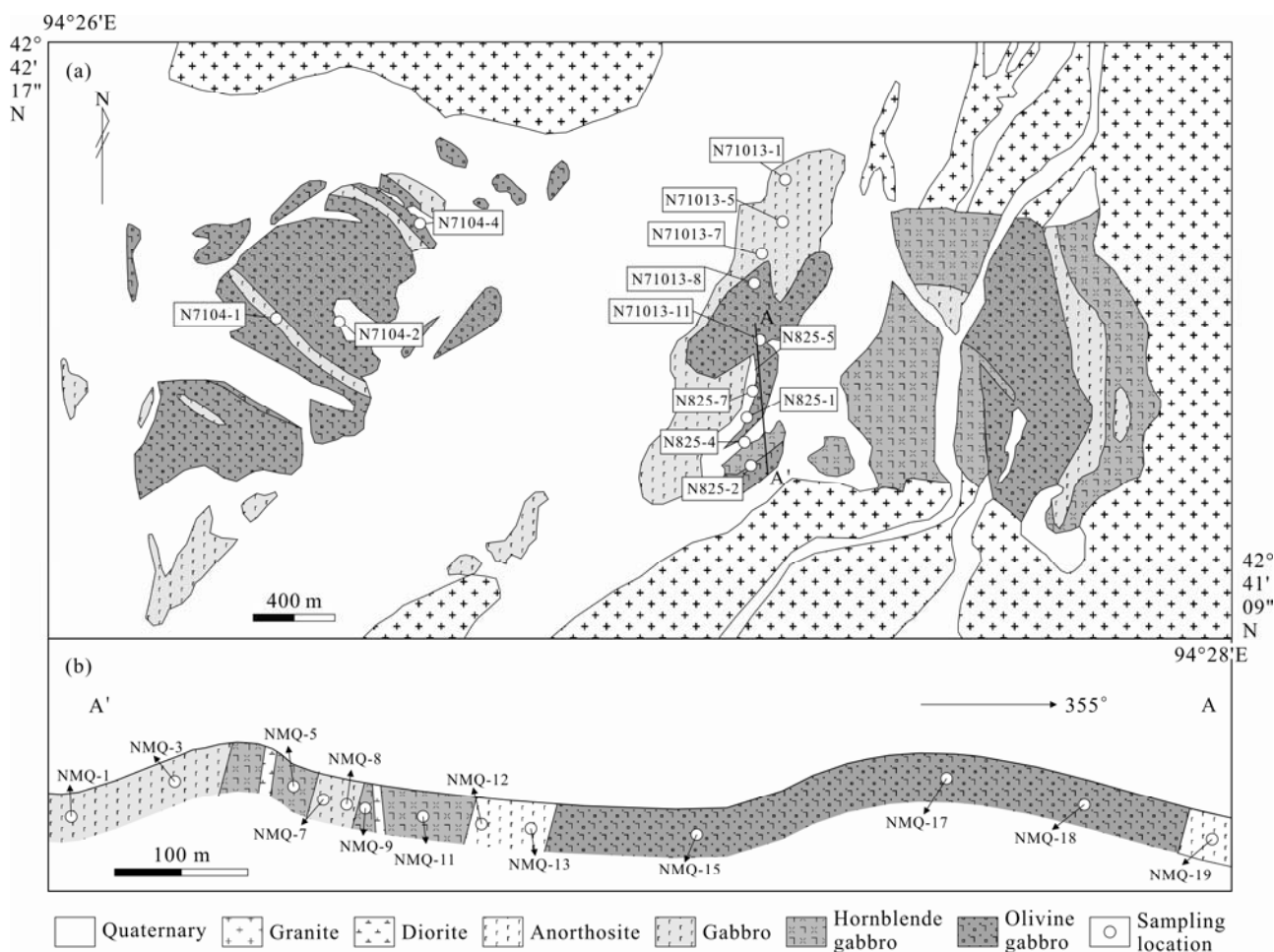


Fig. 2. (a), Simplified geological map of the Niumaoquan intrusion (modified after Wang et al., 2014); (b), geological section showing variation in the lithologies of the Niumaoquan layered gabbroic intrusion.

oxene and orthopyroxene, nearly 25vol % poikilitic hornblende, 15vol% Fe-Ti oxide, and minor amounts of apatite (Fig. 4d). Plagioclase, clinopyroxene, orthopyroxene and Fe-Ti oxides in hornblende gabbro are enclosed by poikilitic hornblende (Fig. 4d).

4 Analytical Methods and Results

4.1 Mineral composition of plagioclase

Plagioclase is the most prominent silicate mineral in Niumaoquan gabbroic rocks, and occurs as a euhedral cumulating mineral in all gabbroic phases, e.g., anorthosite, olivine gabbro, gabbro, and hornblende gabbro, and its anorthosite component (An value) could reflect the relative evolution of a suite of gabbroic rocks (Zhong Hong et al., 2007). Plagioclase occurring as inclusions hosted in olivine grains is the second most common type of plagioclase apart from euhedral cumulating plagioclase in olivine gabbro (Fig. 4a), and the composition difference between these two types of plagioclase is important to understanding the petrogenesis of the Niumaoquan gabbroic intrusion. Euhedral

plagioclase grains from all gabbroic phases and plagioclase inclusions in olivine grains were analyzed using a JEOL JXA-8100 electron microprobe (EMP) at the Institute of Geology and Geophysics of the Chinese Academy of Sciences. The analyses were carried out using a voltage of 15 kV and beam current of 20 nA, focused to a spot of 5 μ m. The peak and background counting times for major elements were 20 s and 10 s, respectively, whereas those for trace elements were 40 s and 20 s, respectively. The standards used for oxide analyses were albite for Si, Na, and Al, plagioclase for Ca, and potassium feldspar for K. The precisions of the major and trace element determinations were better than 2% and 5%, respectively.

Table 1 shows the multi-gabbroic rock plagioclase compositions of the Niumaoquan layered intrusion. Two types of plagioclase from olivine gabbro, occurring either as a euhedral cumulate mineral or as inclusions in olivine grains, have similar An values, ranging from 88.1 to 91.2 (Table 1). This confirms that plagioclase crystallized earlier than olivine during the formation of the Niumaoquan intrusion. Plagioclase in the anorthosite and

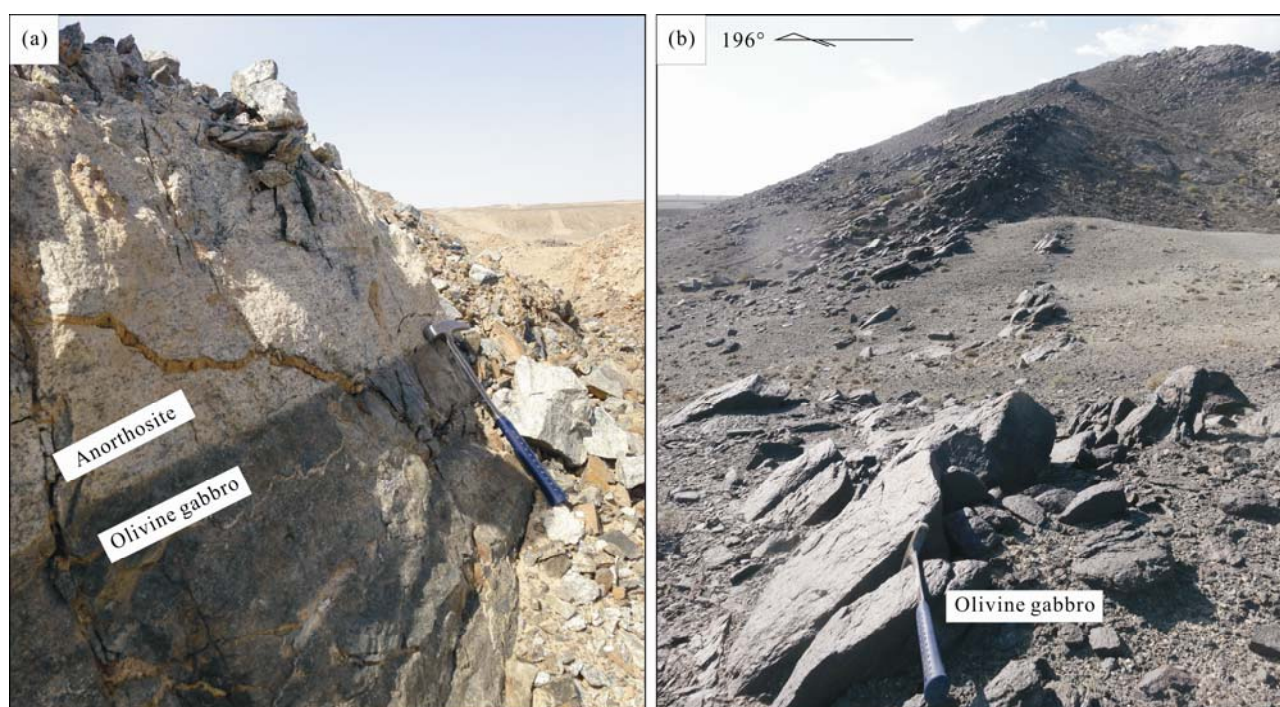


Fig. 3. Field photos of the Niumaoquan layered gabbroic intrusion. (a), Interlayered anorthosite and olivine gabbro; (b), layered olivine gabbro.

Table 1 Major oxides of plagioclase from the Niumaoquan layered gabbroic intrusion

Sample	7104-2	7104-4	71013-1	71013-7	71013-15	71013-11	71013-5	7104-1	825-7	71013-14	825-6	825-1	825-4	825-2
Rocktype	OG	OG	OG	OG	OG	OG	Anor	Anor	Anor	Gb	Gb	HG	HG	HG
N	12	10	2	3	6	3	3	7	3	3	3	2	3	3
Major elements (wt%)														
SiO ₂	45.1	46	45.7	46.1	47.3	45.3	45.9	45.6	47.9	46.7	47.2	47.5	51.3	51.5
Al ₂ O ₃	35.0	34.3	34.6	34.0	33.1	33.4	34.3	34.4	32.8	33.2	33.3	32.5	29.8	30.1
CaO	18.6	17.9	18.2	17.8	16.7	17.7	17.8	18.2	16.7	16.9	17.1	16.6	13.4	13.7
Na ₂ O	0.86	1.26	1.14	1.31	1.94	1.11	1.17	1.13	1.91	1.52	1.65	1.96	3.57	3.53
K ₂ O	0.01	0.02	0.02	0.04	0.04	0.03	0.06	0.02	0.02	0.03	0.03	0.03	0.15	0.13
Total	99.6	99.5	99.7	99.3	99.1	97.5	99.2	99.4	99.3	98.4	99.3	98.6	98.2	99.0
Cations														
Si(O=8)	2.09	2.13	2.11	2.14	2.19	2.14	2.13	2.11	2.21	2.18	2.18	2.21	2.37	2.36
Al	1.91	1.87	1.88	1.86	1.80	1.86	1.87	1.88	1.78	1.82	1.81	1.78	1.62	1.63
Ca	0.92	0.89	0.90	0.88	0.83	0.90	0.88	0.91	0.83	0.84	0.85	0.83	0.66	0.67
Na	0.08	0.11	0.10	0.12	0.17	0.10	0.11	0.10	0.17	0.14	0.15	0.18	0.32	0.31
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Cation	5.00	5.00	5.00	5.00	5.00	4.99	4.99	5.00	4.99	4.98	4.99	4.99	4.98	4.99
End-member compositions (mol%)														
An	92.2	88.6	89.7	88.1	82.5	89.7	89.1	89.8	82.8	85.9	85.0	82.3	66.9	67.7
Ab	7.7	11.3	10.2	11.7	17.3	10.2	10.6	10.1	17.1	14.0	14.8	17.5	32.2	31.5
Or	0.1	0.1	0.1	0.2	0.2	0.2	0.4	0.1	0.1	0.2	0.2	0.2	0.9	0.8

Note: OG, OG, Olivine gabbro; Anor, Anorthosite; Gb, Gabbro; HG, Hornblende gabbro.

gabbro layers have similar An values, ranging from 82.8 to 89.8 and 85.0 to 85.9, respectively (Table 1), and the plagioclase is relatively more evolved than that of olivine gabbro. Plagioclase of hornblende gabbro has An value varying 66.9 to 82.3 and is most evolved in composition.

4.2 Zircon U-Pb ages and Hf isotopes

We performed zircon U-Pb dating on a representative anorthosite sample (NMQ5530-19). Zircon grains were separated using conventional magnetic and density techniques and hand-picked under a binocular microscope. The zircon grains were mounted in epoxy resin slide 2.5

cm in diameter and polished to expose the centers of the zircon grains. Prior to analytical work, we examined all zircon grains under a microscope with transmitted and reflected light as well as with cathodoluminescence images using a scanning electron microscope (CL-SEM) to reveal their internal structures.

Zircon U-Pb dating was performed at the Key Laboratory of Orogenic Belt and Crustal Evolution, Peking University, using a GeoLas 200M 193 nm ArF laser-ablation system coupled with an Agilent 7500a ICP-MS. A spot size of 32 μ m and 10 Hz laser repetition rate were employed for zircon U-Pb dating, and each analysis

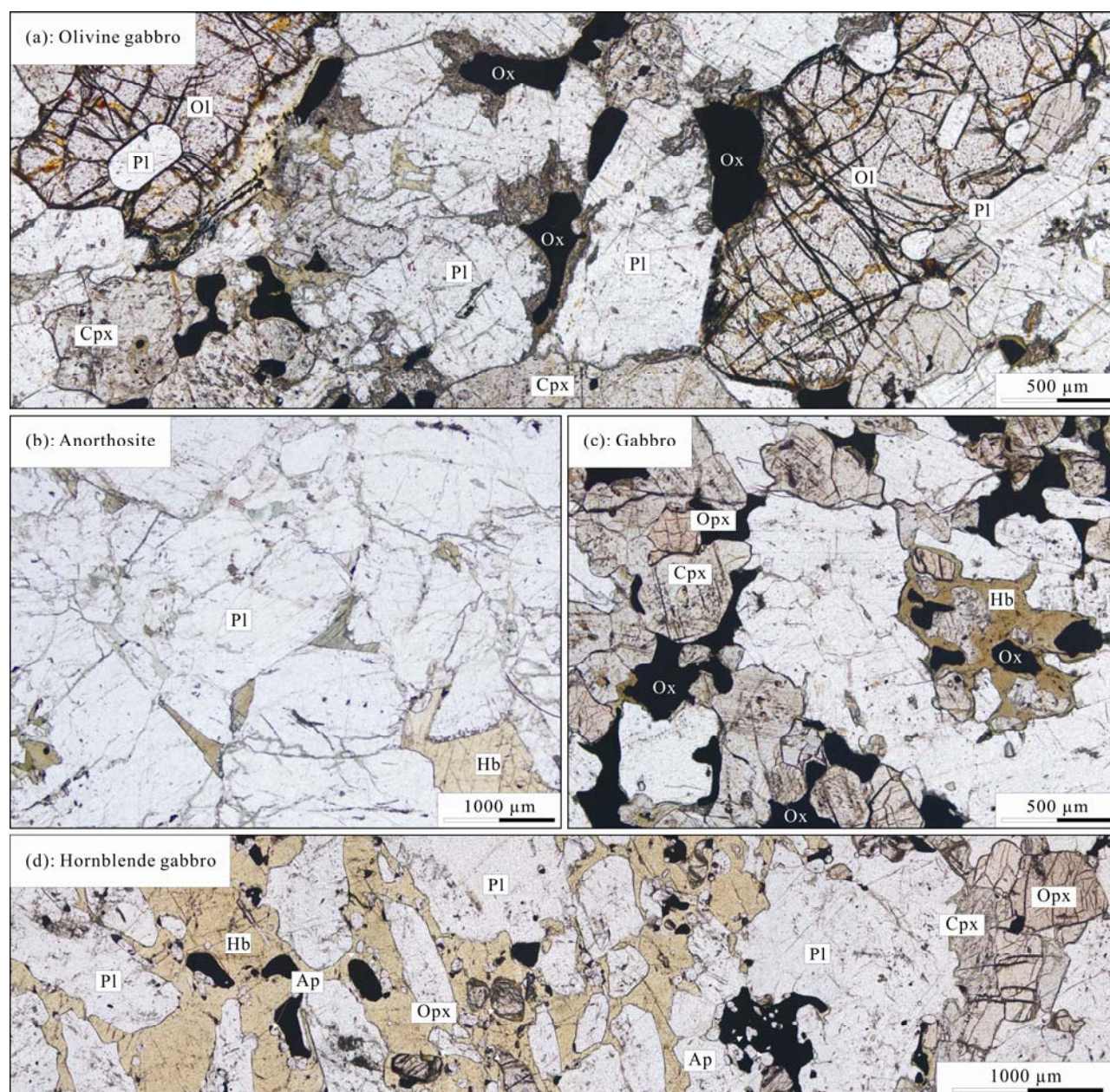


Fig. 4. Microphotographs of Niumaoquan gabbroic rocks.

(a), Olivine gabbro; (b), anorthosite; (c), gabbro; (d), hornblende gabbro. Note: Ol: olivine; Cpx: clinopyroxene; Opx: orthopyroxene; Hb: hornblende; Pl: plagioclase; Ox: Fe-Ti oxides; Ap: apatite. All microphotographs were taken under polarized light.

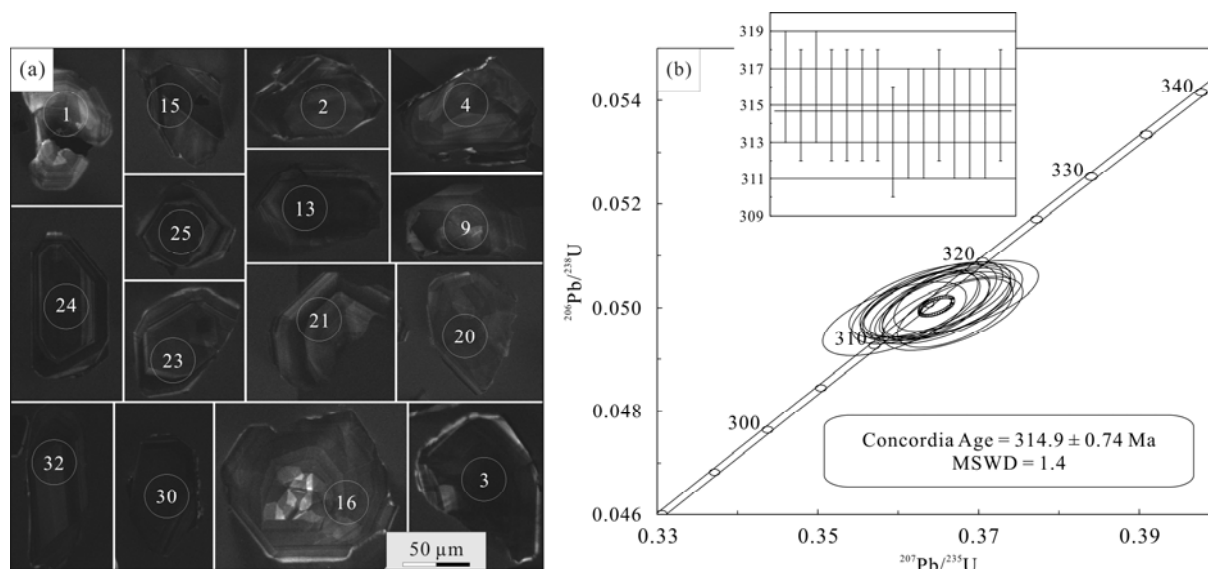
consisted of 20 s for gas blank and 60 s of acquisition following the procedures given in Liu et al. (2010). We achieved calibration using standard procedures that included the use of NIST 610 glass reference material and standard zircon 91500 for external standardization, and stoichiometric zircon SiO_2 content for internal standardization. Data were processed using GLITTER software, and common Pb correction and sample ages were calculated using ComPbCorr#3_17 (Andersen, 2002). Analytical precision was better than 2%. Fifteen analyses of zircon grains are listed in Table 2. Zircon grains from sample NMQ5530-19 are mostly dark in color and stubby to prismatic in shape (Fig. 5a). The zircon

grains generally have low transparency because of their striking high U (63–5745 ppm) and Th (274–7315 ppm) contents (Table 2). Although not all zircon grains exhibited concentric zoning, their well-developed crystal shape, internal banding, and high Th/U ratios (0.43–1.49) were consistent with a mafic igneous origin (Fig. 5a; Table 2). The analyses are clustered on a U-Pb concordia curve (Fig. 5b). The analysis yielded a concordia age of 314.9 ± 0.74 Ma (mean square weighted deviation=1.4) and a mean age of 314.7 ± 1.5 Ma (mean square weighted deviation=0.074), both of which are interpreted as the Niumaoquan layered intrusion's crystallization age.

Hf isotopes of the zircon grains were determined in situ

Table 2 LA-ICP-MS zircon U-Pb dating results of anorthosite from the Niumaoquan layered intrusion

Sample	Content (ppm)			Th/U	Isotopic ratio						Age (Ma)					
	Pb	Th	U		$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ
NMQ19-01	63	274	35	0.43	0.0530	0.0011	0.36659	0.00718	0.0502	0.0005	330	27	317	5	316	3
NMQ19-02	1282	758	78	0.61	0.0530	0.0009	0.36628	0.00545	0.0501	0.0005	331	18	317	4	315	3
NMQ19-03	3383	3759	232	1.11	0.0529	0.0007	0.36624	0.00447	0.0502	0.0004	325	13	317	3	316	3
NMQ19-04	1323	1201	84	0.91	0.053	0.0008	0.36600	0.00527	0.0501	0.0005	331	17	317	4	315	3
NMQ19-05	892	1331	65	1.49	0.0526	0.0009	0.36307	0.00606	0.0501	0.0005	310	21	315	5	315	3
NMQ19-06	5745	7315	396	1.27	0.0529	0.0007	0.36453	0.00454	0.0500	0.0004	322	14	316	3	315	3
NMQ19-07	1967	1242	127	0.63	0.0526	0.0008	0.36263	0.00481	0.0500	0.0005	311	15	314	4	315	3
NMQ19-08	1451	1059	89	0.73	0.0524	0.0009	0.35954	0.0059	0.0498	0.0005	303	21	312	4	313	3
NMQ19-09	2054	2223	134	1.08	0.0531	0.0009	0.36560	0.00562	0.0500	0.0005	331	19	316	4	314	3
NMQ19-10	4350	3966	278	0.91	0.0534	0.0008	0.36709	0.00476	0.0499	0.0004	345	15	317	4	314	3
NMQ19-11	1156	845	70	0.73	0.0529	0.001	0.36554	0.00656	0.0501	0.0005	326	23	316	5	315	3
NMQ19-12	3258	4000	234	1.23	0.0528	0.0008	0.36392	0.00491	0.0500	0.0005	321	15	315	4	314	3
NMQ19-13	2819	2351	181	0.83	0.0534	0.0009	0.36678	0.00576	0.0499	0.0005	344	19	317	4	314	3
NMQ19-14	2011	2920	146	1.45	0.0526	0.0008	0.36222	0.00527	0.0500	0.0005	310	17	314	4	314	3
NMQ19-15	4330	3024	269	0.7	0.0527	0.001	0.36462	0.0062	0.0502	0.0005	318	22	316	5	315	3

**Fig. 5. (a) Cathodoluminescence images and (b) zircon U-Pb concordia plot for the Niumaoquan layered gabbroic intrusion.**

using laser ablation-multiple collectors-inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) analysis at the State Key Laboratory of Continental Dynamics, Northwest University, Xi'an, China. Lu-Hf isotopic analyses were obtained on the same zircon grains previously analyzed for U-Pb isotopes, with ablation pits of 44 μm in diameter, 30 s for gas blank, and acquisition of 50 s. The detailed analytical procedures for Hf isotopes can be found in Yuan et al. (2008). Repeat analyses of zircon standards 91500 and GJ-1 during sample analysis gave 0.282307 ± 0.000031 (2σ) and 0.282015 ± 0.000019 (2σ), respectively, which are consistent within the certified ranges for these standards. Table 3 lists the Hf isotopes of selected zircon crystals determined by LA-MC-ICP-MS. Fourteen in situ Hf isotopic analyses were conducted on Niumaoquan zircon grains, which have high positive $\varepsilon_{\text{Hf}}(t)$ (+2.1 to +12.2), and young T_{DM} (457 to 872 Ma) (Table 3).

4.3 Whole-rock major and trace elements

Whole-rock samples were taken from the best exposed

and least-altered outcrops considered to be representative of the Niumaoquan intrusion's major lithologies. Figure 2b shows the sampling location. All whole-rock analyses were performed at the Key Laboratory of Orogenic Belt and Crustal Evolution, Peking University. Major elements for whole-rock samples were determined using a Shimadzu XRF-1700/1500 X-ray fluorescence spectrometer after samples were fused with lithium tetraborate. Duplicate analysis of Chinese National Reference GSR-3 and GSR-15 show that the precision was 1% for elements with a greater than 5wt% concentration and 10% for elements concentrations less than 5wt%. Loss on ignition was measured as weight loss of the samples after baking for 1 h at 1000°C. Trace element concentrations were determined using an inductively coupled plasma mass spectrometer (ICP-MS) after $\text{HNO}_3 + \text{HF}$ digestion of about 40 mg of sample powder in a Teflon vessel at 150°C. The precision was 5% of the quoted values for elements present at >1 ppm and about 10% for elements present at <1 ppm. Accuracy was

Table 3 Hf isotopes of zircon from the Niumaoquan layered gabbroic intrusion

No	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	2 σ	$(^{176}\text{Hf}/^{177}\text{Hf})_i$	$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	T_{DM1}	fLu/Hf
NMQ19-01	0.016074	0.000674	0.282880	0.000002	0.282876	3.8	10.6	524	-1.00
NMQ19-02	0.032175	0.001406	0.282766	0.000009	0.282758	-0.2	6.4	697	-1.00
NMQ19-03	0.050823	0.002303	0.282727	0.000022	0.282713	-1.6	4.8	772	-0.99
NMQ19-04	0.030177	0.001408	0.282873	0.000012	0.282864	3.6	10.2	544	-1.00
NMQ19-06	0.021977	0.001164	0.282875	0.000006	0.282868	3.6	10.3	537	-1.00
NMQ19-07	0.006615	0.000323	0.282799	0.000001	0.282797	1.0	7.8	631	-1.00
NMQ19-08	0.009585	0.000483	0.282925	0.000001	0.282922	5.4	12.2	457	-1.00
NMQ19-09	0.049813	0.001861	0.282851	0.000007	0.282841	2.8	9.0	582	-0.99
NMQ19-10	0.022294	0.001173	0.282910	0.000003	0.282903	4.9	11.5	488	-1.00
NMQ19-11	0.031894	0.001559	0.282859	0.000007	0.282850	3.1	9.7	566	-0.99
NMQ19-12	0.021059	0.0008535	0.282818	0.000007	0.282813	1.6	8.0	614	-1.00
NMQ19-13	0.012685	0.000683	0.282867	0.000002	0.282863	3.4	10.2	541	-1.00
NMQ19-14	0.031156	0.001406	0.282685	0.000006	0.282677	-3.1	3.6	813	-1.00
NMQ19-15	0.026955	0.001449	0.282644	0.000018	0.282635	-4.5	2.1	872	-0.99

$\varepsilon_{\text{Hf}}(t)$ calculated using the method of Blichert and Albarede (1997), ^{176}Lu decay constant $\lambda = 1.865 \times 10^{-11} \text{y}^{-1}$ (Soderlund et al., 2004), $t = 314.9 \text{ Ma}$.

Table 4 Major (wt%) and trace element (ppm) analysis of gabbroic rocks from the Niumaoquan layered intrusion

Rock	Gabbro				Hornblende gabbro			Anorthosite			Olivine gabbro		
Sample	NMQ-01	NMQ-03	NMQ-07	NMQ-08	NMQ-05	NMQ-09	NMQ-11	NMQ-12	NMQ-13	NMQ-19	NMQ-15	NMQ-17	NMQ-18
SiO ₂	42.77	42.53	44.05	43.22	41.8	41.5	41.81	47.1	45.12	45.12	40.73	38.78	40.35
TiO ₂	2.39	3.32	2.92	2.84	3.26	3.45	3.04	0.76	0.35	0.37	1.96	2.19	2.53
Al ₂ O ₃	15.69	16.04	17.88	17.85	17.18	16.76	16.53	24.19	23.29	27.61	18.71	17.02	16.13
Fe ₂ O ₃	6.17	5.93	5.2	5.04	4.68	7.94	4.97	3.23	2.02	2.4	7.42	7.96	9.29
FeO	9.42	8.46	8.12	8.41	8.89	7.18	9.56	3.74	5.44	2.09	7.64	9.47	7.71
MnO	0.26	0.26	0.23	0.24	0.26	0.27	0.27	0.08	0.14	0.05	0.17	0.18	0.19
MgO	8.08	7.86	6.36	6.55	6.71	6.48	6.97	3.14	6.68	2.31	6.2	7.67	7.49
CaO	11.31	10.59	11.44	12.16	11.87	11.95	12.3	14.72	14.69	17.15	13.56	13.71	13.42
Na ₂ O	1.52	1.56	2.1	1.89	1.99	1.61	1.69	1.73	1.02	1.17	0.87	0.73	0.9
K ₂ O	0.14	0.4	0.12	0.12	0.12	0.08	0.1	0.28	0.05	0.29	0.36	0.14	0.05
P ₂ O ₅	0.1	0.24	0.2	0.23	1.89	1.33	1.28	0.11	0.05	0.02	0.02	0.02	0.02
LOI	0.78	1.66	0.21	0.24	0.11	0.42	0.05	0.37	0.35	1.09	1.21	0.56	0.81
Total	99.69	99.79	99.73	99.72	99.73	99.76	99.62	99.84	99.77	99.89	99.69	99.47	99.77
Sc	58.41	57.41	51.62	53.16	42.98	53.27	68.63	22.81	21.68	9.37	62.9	69.64	71.14
V	425	221	255	277	226	280	359	222	94	108	589	810	788
Cr	2.85	1.26	2.33	0.65	1.73	8.04	38.89	33.31	79.31	12.82	3.64	1.89	80.11
Co	36.64	24.57	27.82	29.01	26.77	24.2	38.06	19.99	36.73	12.28	45.5	61.62	41.96
Ni	3.4	2.1	2.35	4.48	2.58	2.21	3.88	11.42	19.68	8.32	2.4	2.83	25.15
Cu	16.28	10.58	11.34	13.09	10.3	11.18	13.12	23.14	29.96	8.15	27.36	37.17	110.5
Rb	3.73	18.39	2.25	2.73	2.42	1.66	3.27	11.02	1.56	10.47	13.7	3.71	1.08
Sr	351	334	423	403	410	343	438	398	345	402	284	198	191
Y	10.62	11.09	10.54	10.77	22.07	18.45	19.97	5.43	3.69	1.83	6.42	5.99	7.18
Zr	12.35	12.54	12.51	13.18	12.51	14.69	17.07	14.44	9.95	5.04	5.67	5.74	6.1
Nb	5.46	3.65	2.46	2.29	3.04	3.24	2.42	1.36	0.81	0.67	0.55	1.15	0.68
Cs	0.39	0.84	0.31	0.33	0.26	0.12	0.23	0.59	0.52	0.22	0.28	0.2	0.09
Ba	70.57	81.79	41.11	40.04	63.91	46.16	51.7	115.8	50.75	47.47	113.4	37.68	29.85
La	1.73	1.8	1.77	1.94	5.34	4.54	4.25	2.64	1.17	0.9	0.6	0.41	0.49
Ce	4.58	4.74	4.76	5.22	14.91	12.53	11.84	5.85	2.72	2.01	1.66	1.32	1.6
Pr	0.73	0.81	0.79	0.83	2.49	2.03	1.94	0.76	0.38	0.27	0.3	0.26	0.32
Nd	3.81	4.2	4.19	4.38	12.48	10.1	10	3.11	1.7	1.1	1.8	1.62	2.11
Sm	1.38	1.57	1.49	1.53	4.13	3.37	3.42	0.86	0.53	0.31	0.7	0.72	0.9
Eu	0.81	0.91	0.87	0.83	1.61	1.24	1.41	0.56	0.41	0.31	0.47	0.41	0.49
Gd	1.8	2.06	1.92	1.97	5.05	4.11	4.22	0.97	0.63	0.35	1.11	1.1	1.35
Tb	0.33	0.36	0.34	0.35	0.8	0.67	0.71	0.17	0.11	0.06	0.2	0.2	0.24
Dy	2.12	2.28	2.14	2.2	4.67	3.95	4.23	1.02	0.72	0.36	1.33	1.28	1.56
Ho	0.45	0.47	0.44	0.46	0.92	0.79	0.85	0.21	0.15	0.08	0.28	0.27	0.32
Er	1.22	1.27	1.19	1.24	2.35	2.03	2.2	0.59	0.41	0.2	0.75	0.72	0.86
Tm	0.17	0.17	0.16	0.17	0.29	0.26	0.29	0.08	0.06	0.03	0.1	0.1	0.12
Yb	1.03	1.05	1.00	1.06	1.7	1.6	1.71	0.51	0.38	0.19	0.6	0.59	0.7
Lu	0.15	0.15	0.14	0.15	0.23	0.21	0.24	0.08	0.06	0.03	0.09	0.08	0.1
Hf	0.42	0.41	0.41	0.42	0.39	0.47	0.57	0.39	0.26	0.11	0.22	0.23	0.25
Ta	0.47	0.31	0.21	0.21	0.25	0.30	0.28	0.19	0.14	0.14	0.11	0.24	0.13
Pb	4.34	0.87	2.1	0.62	0.99	0.83	6.07	10.15	2.15	0.97	1.05	0.66	0.95
Th	0.17	0.1	0.11	0.15	0.24	0.22	0.26	2.15	0.14	0.07	0	0.01	0.01
U	0.05	0.11	0.05	0.07	0.12	0.1	0.11	0.44	0.06	0.1	0.03	0.01	0.12

estimated to be better than 5% for the reported values.

Table 4 shows results of whole-rock major and trace element analyses. The large compositional variations reflect large differences in the relative abundances of cumulus minerals. For example, SiO₂ and CaO decrease

(Figs. 6a and 6g) and TiO₂, Fe₂O₃^T, MnO, and Al₂O₃ increase (Figs. 6b, 6c, 6d, and 6e) with decreasing Al₂O₃, which is consistent with fractionation/accumulation of high-An plagioclase (Fig. 6). The composition variation of olivine gabbro and anorthosite are strongly controlled by

the accumulation of high-An plagioclase (Fig. 6), whereas gabbro and hornblende gabbro are controlled by accumulations of Fe-Ti oxides and apatite, which is suggested by rapid increases of TiO_2 , Fe_2O_3^T , and P_2O_5 with decreasing Al_2O_3 (Figs. 6b, 6c, and 6h).

The Niumaoquan gabbroic intrusion generally consists of olivine gabbro, anorthosite, gabbro, and hornblende gabbro, all of which contain variable rare Earth element (REE) contents and different chondrite-normalized REE patterns. This reflects different mineral assemblages and varying abundances of intercumulus liquids. Olivine gabbros have the lowest REE content and display light REE (LREE) depletion and slight positive Eu anomalies (Fig. 7a), which is consistent with large amounts of olivine and clinopyroxene. Anorthosites are also characterized by low REE content and display LREE enrichment and significant positive Eu anomalies (Fig. 7a), possibly caused by accumulation of plagioclase, which is relatively enriched in LREE and Eu. Gabbros have a moderate REE content and display relatively flat REE patterns, with positive Eu anomalies (Fig. 7a). Hornblende gabbros have the highest REE contents and are enriched in medium REE (MREE), displaying convex REE patterns (Fig. 7a). This is possibly caused by crystallization of poikilitic hornblende, which is enriched in MREE. The gabbroic rocks show positive Sr and Ti anomalies, and show Th, Nb, Ta, Zr, and Hf depletion (Fig. 7b). Olivine gabbro, anorthosite, and gabbro mainly display significant positive Pb anomalies, whereas hornblende gabbro displays negative to slight positive Pb anomalies (Fig. 7b).

4.4 Whole-rock Sr-Nd isotopes

Rb-Sr and Sm-Nd isotopes were determined using an ISOPROBE-T thermal ionization mass spectrometer at the Beijing Research Institute of Uranium Geology. The rock powders were treated with 0.3 N HCl for 1 h at 100°C, and dried after rinsing with purified water. The samples were weighed and spiked with mixed isotope tracers and dissolved in Teflon capsules with HF + HNO_3 at 120°C

for 7 days. Procedural blanks were <50 pg for Sm and Nd and <500 pg for Rb and Sr. Mass fractionation corrections for Sr and Nd isotopic ratios were based on values of $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$. Typical within-run precision (2σ) for Sr and Nd isotopic ratios is better than $\pm 0.5\%$. The measured values for the JMC Nd standard and the NBS987 Sr standard were $^{143}\text{Nd}/^{144}\text{Nd}=0.512109\pm 3$ and $^{87}\text{Sr}/^{86}\text{Sr}=0.710250\pm 7$ during the data acquisition period.

Table 5 lists the Rb-Sr and Sm-Nd isotopes of whole-rock samples from the Niumaoquan intrusion. The initial Sr-Nd isotopic ratios of the Niumaoquan intrusion were calculated using the zircon U-Pb age of 314.9 Ma from this study. The calculated $\varepsilon_{\text{Nd}}(t)$ and $(^{87}\text{Sr}/^{86}\text{Sr})_i$ values of the Niumaoquan intrusive rocks vary from +3.3 to +5.2, and from 0.7039 to 0.7047 (Table 5), respectively, and are plotted on the mixing curve between depleted mantle (DM) and enriched mantle I (EMI; Fig. 8a).

5 Discussion

5.1 Chronology

In this study, we analyzed magmatic zircon from the Niumaoquan layered gabbroic intrusion using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), obtaining a concordia age of 314.9 ± 0.74 Ma and a weighted $^{206}\text{Pb}/^{238}\text{U}$ age of 314.7 ± 1.5 Ma (Fig. 5b). The zircon U-Pb age of the Niumaoquan intrusion we obtained in this study is much older than the previously published hornblende Ar-Ar age, which yielded a plateau age of 289.7 ± 2.4 Ma, and an Ar-Ar isochron age of 286.4 ± 1.0 Ma (Li Dedong et al., 2012). Zircon U-Pb dating is more reliable for representing emplacement age of mafic-ultramafic intrusions than the Ar-Ar method, which is characterized by a much lower closure temperature and is more easily influenced by post-thermal events. The hornblende Ar-Ar age of the Niumaoquan intrusion matches well with the extensive Early Permian magmatism thermal event in eastern Xinjiang, which

Table 5 Rb-Sr and Sm-Nd isotopic data of the Niumaoquan layered gabbroic rocks

Rock type	Hornblende gabbro		Anorthosite	Olivine gabbro	Gabbro	
Sample No.	N825-2	N825-4	N7104-1	N7104-2	N71013-3	N71013-14
Rb(ppm)	2.5	6.4	1.4	15.2	39.7	2.6
Sr(ppm)	449	459	332.44	108.28	459.48	188.71
$^{87}\text{Rb}/^{86}\text{Sr}$	0.0159	0.0402	0.0123	0.407	0.2502	0.0398
$^{87}\text{Sr}/^{86}\text{Sr}$	0.704159	0.704139	0.704055	0.705692	0.705149	0.70492
2σ	10	17	13	11	13	12
$(^{87}\text{Sr}/^{86}\text{Sr})_i$	0.7041	0.7040	0.7040	0.7039	0.7040	0.7047
Sm(ppm)	1.1	1.64	1	0.81	1.75	0.91
Nd(ppm)	4.2	6.7	2.4	2.88	6.75	2.14
$^{147}\text{Sm}/^{144}\text{Nd}$	0.1607	0.1479	0.2515	0.1711	0.1571	0.2562
$^{143}\text{Nd}/^{144}\text{Nd}$	0.512774	0.51278	0.512921	0.512834	0.512783	0.513025
2σ	17	14	15	22	15	15
$(^{143}\text{Nd}/^{144}\text{Nd})_i$	0.512444	0.512476	0.512404	0.512482	0.51246	0.512498
$\varepsilon_{\text{Nd}}(t)$	4.1	4.73	3.33	4.85	4.42	5.17

Note: $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and $\varepsilon_{\text{Nd}}(t)$ were calculated relative to present-day chondrite values $^{143}\text{Nd}/^{144}\text{Nd}=0.512638$, $^{147}\text{Sm}/^{144}\text{Nd}=0.1967$, $^{87}\text{Sr}/^{86}\text{Sr}=0.7045$, $^{87}\text{Rb}/^{86}\text{Sr}=0.0816$, and $\lambda(^{87}\text{Rb})=1.42\times 10^{-11}\text{y}^{-1}$, $\lambda(^{147}\text{Sm})=6.54\times 10^{-12}\text{y}^{-1}$, $t=314.7$ Ma.

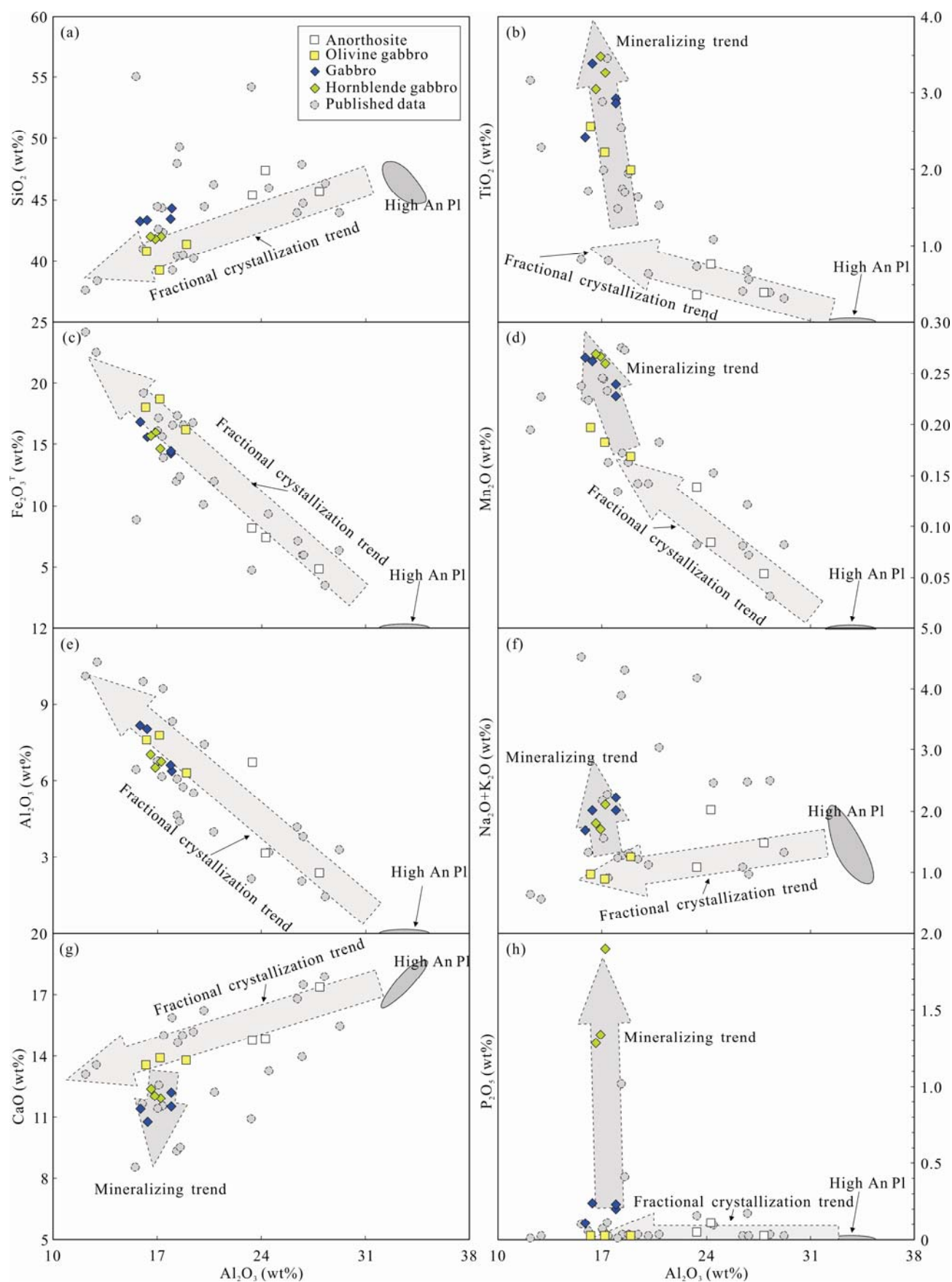


Fig. 6. Harker diagrams for the Niumaoquan layered intrusion.

Published data of the Niumaoquan gabbroic rocks are from Wang Yuwang et al. (2010), Li Dedong et al. (2012), and Wang et al. (2014).

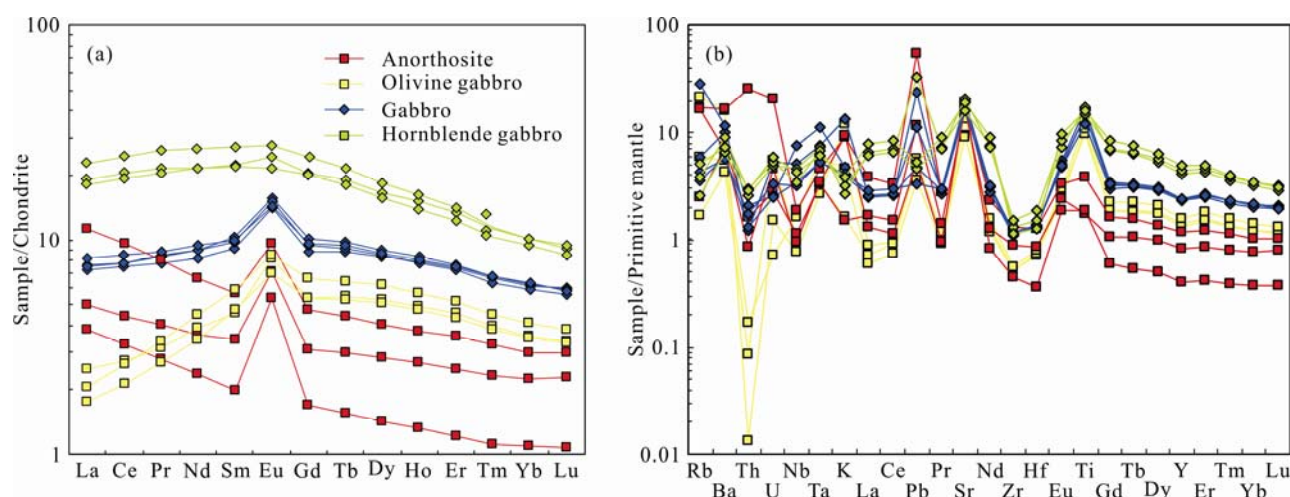


Fig. 7. (a) Chondrite-normalized REE patterns and (b) spider diagram for the Niumaoquan layered intrusion. Chondrite and primitive mantle values are from Sun and McDonough (1989).

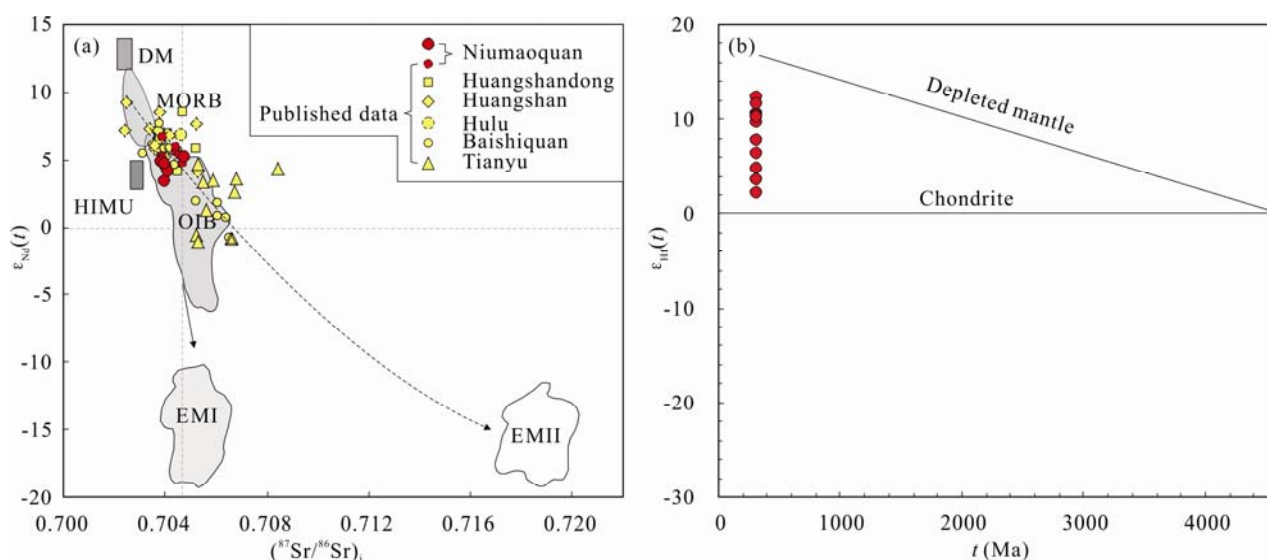


Fig. 8. (a) Sr-Nd isotope diagram and (b) $\epsilon_{\text{Hf}}(t)$ vs. Zircon U-Pb age diagram for the Niumaoquan intrusion (after Zindler and Hart, 1986).

Published data are cited from Zhou et al. (2004), Chai et al. (2008), Deng Yufeng et al. (2011, 2015), Tang et al. (2011, 2013), Li Dedong et al. (2012), Chen Bin et al. (2013), Sun et al. (2013), and Wang et al. (2014). DM, depleted mantle; MORB, middle ocean ridge basalt; HIMU, mantle with high U/Pb ratio; OIB, ocean island basalt; EMI and EMII, enriched mantle end-members.

produced numerous mafic-ultramafic intrusions distributed in multiple tectonic bodies, such as the Beishan Rift (Qin et al., 2011), the Middle Tianshan Massif (Wu Hua et al., 2005; Tang et al., 2011), the Jueluotage Belt (Han Baofu et al., 2004; Zhou et al., 2004; Han et al., 2010; Zhao et al., 2015; Shi Yu et al., 2017b), and the Dananhu-Tousuquan island arc (Wang Yalei et al., 2015). Therefore, the Niumaoquan layered gabbroic intrusion that hosts a Fe-Ti oxide deposit was likely emplaced during the Late Carboniferous, whereas the hornblende Ar-Ar age possibly recorded a post-thermal event in the Eastern Tianshan.

The Harlik Arc was formed by consumption of Kelameli ocean crust and the accretion of the Harlik Arc

to the southern margin of Angara (Xiao et al., 2004). Then, the Harlik Arc had accreted to Junggar (southern margin of Angara) by the end of the Carboniferous (Xiao et al., 2004; Charvet et al., 2007). Thus, the Niumaoquan layered gabbroic intrusion is like other Early Permian gabbroic intrusions in the Harlik Arc and was possibly formed during a post-collision stage induced by a slab break-off (Yuan et al., 2010).

5.2 Petrogenesis of the Niumaoquan intrusion

Plagioclase grains are euhedral, occurring either as a cumulus phase in gabbroic rocks, or as inclusions in olivine and clinopyroxene crystals (Fig. 4a). These two types of plagioclase in olivine gabbro have identical An

values (Table 1), suggesting that the plagioclase crystallized from similar melt before the olivine and clinopyroxene crystallized. Orthopyroxene mainly crystallized in the relatively evolved gabbroic phases, such as gabbro and hornblende gabbro (Figs. 4c and 4d), and possibly crystallized after clinopyroxene. Fe-Ti oxides are mainly anhedral and grow interstitially to plagioclase, olivine, and pyroxene (Figs. 4a, 4c, and 4d). Hornblende occurs either as a reaction rim of clinopyroxene, or as a poikilitic phenocryst enclosing plagioclase, clinopyroxene, orthopyroxene, and Fe-Ti oxides (Fig. 4d). Thus, the textural relationship among minerals of the Niumaoquan gabbroic intrusion indicates that the general crystallization sequence order was plagioclase $\rightarrow$ olivine $\rightarrow$ clinopyroxene $\rightarrow$ orthopyroxene $\rightarrow$ Fe-Ti oxides $\rightarrow$ hornblende.

SiO_2 , $\text{Fe}_2\text{O}_3^{\text{T}}$, MgO , CaO , and Al_2O_3 are the major oxides of plagioclase, olivine, clinopyroxene, and hornblende of the Niumaoquan gabbroic rocks, accounting for more than 91.1wt% of the bulk rock (Table 4); therefore, variations in these major elements could reflect the proportion and variation of cumulating silicate minerals. With decreasing Al_2O_3 , SiO_2 , and CaO decrease (Figs. 6a and 6g) and $\text{Fe}_2\text{O}_3^{\text{T}}$ and Al_2O_3 increase (Figs. 6c and 6e). This is strongly controlled by the fractional crystallization of high-An plagioclase (Figs. 6a, 6c, 6e, and 6g). Accumulation of early crystallized plagioclase during the differentiation process is also supported by positive Eu anomalies in the REE-chondrite normalized pattern (Fig. 7a) and positive Sr anomalies in the spider diagram (Fig. 7b). Therefore, crystallization and accumulation of high-An plagioclase strongly controlled the evolution of the Niumaoquan gabbroic intrusion and contributed to the formation of anorthosite layers.

Previous studies of plagioclase-melt equilibria demonstrated that the $\text{Al}_2\text{O}_3/\text{SiO}_2$ and $\text{CaO}/\text{Na}_2\text{O}$ ratios and H_2O content of the melt affect plagioclase An content (Longhi et al., 1993; Panjasawatwong et al., 1995). Additionally, pressure ranges of 2–3 kbar are optimal in terms of element partitioning and phase equilibrium relations for crystallizing An-rich plagioclase (Takagi et al., 2005). Poikilitic hornblende from the hornblende gabbro crystallized during the formation of the Niumaoquan intrusion, and crystallization pressure calculated using barometry proposed by Ridolfi et al. (2008, 2010) suggested that the Niumaoquan intrusion crystallization pressure varied in the range of 2.4–2.8 kbar (Shi Yu et al., 2017a). Therefore, early crystallized high-An plagioclase of the Niumaoquan intrusion was likely formed by a basaltic melt characterized by high $\text{CaO}/\text{Na}_2\text{O}$, $\text{Al}_2\text{O}_3/\text{SiO}_2$, and H_2O contents under a pressure of 2.4 to 2.8 kbar.

5.3 Contamination and mantle source

Crustal contamination may modify elemental and isotopic compositions during magma evolution. Minor crustal contamination might result in negative Nb-Ta anomalies relative to large ion lithophile elements and LREE, but can also produce positive Zr-Hf anomalies due to enrichment of these elements in crustal materials (Zhao and Zhou, 2007; Zhao et al., 2010). The negative Zr-Hf anomalies observed in the basic rock spider diagrams (Fig. 7b) suggest that little to no crustal contamination occurred. Most of the gabbroic samples from the Niumaoquan intrusion have low Th/Ce (0–0.05) and Th/La (0–0.12) ratios, indicating that crustal contamination did not play a significant role in generating magmas. This is because continental crust has relatively high Th/Ce (~ 0.15 ; Taylor and McLennan, 1995) and Th/La (~ 0.30 ; Plank, 2005) ratios and mantle-derived magmas have low Th/Ce (0.02–0.05) and Th/La (~ 0.12) ratios (Sun and McDonough, 1989). Their narrow range of ($^{87}\text{Sr}/^{86}\text{Sr}$)_i values (0.7039 to 0.7047) and high positive $\varepsilon_{\text{Nd}}(t)$ (+3.3 to +5.2) and zircon $\varepsilon_{\text{Hf}}(t)$ values (+2.1 to +12.2; Figs. 8a and 8b), and the lack of a good correlation between $\varepsilon_{\text{Nd}}(t)$ and SiO_2 further confirm the low level of crustal contamination.

Incompatible element pairs Nb-Ta and Zr-Hf have similar geochemical properties and do not fractionate during partial melting and fractional crystallization. However, the fractionation of Nb from Ta and Zr from Hf mainly occurs in subduction zones (Stolz et al., 1996). The Nb/Ta and Zr/Hf ratios of Niumaoquan gabbroic rocks vary from 4.7 to 12.1 and 24.4 to 45.8, respectively, and are different from those of primitive mantle (17.8 for Nb/Ta and 37 for Zr/Hf; Sun and McDonough, 1989) and crust (8.3 to 16.7 for Nb/Ta and 33.9 to 36.4 for Zr/Hf; Rudnick and Gao, 2004), suggesting that the Niumaoquan gabbroic rocks might be related to subducted material. The trace elements ratios, positive $\varepsilon_{\text{Nd}}(t)$, and zircon $\varepsilon_{\text{Hf}}(t)$ values, as well as generally low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Niumaoquan intrusions are consistent with depleted mantle-derived magmas that had little interaction with older continental crust. The isotopic data of the Niumaoquan intrusion is characterized by variable $\varepsilon_{\text{Nd}}(t)$ (+3.5 to +5.2) and zircon $\varepsilon_{\text{Hf}}(t)$ (+2.1 to +12.2) values (Fig. 8b), but relatively constant initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7039 to 0.7047), lying on the mixing trend of DM and EMI end-member components (Fig. 8a). Usually, the EMI component is related to lithospheric mantle, whereas enriched mantle II (EMII) component is associated with crustal material (Hawkesworth et al., 1990; Menzies, 1990). Hence, we propose that the parental magma of the Niumaoquan intrusion could have been generated by asthenosphere-lithosphere interaction or ascending asthenospheric melt contaminated by the lithospheric

mantle.

5.4 Origin of the ore

The variation of $\varepsilon_{\text{Nd}}(t)$ and $\varepsilon_{\text{Hf}}(t)$ values of mafic-ultramafic intrusions in the Eastern Tianshan formed during the post-collision stage suggest that mafic magmatism progressed from lithosphere-derived to asthenosphere-derived melts over time (Zhou et al., 2004; Sun et al., 2013; Deng et al., 2015). The Niumaoquan is a prominent mafic-ultramafic intrusion that hosts Fe-Ti oxide ore, and its $\varepsilon_{\text{Nd}}(t)$ and $(^{87}\text{Sr}/^{86}\text{Sr})_i$ plot on the DM and EMI mixing trends (Fig. 8a) is significantly different from that of Early Permian Ni-Cu sulfide mineralized mafic-ultramafic intrusions in the Eastern Tianshan, which are mainly mixed products of DM and EM II (Chai et al., 2008; Tang et al., 2011). Consequently, it is reasonable to speculate that the Fe-Ti oxide enrichment of the Niumaoquan Fe-Ti oxide deposit possibly benefited from the interaction between upwelling asthenospheric melts and metasomatized lithospheric mantle. During the early stages of the post-collision stage, upwelling asthenospheric melts would have encountered a thicker metasomatized lithospheric mantle. Thus, addition of a metasomatized lithospheric component possibly contributed to the genesis of the Niumaoquan Fe-Ti oxide deposit.

The parental magma composition of the Niumaoquan gabbroic layered intrusion is difficult to estimate, because of the absence of chilled margins. Regional diabase dykes widely distributed in the Qijiaoqing and Balikun areas, emplaced at 314.7 ± 1.5 Ma (Cui Fanglei et al., 2015), are coeval with the Niumaoquan intrusion, and possibly represent the Niumaoquan intrusion's parental magma. The diabase dykes are characterized by low TiO_2 content (average 1.1wt%) and moderate Ti/Y ratios (average 384; Cui Fanglei et al., 2015), which are significantly lower than the high-Ti basalt in Emeishan large igneous province. Fe-Ti oxide deposits associated with gabbros are mainly crystallized from evolved basaltic melts of evolved picritic melts, such as the Fe-Ti oxide deposits in the Panxi district (Zhou et al., 2005; Song et al., 2013; Luan et al., 2014; Fan Hongpeng and Zhu, 2017) and the Wajilitag and Mazaertag deposits in the Tarim craton (Cao Jun et al., 2017; Cao and Wang, 2017). The Niumaoquan gabbroic intrusion hosts low Fo value olivine grains (76 to 70; Wang Shuo et al., 2012), suggesting that the parental magmas were highly evolved. The magnetite ores and gabbroic rocks of the Niumaoquan intrusion are relatively rich in Cu, resulting in high Cu/Ni ratios (average 4.9; Table 4), a feature characteristic of a fractional crystallization degree (Zhou et al., 2005). The depletion of Ni relative to Cu can be explained by fraction of olivine,

which preferentially concentrates Ni (Barnes et al., 1985).

The enrichment of metallogenic elements and elevation of oxygen fugacity are two major issues in producing the Niumaoquan Fe-Ti oxide deposit. Fractional crystallization of high-An plagioclase strongly controlled the evolution of the Niumaoquan gabbroic intrusion (Figs. 6a, 6c, 6e, and 6g), which was supported by positive Eu anomalies in chondrite-normalized REE patterns (Fig. 7a), and positive Sr anomalies in the spider diagram (Fig. 7b). Anorthosite layers of the Niumaoquan intrusion were formed by accumulation of early crystallized high-An plagioclase, and its formation would induce efficiently enriched metallogenic elements (e.g., Fe, Ti, and V) in the residual melt.

Precipitation of titanomagnetite from silicate magmas depends largely on the melt's $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio, which is a function of the magma's $f\text{O}_2$, temperature, and H_2O content (Reynolds, 1985; Kress and Carmichael, 1991). Crystallization of titanomagnetite from basaltic liquid is controlled largely by temperature and $f\text{O}_2$ (Hill and Roeder, 1974). Fractional crystallization of mafic-intermediate magma eventually leads to saturation in Fe_2O_3 -bearing phases, such as chromite and titanomagnetite. A completely solid solution exists between chromite and titanomagnetite at magmatic temperatures (Evans and Moore, 1968), in which titanomagnetite is the low-temperature component. Therefore, the onset of titanomagnetite precipitation in the Niumaoquan intrusion may reflect a significant overall decrease in the residual melt temperature. The $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio and Fe_2O_3 content of the parental magma would be elevated with the crystallization of ilmenite and Fe^{2+} -bearing silicates, such as olivine, orthopyroxene, and clinopyroxene. This is evidenced by higher $\text{Fe}_2\text{O}_3^{\text{T}}$ content in ore-bearing gabbroic phases, e.g., hornblende gabbro and gabbro, than in olivine gabbro and anorthosite (Table 4).

Anhydrous silicate fractionation in a closed system will also increase the H_2O content of the residual melt. H_2O content has complex effects on $f\text{O}_2$ in water-undersaturated basaltic magmas (Eggler and Burnham, 1973). It has been suggested that more than 2wt% H_2O in a basaltic melt could theoretically oxidize slightly more than 15% of FeO in the melt into Fe_2O_3 . Centimeter-scaled poikilitic hornblende is ubiquitous in the hornblende gabbro (Fig. 4d), which is possibly a high fractionation product for hosting the most evolved plagioclase (An: 66.9–82.3; Table 1). The occurrence of poikilitic hornblende in the Hongge gabbro in the Panxi district suggests that the H_2O content in the residual magma possibly reached 2wt% to 3wt% (Luan et al., 2014). Therefore, the H_2O content of the residual magma gradually increased and reached 2wt%

to 3wt% during the formation of the Niumaoquan hornblende gabbro, and could have positively affected the increase of the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio.

Lindsley et al. (1968) demonstrated that magma $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios increase with an increase in alkali content, and termed this the alkali-ferric iron effect. The $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio would tend to rise in the residual liquid during fractional crystallization, which would be enhanced by falling temperature. Progressive fractional crystallization of silicate minerals led to an increase in alkali content in the evolved gabbroic rocks (Fig. 6f), which may represent an important mechanism by which the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio in a fractionating magma increases.

Therefore, accumulation of early crystallized plagioclase induced metallogenic elements enriched in the residual melt, and crystallization of Fe^{2+} -bearing magnesian minerals followed by plagioclase elevated oxygen fugacity, which led to the mineralization of the Niumaoquan Fe-Ti oxide deposit.

6 Conclusions

The Niumaoquan Fe-Ti oxide deposit hosted by a layered gabbroic intrusion was emplaced during Late Carboniferous, with a zircon U-Pb age of 314.9 ± 0.74 Ma, during the early post-collision stage. The Niumaoquan intrusion was derived from DM, which had been metasomatized by subducted slabs, and the parental magma had interacted with lithospheric mantle during its ascent. The mixed derivation of DM and EMI possibly produced a Fe-enriched basaltic magma. The ore bodies hosted in the evolved gabbroic phase mainly benefited from enrichment of metallogenic elements by the crystallization of large amounts of plagioclase, and elevated oxygen fugacity due to crystallization of Fe^{2+} -bearing silicate minerals, such as olivine and clinopyroxene. Therefore, the formation of the Niumaoquan Fe-Ti oxide ore in the evolved gabbroic phases benefited from a combined effect of interaction with lithospheric mantle and high fractional crystallization.

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