Ca. 2.5 Ga TTG rocks in the western Alxa Block and their implications

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The Alxa Block is considered part of the North China Craton, but the unambiguous Archean basement has not been reported. In this study, we present the first evidence of the Neoproterozoic rocks in the Beidashan area of the western Alxa Block. The petrographic and geochemical data show that these rocks are granodiorite with TTG (tonalite-trondhjemite-granodiorite) characteristics. Zircon U-Pb dating gave an age of 2522 ± 30 Ma for the magmatic core and 2496 ± 11 Ma for the metamorphic recrystallized rim. The near-identical age between the Latest Neoproterozoic magmatism and the high-grade metamorphism shows that these features were related to the same Latest Neoproterozoic-Early Paleoproterozoic tectonothermal event. The age-corrected $\varepsilon_{\text{Hf}}(t)$ value is mainly between 0.4 and 4.9. The two-stage zircon Hf model age ranges from 2.7 to 3.0 Ga, suggesting that the Mesoproterozoic-Neoproterozoic (2.7–3.0 Ga) juvenile crust was reworked at the end of the Neoproterozoic in the western Alxa Block. These data suggest that the western Alxa Block experienced a Mesoproterozoic-Neoproterozoic crust growth and Latest Neoproterozoic-Early Paleoproterozoic tectonothermal event similar to the North China Craton.

TTG, 2.5 Ga, Zircon U-Pb dating, Hf isotope, Beidashan, Alxa Block, North China Craton

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The westernmost North China Craton (NCC), termed the Alxa block, is bounded by the Central Asian Orogenic Belt and the Tarim Block to the north and west and the Qilian-Qinling Orogen to the south (Figure 1(a)). Although there is still controversy, the Alxa Block is commonly considered part of the NCC [1–6]. Compared with other parts of the NCC, however, the Alxa Block is poorly studied. A lack of information about the composition, properties and formation age of the Precambrian metamorphic basement of the Alxa Block has hampered our understanding of the formation and evolution of the NCC.

In recent years, important progress in studies on the Precambrian basement of the eastern Alxa Block has been achieved. Geng et al. [7,8] disassembled the traditional Alxa Group into medium to high-grade metamorphic complexes

and low-grade sedimentary sequences, with the latter being redefined as the new Alxa Group. Three high-grade metamorphic complexes were recognized: the Neoproterozoic Diebusige Group, the Paleoproterozoic Bayanwulashan Group and the Boluositanmiao Complex. Li [9] obtained a 3018 ± 49 Ma Nd model age of the amphibolite in the lower Diebusige Group and proposed that a Mesoproterozoic crust exists in the Alxa Block. Other scholars obtained Paleoproterozoic ages from the metamorphic basement of the Bayanwulashan and Qinggeletu areas [10–12]. Lately, zircon U-Pb dating of detrital zircons from paragneisses in the Diebusige complexes, which were previously considered a Neoproterozoic basement, yielded ages ranging from 2.0 to 2.45 Ga, suggesting a Paleoproterozoic depositional age for protoliths of the Diebusige paragneisses [13]. These U-Pb zircon age data do not support the existence of exposed Archean rocks in the eastern Alxa Block, although zircon Hf isotopic data

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Figure 1 Geological sketch map showing the geological setting of the Alxa Block.

imply that the possibility of Archean rocks at deeper crustal levels cannot be ruled out [13].

Several studies of the western part of the Alxa Block focus on the Longshoushan area north of the Hexi Corridor in Gansu Province, whose crystalline basement is composed predominantly of Paleoproterozoic amphibolite-facies metamorphosed igneous rocks and metasedimentary rocks [14–17]. Our latest geochronology results also indicated that the primary magmatic ages of the orthogneisses in the Longshoushan area range between 2.04 and 2.17 Ga and that the depositional ages of the protoliths of the metasedimentary rocks are between 1.94 and 2.01 Ga [18]. Both types of rocks were overprinted by metamorphic events at ca. 1.85–1.94 Ga. These data support the formation age of the Longshoushan Group is Paleoproterozoic rather than Archean.

Therefore, there is no evidence to date that Archean metamorphic rocks outcrop in the Alxa Block. However, Archean rocks, especially the Neoarchean TTG rocks, are widely distributed in the NCC [19,20]. Answering the question of whether Archean metamorphic rocks outcropped in the Alxa Block is crucial to constrain the affinity of the Alxa block with the NCC. In this paper, based on zircon dating, we report the first ca. 2.5 Ga TTG rock outcropped in the Beidashan area of the western Alxa Block, indicating the existence of a Neoarchean metamorphic basement in the Alxa block. Combined with Lu-Hf isotopic data, we will discuss the origin and affinity of the Alxa Block.

1 Geological setting

The Precambrian basement of the western Alxa Block is mainly exposed in the Longshoushan, Beidashan and Yabulaishan areas, which lie to the north of the Hexi Corridor

and is separated from the eastern Alxa Block by the Tenggel Desert. The Beidashan, which extends in a NWW-SEE trend, is bounded by the Yabulaishan and the Badanjilin Desert to the north, by the Tenggel Desert to the east, and is separated from the parallel Longshoushan by the Chaoshui basin to the south (Figure 1(b)).

As shown in Figure 1, the high-grade metamorphic rocks in the Beidashan area are intruded by widely-distributed granitic rocks. These rocks were first called “Beidashan Group” by the Regional Geological Surveying Team of the Gansu Province in 1971 [21]. The Gansu Bureau of Geology [22] further divided the Beidashan Group into three parts: Group A is mainly exposed in the western part of the Beidashan area and consists of amphibolite-facies metamorphic rocks, including biotite-plagioclase gneiss, biotite-amphibole-plagioclase gneiss, micaschist, amphibolite, quartzite and marble; Group B is exposed in the central part of the Beidashan area and consists of amphibolite-facies metamorphic rocks, including marble, dolostone, amphibole-bearing gneiss, biotite-plagioclase gneiss and garnet-bearing micaschist with minor amounts of leptynite and quartzite; Group C is exposed in the Eastern part of the Beidashan area and consists of high greenschist to amphibolite facies metamorphic rocks, including micaschists, amphibolites, leptynite and biotite-plagioclase gneiss. Given that the exposed basement in the Beidashan area contains both metamorphosed pluton and supracrustal sequences that were strongly deformed, we renamed “the Beidashan Group” as “the Beidashan Complex”.

2 Field geology and sample descriptions

Sample LS10-8-1.1 (39°9.613'N, 101°47.613'E) was collected from the central part of the Beidashan Complex 10 km

southeast of Alxa Youqi, in western Inner Mongolia (Figure 2). As shown in Figure 3, the Beidashan Complexes at this location are mainly composed of banded gneisses intercalated with a few layered amphibolites with minor marble and are intruded by pegmatites and some mafic dykes.

The gneiss LS10-8-1.1 is gray, medium- to coarse-grained and displays a homogenous granoblastic texture with gneissic structure. This sample is mainly composed of plagioclase (30%–35%), quartz (25%–30%), hornblende (10%–15%), K-feldspar (10%–15%) with minor epidote, chlorite and accessory minerals, including apatite, sphene and zircon (Figure 4). Whole-rock major and trace element analysis indicates that gneiss LS10-8-1.1 shares similar geochemical characteristics with the average Archean TTG [24] (Table 1), with relatively high SiO_2 (~70%), Al_2O_3 (>15%), Sr (>500 ppm) and Ba (>1000 ppm) and low Mg# (<50), Y (<20 ppm), Yb (<1.8 ppm), Nb (<1 ppm), and Ta (<0.05 ppm), corresponding to high La/Yb and Sr/Y ratios. In the An-Ab-Or diagram [26], this sample plot falls within the granodiorite field. Combining the petrography with geochemical data shows that sample LS10-8-1.1 is granodiorite

with TTG characteristics.

3 Analytical methods and results

3.1 Analytical methods

Zircon grains were mechanically separated from sample LS10-8-1.1 by crushing and sieving, followed by standard magnetic, heavy liquid and hand-picking methods. The zircons were mounted in epoxy resin and polished until the grains were exposed as suitable for laser ablation inductively coupled plasma mass spectrometer (LA-ICPMS) analysis. Before U-Pb dating and Hf isotopic analyses, cathode luminescence (CL) images were obtained at the Beijing SHRIMP Center, Chinese Academy of Geological Sciences (CAGS), to identify the internal structures of the zircons and to choose potential target sites for U-Pb dating and Hf analysis. The zircons were first analyzed for their U-Pb isotopic composition followed by Hf isotope analysis on the same domains to obtain the coupled U-Pb-Hf isotope data.

In-situ U-Pb dating of the zircons was performed using

Figure 2 Distributions of Precambrian basement rocks in the Beidashan area.

Figure 3 Geological section and sample location.

Figure 4 Photomicrographs showing texture and mineral assemblages of sample LS10-8-1.1. Qtz, Quartz; Pl, plagioclase; Hbl, hornblende; Kf, kfeldspar; mineral abbreviation by [23].

Table 1 Geochemical data for the Sample LS10-8-1.1 and average Neoproterozoic TTG^{a)}

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	CaO	MgO	K ₂ O	Na ₂ O	TiO ₂	MnO	P ₂ O ₅	H ₂ O ⁺	CO ₂	LOI	K ₂ O/Na ₂ O	Mg#
LS10-8-1.1	66.51	16.24	1.02	1.67	3.42	1.54	3.53	4.37	0.12	0.04	0.14	0.50	0.26	0.64	0.81	37.3
Average Neoproterozoic TTG	68.30	15.50	3.42	—	3.26	1.39	2.20	4.51	0.42	0.07	0.14	—	—	—	0.51	46.2
	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Y	Lu	Ba
LS10-8-1.1	16.0	29.2	3.47	13.8	2.79	1.70	2.70	0.35	1.69	0.30	0.86	0.10	0.64	8.99	0.11	1443
Average Neoproterozoic TTG	36	65	—	25	4.20	1.07	2.90	0.38	—	—	—	—	0.71	9.10	0.11	769
	Sc	V	Cr	Co	Cu	Ni	Rb	Sr	Zr	Nb	Hf	Ta	Th	U	La/Yb	Sr/Y
LS10-8-1.1	10.50	37.60	63.00	7.09	6.00	22.6	58.5	686	149	0.41	3.17	<0.05	0.22	0.16	25	76.30
Average Neoproterozoic TTG	—	—	35	—	—	22	67	515	154	6.2	4.7	0.8	8.1	1.5	36	89

a) Whole-rock major element analysis was performed with XRF and trace element and REE analyses were done using LA-ICP-MS, both in the National Research Center of Geoanalysis, Beijing [25]; major element (%), trace and REE elements (ppm); Mg# = MgO/(MgO+Fe²⁺), Fe²⁺ = 0.8998×Fe₂O₃+FeO.

the LA-MC-ICP-MS facility at the Tianjin Institute of Geology and Mineral Resources, China Geological Survey. The sites for dating were selected based on CL and photomicrograph images. Laser sampling was performed using a New Wave UP 213 laser ablation system. All analyses were performed with a beam diameter of 35 μm, a 10 Hz repetition rate, and an energy of 2.5 J/cm². Helium was used as a carrier gas to provide efficient aerosol delivered to the torch. Standards GJ1 and 91500 were used during our analyses, and was analyzed twice every 10 analyses. The U, Th and Pb concentrations were calibrated by using NIST 610 as an external standard. Data were evaluated by ICPMS DataCal 3.4 [27]. Concordia diagrams and weighted mean calculations were made using Isoplot/Ex ver3 [28]. The measured ²⁰⁸Pb was applied for common lead correction [29].

Zircon Hf isotopic analyses were performed *in-situ* using a Neptune MC-ICPMS with a New Wave UP213 laser ablation system at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing. The analyses were performed on the same or nearby zircon domains on which the U-Pb dating had been conducted. The instrumental conditions and data acquisition have been comprehensively described by Hou et al. [30]. Zircon GJ1 was used as

the reference standard during our routine analyses, with a weighted mean ¹⁷⁶Hf/¹⁷⁷Hf ratio of 0.282007±0.000007 (2σ, n=36) [30,31]. Calculation of the ε_{Hf}(t) values was based on zircon U-Pb ages and the chondritic values [32] (¹⁷⁶Hf/¹⁷⁷Hf=0.282772, ¹⁷⁶Lu/¹⁷⁷Hf=0.0332). Calculation of the Hf-model age (single-stage model age) (*T*_{DM}) is based on a depleted-mantle source with present-day ¹⁷⁶Hf/¹⁷⁷Hf at 0.28325 using the ¹⁷⁶Lu decay constant of 1.865×10⁻¹¹ a⁻¹ [33]. Calculation of the “crust” (two-stage) of the Hf model age (*T*_{DMC}) is based on the assumption of a mean ¹⁷⁶Hf/¹⁷⁷Hf value of 0.015 for the average continental crust [34].

3.2 Analytical results

(1) U-Pb dating result. The zircon grains from sample LS10-8-1.1 range in length from 200–400 μm, with length-to-width ratios between 2:1 and 3:1. All zircon grains are euhedral and elongate in shape, colorless or slightly yellow, and commonly have core-rim structures under CL (Figure 5(a)–(f)). Most cores appear weakly luminescent with distinct oscillatory zoning (Figure 5(b),(d)). A few cores appear gray with weakly oscillatory zoning (Figure 5(a),(c)), indicating that they were likely magmatic zircons modified

Figure 5 Representative CL images of zircons from sample LS10-8-1.1. The smaller circles show locations for U-Pb analyses, and the bigger circles for Hf isotopic analyses. Each spot is labeled with its individual $^{207}\text{Pb}/^{206}\text{Pb}$ ages.

by subsequent metamorphic recrystallization [35]. The rims are irregular in shape with a relatively bright CL intensity and show no discernible internal structure, suggesting metamorphic origin. The contact between the core and rim is commonly marked by a thin semicontinuous dark seam (Figure 5(a),(c)), possibly indicating recrystallization. In addition, there is a weakly luminescent domain that extends around the outer surface (Figure 5(a),(c)), forming a discontinuous edge less than 5 μm in width, which was too narrow to analyze.

A total of 61 analyses on 52 zircon grains (Table 2) from sample LS10-8-1.1 were determined, including 29 analyses on the oscillatory zoned cores and 32 analyses on the structureless rims. The magmatic cores yield U and Pb contents ranging from 106 to 2142 ppm and from 48 to 933 ppm, respectively, with Th/U ratios of 0.12–1.12. The rims yield U and Pb contents ranging from 18 to 220 ppm and from 10 to 94 ppm, respectively, with Th/U ratios of 0.27–1.14. There is little change in the Th/U ratio, but there are significant differences in U and Pb concentrations between the cores and rims. A few CL-gray cores with weakly oscillatory zoning and relatively low U and Pb concentrations are interpreted to be the result of partial recrystallization.

The dating data are shown on a concordia plot in Figure 6(a). Most analyses from the zircons gave discordant ages with a wide range of $^{207}\text{Pb}/^{206}\text{Pb}$ ages, indicating isotopic disturbance due to radiogenic Pb loss. Most dating ages of the cores and rims are nearly identical within error (Figure 5(a),(b)); however, some cores yield younger ages than the

rims (Figure 5(d),(e)), implying that radiogenic Pb loss has a much stronger influence on the cores than the rims in these zircons. Except for Spot 52, with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2689 $\pm$ 7 Ma, which is probably an inherited zircon grain, the other 28 core analyses show strong lead loss and define an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2522 $\pm$ 30 Ma (MSWD=3.6) (Figure 6(b)). The 32 rim analyses also show variable discordance and define an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2506 $\pm$ 20 Ma (MSWD=1.12) (Figure 6(c)). Of the 32 rim analyses, 10 are concordant and near concordant, and they yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages between 2460 $\pm$ 50 Ma and 2526 $\pm$ 18 Ma, combining to a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2496 $\pm$ 11 Ma (MSWD=0.96) (Figure 6(d)), which is identical to the upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age within error.

(2) Hf isotopic result. The Lu-Hf isotopes were analyzed on the same or nearby zircon spots on which the U-Pb dating had been conducted. Lu-Hf isotopic analyses were performed on the 44 zircon grains that yielded ca. 2.5 Ga $^{207}\text{Pb}/^{206}\text{Pb}$ ages, with 21 analysis spots on the cores and 23 spots on the rims (Table 3). Except for an inherited core with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2689 $\pm$ 7 Ma ($\epsilon_{\text{Hf}}(t)$ calculated with $t=2.7$ Ga), the $\epsilon_{\text{Hf}}(t)$ values of all other Hf isotopic analysis spots were calculated based on 2500 Ma.

The zircon cores have $^{176}\text{Hf}/^{177}\text{Hf}$ ratios varying from 0.281223 to 0.281483, mainly concentrating on a range from 0.281223 to 281296. Their age-corrected $\epsilon_{\text{Hf}}(t)$ value of these cores is between 0.37 and 7.42 and is concentrated on a range of 0.37 to 4.44, except for two relatively high $\epsilon_{\text{Hf}}(t)$ values (6.7 and 7.42). The corresponding two-stage

Table 2 LA-MC-ICP-MS U-Pb zircon dating results

Spot	Pb (ppm)	U (ppm)	Th/U	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	Age (Ma)			Analysis position
										$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ
1	696	1389	0.43	10.0867	0.0857	0.4545	0.0036	0.1610	0.0005	2415	19	2443	21
2	39	67	0.88	11.1226	0.2368	0.4836	0.0068	0.1668	0.0018	2543	36	2533	54
3	73	123	1.12	10.5150	0.0802	0.4652	0.0041	0.1639	0.0006	2463	21	2481	19
4	34	64	0.92	9.6016	0.1039	0.4348	0.0036	0.1601	0.0014	2328	19	2397	26
5	47	95	0.78	9.0949	0.1285	0.4186	0.0048	0.1576	0.0017	2254	26	2348	33
6	73	139	0.46	10.6169	0.1903	0.4707	0.0060	0.1636	0.0012	2487	32	2490	45
7	296	583	0.79	9.3331	0.1461	0.4271	0.0044	0.1585	0.0013	2293	24	2371	37
8	10	18	0.81	10.1237	0.3284	0.4576	0.0046	0.1604	0.0048	2429	24	2446	79
9	98	178	0.78	10.2181	0.1074	0.4629	0.0046	0.1601	0.0004	2452	25	2455	26
10	50	104	0.72	8.6760	0.0710	0.4062	0.0032	0.1549	0.0004	2198	17	2305	19
11	119	253	0.83	8.2036	0.0813	0.3883	0.0028	0.1532	0.0014	2115	15	2254	22
12	108	212	0.73	9.5794	0.0940	0.4277	0.0034	0.1624	0.0009	2295	18	2395	24
13	13	25	0.76	9.4668	0.2027	0.4277	0.0039	0.1605	0.0031	2295	21	2384	51
14	177	371	1.00	7.4000	0.0854	0.3727	0.0032	0.1440	0.0005	2042	17	2161	25
15	43	104	0.42	7.8777	0.2656	0.3760	0.0055	0.1520	0.0033	2057	30	2217	75
16	13	25	0.77	9.6800	0.2634	0.4342	0.0046	0.1617	0.0038	2325	25	2405	65
17	18	35	0.96	8.7648	0.1505	0.3993	0.0041	0.1592	0.0026	2166	22	2314	40
18	18	48	0.67	6.0075	0.1291	0.3194	0.0028	0.1364	0.0025	1787	16	1977	42
19	48	106	0.46	8.5362	0.0559	0.4015	0.0036	0.1542	0.0009	2176	20	2290	15
20	28	59	0.46	9.3412	0.1080	0.4234	0.0042	0.1600	0.0018	2276	22	2372	27
21	12	25	0.80	8.5300	0.2790	0.3984	0.0035	0.1553	0.0048	2162	19	2289	75
22	26	55	0.80	7.8101	0.1066	0.3847	0.0046	0.1472	0.0015	2098	25	2209	30
23	43	90	0.64	8.8829	0.1776	0.4034	0.0057	0.1597	0.0014	2185	31	2326	47
24	42	79	0.71	9.7174	0.1250	0.4432	0.0035	0.1590	0.0012	2365	19	2408	31
25	18	36	0.74	9.2789	0.1730	0.4156	0.0044	0.1619	0.0027	2240	24	2366	44
26	94	220	0.46	8.1414	0.1274	0.3749	0.0042	0.1575	0.0009	2052	23	2247	35
27	25	54	0.45	8.9595	0.1477	0.4142	0.0040	0.1569	0.0017	2234	22	2334	38
28	36	76	1.03	7.4161	0.0735	0.3768	0.0025	0.1427	0.0013	2061	14	2163	21
29	10	18	0.81	9.6566	0.3520	0.4413	0.0036	0.1587	0.0055	2357	19	2403	88
30	10	19	0.87	9.8927	0.2830	0.4538	0.0038	0.1581	0.0042	2412	20	2425	69
31	64	139	0.45	8.7562	0.0955	0.4069	0.0047	0.1561	0.0013	2201	25	2313	25

(To be continued on the next page)

(Continued)

Spot	Pb (ppm)	U (ppm)	Th/U	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	Age (Ma)		1σ	Analysis position
										$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$		
32	14	31	0.81	7.7372	0.2218	0.3752	0.0054	0.1496	0.0032	2054	2201	63	Rim
33	7	13	0.74	10.8335	0.4227	0.4756	0.0061	0.1652	0.0062	2508	2509	98	Rim
34	25	50	0.57	9.7032	0.1143	0.4404	0.0053	0.1598	0.0012	2353	2407	28	Core
35	29	58	0.63	9.3433	0.1274	0.4268	0.0027	0.1588	0.0021	2291	2372	32	Rim
36	442	977	0.53	8.4514	0.1679	0.4070	0.0059	0.1506	0.0009	2201	2281	45	Core
37	25	45	1.14	9.2164	0.1070	0.4222	0.0038	0.1583	0.0016	2270	2360	27	Rim
38	933	2142	0.34	8.7079	0.0591	0.4014	0.0035	0.1573	0.0007	2175	2308	16	Core
39	8	18	0.70	8.1647	0.3549	0.3667	0.0026	0.1615	0.0069	2014	2249	98	Rim
40	10	21	0.99	7.8316	0.2687	0.3800	0.0040	0.1495	0.0047	2076	2212	76	Rim
41	324	614	0.70	10.0834	0.0760	0.4457	0.0044	0.1641	0.0009	2376	2442	18	Core
42	225	456	0.40	10.2215	0.0628	0.4527	0.0035	0.1638	0.0007	2407	2455	15	Core
43	15	26	1.02	10.6163	0.2641	0.4692	0.0037	0.1641	0.0037	2480	2490	62	Rim
44	27	48	0.84	10.4682	0.1179	0.4592	0.0019	0.1653	0.0016	2436	2477	28	Rim
45	100	226	0.66	7.8318	0.1625	0.3827	0.0047	0.1484	0.0020	2089	2212	46	Core
46	19	34	1.02	10.2360	0.1616	0.4490	0.0034	0.1653	0.0020	2391	2456	39	Rim
47	41	83	0.46	9.9595	0.0988	0.4438	0.0035	0.1627	0.0014	2368	2431	24	Core
48	41	73	0.87	10.6328	0.1426	0.4662	0.0038	0.1654	0.0013	2467	2492	33	Core
49	86	157	0.68	10.5582	0.0954	0.4670	0.0046	0.1640	0.0008	2471	2485	22	Rim
50	395	996	0.26	7.6450	0.0868	0.3746	0.0032	0.1480	0.0015	2051	2190	25	Core
51	12	22	0.82	9.9857	0.2351	0.4492	0.0036	0.1612	0.0034	2392	2433	57	Rim
52	295	506	0.64	12.6369	0.0728	0.4983	0.0034	0.1839	0.0008	2606	2653	15	Core
53	168	339	0.70	9.1280	0.1498	0.4228	0.0046	0.1566	0.0013	2273	2351	39	Core
54	362	902	0.39	7.4100	0.1519	0.3696	0.0046	0.1454	0.0018	2027	2162	44	Core
55	19	37	0.79	9.3737	0.1587	0.4278	0.0036	0.1589	0.0021	2296	2375	40	Rim
56	58	124	0.27	9.7671	0.0735	0.4401	0.0030	0.1610	0.0010	2351	2413	18	Rim
57	229	455	0.82	9.0952	0.1292	0.4228	0.0055	0.1560	0.0016	2273	2348	33	Core
58	16	28	0.76	10.3651	0.1993	0.4673	0.0057	0.1609	0.0018	2472	2468	47	Rim
59	38	82	0.64	8.6528	0.0819	0.4091	0.0033	0.1534	0.0013	2211	2302	22	Rim
60	766	1882	0.12	8.6086	0.0733	0.3929	0.0024	0.1589	0.0005	2136	2297	20	Core
61	130	270	0.83	8.2308	0.0593	0.3863	0.0026	0.1545	0.0009	2105	2257	16	Core

Figure 6 Concordia diagrams for zircon U-Pb analyses of sample LS10-8-1.1.

zircon Hf model age (T_{DMC}) ranges from 2.73 to 2.98 Ga. The zircon rims have $^{176}\text{Hf}/^{177}\text{Hf}$ ratios varying from 0.281229 to 0.281343. The $\varepsilon_{\text{Hf}}(t)$ values range from -0.71 to 5.74 , with most concentrated on a relatively narrow range from 0.38 to 4.89 except for two lower (-0.71 and -0.05) and two higher (5.74 and 5.63) $\varepsilon_{\text{Hf}}(t)$ values. The corresponding two-stage zircon Hf model age (T_{DMC}) ranges from 2.70 to 2.98 Ga.

4 Discussion

4.1 Explanation of U-Pb dating and Lu-Hf analysis results

The interpretation of zircon U-Pb age data from high-grade metamorphic rocks, particularly those of Archean to Proterozoic gneiss terranes, is difficult because the zircon grains may have grown during more than one geological event and/or may have been affected by multiple alteration processes [36]. Zircon grains collected from the granodiorite gneiss in the Beidashan Complex show a typical core-rim structure under CL. Although the cores and rims can be easily distinguished by their luminescence intensity and

different U and Pb concentrations, which indicate different origins, the U-Pb dating results show that the cores and rims yield an indistinguishable $^{207}\text{Pb}/^{206}\text{Pb}$ age range and a similar upper intercept age (2522 ± 30 Ma and 2506 ± 20 Ma, respectively). This result implies a short time interval between the crystallization of the TTG magmatism and high-grade regional metamorphism. Therefore, the western Alxa block underwent the emplacement of the TTG magmatism and a subsequent high-grade metamorphic event at the close of the Archean. The short time interval between the initial magmatism and the high-grade regional metamorphism signifies the two were related to the same tectonothermal event. Similar cases have been widely reported in NCC [35,37–39].

The Lu-Hf isotopic analyses show the zircon cores and rims have similar measured $^{176}\text{Hf}/^{177}\text{Hf}$ ratios. This result suggests that the zircon rims were formed in a Lu-Hf closed system, i.e. the U-Pb system is reset, whereas the Lu-Hf system remains closed because the initial $^{176}\text{Hf}/^{177}\text{Hf}$ in the zircon lattice is largely unaffected by the alteration [36,40–42]. The relict weak oscillatory zone in the zircon rims also implies that they resulted from metamorphic recrystallization rather than metamorphic overgrowth or growth from

Table 3 Lu-Hf isotope compositions of zircons from Sample LS10-8-1.1

Spot	Age (Ma)	$^{176}\text{Hf}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Yb}/^{177}\text{Hf}$	$\delta_{\text{Hf}}(t)$	T_{DM}	T_{DMC}	Analysis position
1	2500	0.281396	0.001817	0.134160	4.41	2647	2730	Core
2	2500	0.281281	0.000383	0.026642	2.74	2705	2833	Core
3	2500	0.281233	0.000500	0.034488	0.84	2777	2949	Core
4	2500	0.281327	0.000768	0.052284	3.71	2670	2773	Rim
5	2500	0.281242	0.000416	0.027905	1.31	2759	2920	Rim
6	2500	0.281214	0.000374	0.026431	0.38	2794	2977	Rim
7	2500	0.281316	0.000739	0.048596	3.39	2682	2793	Core
8	2500	0.281247	0.000494	0.032829	1.33	2758	2918	Core
9	2500	0.281202	0.000373	0.026173	-0.05	2809	3003	Rim
10	2500	0.281281	0.000505	0.032083	2.52	2713	2846	Rim
11	2500	0.281217	0.000408	0.026897	0.43	2792	2974	Rim
12	2500	0.281318	0.000998	0.067898	3.01	2698	2816	Core
13	2500	0.281366	0.000459	0.028053	5.63	2596	2655	Rim
14	2500	0.281301	0.000711	0.046355	2.89	2701	2823	Core
15	2500	0.281341	0.000369	0.023280	4.89	2623	2701	Rim
16	2500	0.281223	0.000575	0.036481	0.37	2795	2978	Core
17	2500	0.281341	0.000764	0.049867	4.24	2650	2741	Core
18	2500	0.281281	0.000898	0.054017	1.88	2740	2885	Rim
19	2500	0.281265	0.000420	0.025907	2.09	2729	2872	Rim
20	2500	0.281250	0.000370	0.022152	1.66	2745	2898	Core
21	2500	0.281242	0.000424	0.026590	1.27	2760	2922	Rim
22	2500	0.281289	0.000455	0.026605	2.90	2699	2823	Rim
23	2500	0.281297	0.000779	0.048011	2.63	2711	2840	Core
24	2500	0.281302	0.000416	0.023742	3.43	2679	2790	Rim
25	2500	0.281229	0.000683	0.041322	0.38	2796	2977	Core
26	2500	0.281182	0.000349	0.020740	-0.71	2834	3044	Rim
27	2500	0.281257	0.000525	0.031061	1.66	2746	2899	Rim
28	2500	0.281483	0.002283	0.132363	6.70	2558	2590	Core
29	2500	0.281242	0.000387	0.021015	1.34	2757	2918	Rim
30	2500	0.281420	0.001528	0.084990	5.74	2594	2649	Rim
31	2500	0.281258	0.000298	0.018355	2.08	2729	2873	Rim
32	2500	0.281258	0.000480	0.026625	1.76	2742	2892	Core
33	2500	0.281338	0.001242	0.078412	3.31	2688	2798	Rim
34	2500	0.281278	0.000530	0.031052	2.38	2719	2855	Core
35	2500	0.281347	0.000756	0.044439	4.44	2642	2729	Core
36	2700	0.281228	0.001228	0.072941	3.87	2837	2918	Core
37	2500	0.281305	0.000507	0.030008	3.37	2682	2794	Core
38	2500	0.281257	0.000530	0.032927	1.63	2747	2901	Core
39	2500	0.281303	0.000714	0.043028	2.97	2698	2818	Rim
40	2500	0.281444	0.001047	0.067266	7.42	2529	2546	Core
41	2500	0.281328	0.000577	0.032603	4.07	2655	2751	Rim
42	2500	0.281307	0.000873	0.048096	2.84	2704	2827	Core
43	2500	0.281270	0.000447	0.025180	2.25	2723	2862	Rim
44	2500	0.281291	0.000461	0.027557	2.97	2696	2818	Rim

fluid [40,43,44].

4.2 Geological implications

The North China Craton (NCC) is one of the oldest cratons

in the world [45–47]. The NCC consists of an Early Archean to Paleoproterozoic basement overlain by a Mesoproterozoic to Cenozoic unmetamorphosed cover. Neoproterozoic basement rocks are widespread over the whole of the NCC and constitute approximately 85% of the area of the exposed

Archean basement in the NCC. These rocks consist of a 2.6–2.5 Ga tonalite-trondhjemite-granodiorite (TTG) suite, ca. 2.5 Ga syntectonic granites and a variety of supracrustal rocks that underwent greenschist to granulite facies regional metamorphism and polyphase deformation at approximately 2.5 Ga [19]. Among these rock units, the TTG gneisses dominate in the preserved Archean crust of the NCC. Most studies in recent years have focused on TTG gneisses from the eastern and central part of the NCC, but there are few studies on TTG gneisses from the western NCC. A large number of geochronological data of TTG gneisses from the NCC suggest that the time of magmatic crystallization and subsequent metamorphism is almost identical at the end of the Neoproterozoic. A ca. 2.5 Ga magmatism soon followed by high-grade metamorphism with a short time span (10–50 Ma) have become a significant feature for many areas of the NCC [19,35,48–72] and are related to the same Neoproterozoic major tectonothermal event [35,73]. TTG gneisses from the Trans-North China Orogen of the NCC also yield ca. 2.5 Ga magma emplacement ages, while the metamorphic ages are concentrated on approximately 1.8–1.9 Ga (peak at 1.85 Ga), which has been explained as the time of collision between the Eastern and Western Blocks [74]. However, TTG gneisses are not the only rocks that have recorded Late Archean to Early Paleoproterozoic magmatic-metamorphic events in the NCC. The age spectra of magmatic, metamorphic and detrital zircons from different rocks of the NCC Precambrian basement show two predominant age peaks at ca. 2.5 Ga and 1.8–1.9 Ga, indicating two main tectonothermal events in the NCC [3,75–77].

The Alxa Block is considered the westernmost compo-

ment of the NCC. However, its nature and affinity are still controversial. Based on studies on the late Paleoproterozoic tectonothermal events of the eastern Alxa block, Geng et al. [78] proposed that the Khondalite Belt probably extends westward to the eastern Alxa block. Dan et al. [13] believed that the Alxa Block was likely an independent Paleoproterozoic terrane rather than the western extension of the Yinshan Block [74] or part of the Khondalite Belt. For the western Alxa block, our zircon U-Pb data show that the TTG gneiss from the Beidashan Complex experienced a magmatic crystallization at 2522 ± 30 Ma and subsequent metamorphism at 2496 ± 11 Ma, which proves that a Neoproterozoic metamorphic basement really exists in the Alxa Block. In addition, as mentioned above, the close temporal association between the TTG magmatism and subsequent metamorphism at ca. 2.5 Ga is very similar to the other part of the NCC, suggesting that the western Alxa Block experienced a similar Latest Neoproterozoic-Earliest Paleoproterozoic tectonothermal event as the NCC. Compared with the TTG gneisses from the Trans-North China Orogen, a 1.8–1.95 Ga metamorphic event was not recognized in the LS10-8-1.1 TTG gneiss. However, a large number of 1.8–1.95 Ga metamorphic zircons were recognized in gneisses from the Longshoushan Group [18], to the south of Beidashan area, that were identical to the metamorphic ages recorded in the Trans-North China Orogen (peak at 1.85 Ga) and in the Khondalite Belt (peak at 1.95 Ga) [19,79–81]. This result suggests that the western Alxa Block also experienced a late Paleoproterozoic tectonothermal event similar to that of the NCC. Our new zircon dating results of the TTG gneisses collected from different areas in the Beidashan

Figure 7 $\epsilon_{\text{Hf}}(t)$ vs. $^{207}\text{Pb}/^{206}\text{Pb}$ age diagram for Sample LS10-8-1.1 and typical TTG gneisses in the North China Craton and Tarim Craton. Dengfeng TTG by Diwu [68]; Sushui TTG by Guo et al. [65]; Wutai TTG by Chen et al. [90]; Tarim TTG by Long et al. [91,92].

Complex record both Neoproterozoic (ca. 2.5 Ga) and Late Paleoproterozoic (1.9–1.8 Ga) metamorphic events (Zhang et al., unpublished data), further illustrating the affinity between the western Alxa Block and the NCC.

Numerous geochronology studies, especially of zircon U-Pb ages, suggest that the strongest tectonothermal event in the NCC occurred at ca. 2.5 Ga. Some geologists have also presumed that the 2.5 Ga peak was the major crustal growth period of the NCC [82]. However, the recently published whole-rock Sm-Nd and zircon Lu-Hf isotopic data indicate that the major crustal growth in the NCC took place at 2.7–3.0 Ga [83–86], similar to most other cratons in the world [87], and that the ca. 2.5 Ga magmatic events represent the reworking of the older crust. However, some authors still consider ca. 2.5 Ga as a time of subdominant crustal growth in the NCC [55,68]. Based on Hf isotopic data of zircons from the Precambrian lower crustal rocks overlying a sedimentary cover, modern river sediments and late Neoproterozoic syenogranites, Wang and Liu [88] suggested that both 2.7–2.8 Ga and 2.5–2.6 Ga crustal growth were distributed over the NCC and that the former was much wider than previously suggested. In this study, the zircon Lu-Hf isotopic analyses for TTG gneiss LS10-8-1.1 show no distinct differences between the zircon cores and rims. Also, the age-corrected $\varepsilon_{\text{Hf}}(t)$ value is mainly between 0.4 and 4.9, corresponding to two-stage zircon Hf model age ranges from 2.7 to 3.0 Ga. These ages suggest that the TTG gneiss from the Beidashan Complex formed during a Mesoarchean-Neoproterozoic (2.7–3.0 Ga) juvenile crustal growth event in the western Alxa block and that it was reworked at the end of the Neoproterozoic. However, a ca. 2.5 Ga juvenile crust growth cannot be ruled out, similar to the case of the TTG gneisses in the central and eastern NCC. Therefore, these data show that the western Alxa block has a crustal growth history consistent with that of the NCC during the Mesoarchean-Neoproterozoic (Figure 7). In addition, ca. 2.7 Ga inherited zircon grains widely distributed in TTG and granitic rocks are a prominent characteristic in the NCC [59,89]. An inherited zircon grain with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2689 ± 7 Ma (Spot 52) is recognized in TTG gneiss LS10-8-1.1 in the Beidashan Complex, and it yields a two-stage zircon Hf model age of ca. 2.9 Ga, further supporting the 2.7–2.9 Ga crustal growth event in the western Alxa Block.

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