



LA-ICP-MS zircon U–Pb dating of the Langshan Group in the northeast margin of the Alxa block, with tectonic implications



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ABSTRACT

The relationship between the Alxa block and the North China Craton (NCC) is one of the controversial tectonic issues in China. The age spectra of detrital zircons from sedimentary rocks may help resolve the tectonic affinity of the Alxa block. The Langshan terrane is located in the northeast margin of the Alxa block which is connected to the northwest margin of the NCC. Detailed U–Pb dating of zircon from the meta-volcanic rocks and meta-sedimentary rocks of the Precambrian Langshan group shows that the Langshan Group formed in the Neoproterozoic. The evidence includes the zircon age of 804.1 ± 3.5 Ma for the meta-volcanic rocks and the youngest detrital zircon age peak at 1187–810 Ma for the meta-sedimentary rocks. The detrital zircon age patterns of the Langshan group and Precambrian strata of the Alxa block and the NCC are similar. The older and younger detrital zircon age peaks of the Langshan group are comparable to those of the NCC and the Alxa block, respectively. The 1.7–1.5 Ga detrital zircons in the Langshan Group, which might be derived from the “Zhaertai–Bayan Obo–Huade” Mesoproterozoic rift system in the northern margin of the NCC, are not found in the Precambrian strata of the Alxa block. The detrital zircon age peaks of the Langshan group are well correlated to the known Precambrian tectono-thermal events that affected both the Alxa block and the NCC. The development of the Langshan Neoproterozoic rift system is shown by the contemporaneous magmatism in the Alxa block and the adjacent NCC. The results from this study indicate that the Alxa block and the NCC were together in the Neoproterozoic.

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1. Introduction

The Alxa block is located in western China. It is bounded by the Ordos block to the east and by the Tarim block to the west (Wang and Mo, 1995). The relationship between the Alxa block and the North China Craton (NCC) is controversial. Some researchers believe that the Alxa block was part of the NCC in Rodinia (e.g., Li and Ripley, 2011). Zhai and Santosh (2011) suggested that the Alxa block was welded with other micro blocks to form the NCC at ~ 2.5 Ga. Zhao et al. (2006) and Yin et al. (2009, 2011) suggested that the Alxa block was amalgamated with the NCC along the Khondalite belt between them at ~ 1.95 Ga based on the geochronological and metamorphic constraints from khondalites in the Helanshan–Qianlisan area. In contrast, other researchers believe that the Alxa block was independent of the NCC until the Paleozoic because (1)

their different apparent palaeomagnetic polar wandering paths and crustal structures (Tung et al., 2007; Huang et al., 1999, 2000; Li et al., 2004a,b; Geng and Zhou, 2010; Ge et al., 2009; Zhang et al., 2009a,b; Peng et al., 2010) and (2) the occurrence of Neoproterozoic magmatic activities in the Alxa block but not in the NCC (Li et al., 2004a,b; Geng and Zhou, 2010; Geng et al., 2002). Most recently, some researchers suggested that the closure of a hypothetical early-Paleozoic oceanic basin between the Alxa block and the NCC resulted in the amalgamation of these two blocks (Li et al., 2012; Zhang et al., 2012a,b), although such a suture has not been found.

The continental blocks from a Precambrian supercontinent should have similar tectonic evolution history i.e., experiencing the same main geological events. Zircons can retain their isotopic integrity through many geological processes such as weathering, erosion, transportation, sedimentation and low-grade metamorphism with low fluid/rock ratios (Ying et al., 2011). The age spectra of detrital zircons from sedimentary rocks are useful for the provenance and age studies of the evolution of continental crust, and evaluating the tectonic affinity of suspect terranes (Wan et al., 2011).

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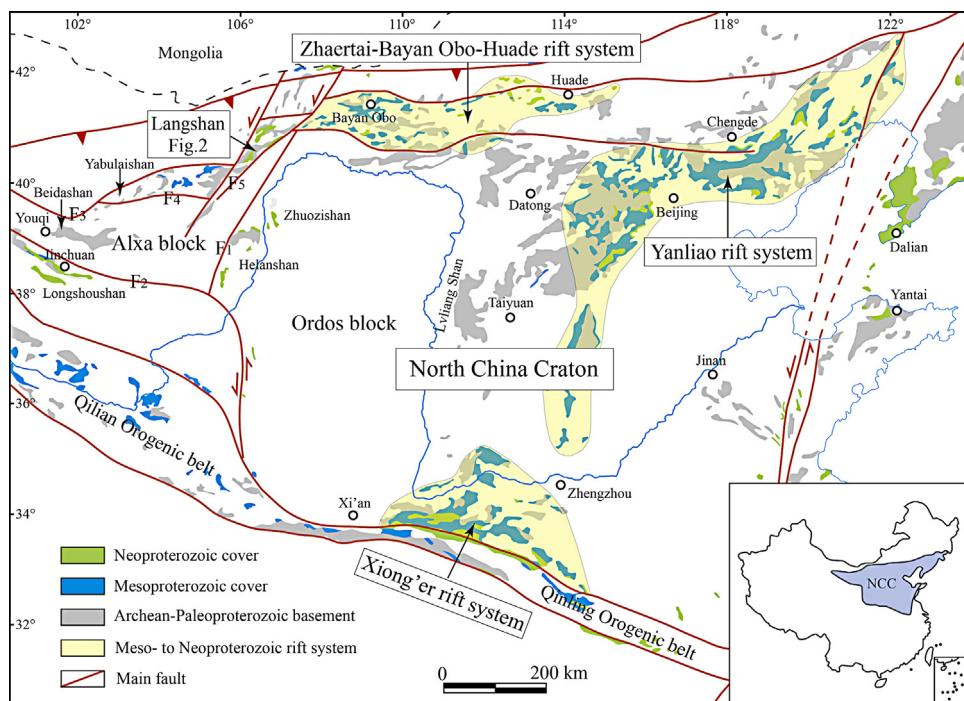


Fig. 1. Locations of the Alxa block and the North China Craton.

The Langshan terrane is situated in the northeast corner of the Alxa block which is currently connected to the northwest margin of the NCC. The Langshan Group is the main Precambrian unit in this area. It is composed of low-grade meta-volcanic and meta-sedimentary rocks. The deposition age of the Langshan Group was uncertain until now. Based on stratigraphic correlations, some researchers suggested that the Langshan group and the Zhaertai group in the Zhaertaishan area, the Bayan Obo group in the Bayan Obo area and the Huade group in the Huade area all formed at the same time in the Mesoproterozoic during the development of the so-called “the Langshan-Zhaertai-Bayan Obo-Huade rift system” in the northern margin of the NCC, which coincided with the breakup of the Columbia supercontinent (Zhao et al., 2004a,b; Zhao, 2006; Peng et al., 2006; Hou et al., 2009; Yang et al., 2011; Zhai et al., 2011; Zhang et al., 2012a,b) (Fig. 1). However, the U-Pb ages of 816.9 ± 4.5 Ma and 805.0 ± 5.0 Ma for comagmatic zircon from felsic volcanic rocks in the Langshan Group in the Inner Mongolia indicate that the Langshan Group formed in the Neoproterozoic (Peng et al., 2010; Zhai and Santosh, 2013). The detrital zircon age patterns of the Langshan Group may be useful for determining the tectonic relationship between the Alxa block and the NCC. If the Alxa block and the NCC were separate continents in the Neoproterozoic, previous felsic magmatism in the Alxa block, which is revealed by the detrital zircon age patterns of the Langshan Group, could be absent in the NCC. If the Alxa block was the westmost part of the NCC in Rodinia, the detrital zircon crystals from the Langshan Group would show the common pre-Neoproterozoic age patterns for the Alxa block and the NCC.

This paper reports zircon U-Pb age data for the meta-volcanic rocks and meta-sedimentary rocks of the Langshan Group. The detrital zircon age patterns of the Langshan Group are compared to those of the Precambrian and Paleozoic strata in the Alxa block and the NCC. The results are used to define the age of the Langshan Group, to correlate the Neoproterozoic rifting in the Alxa block and the adjacent Langshan terrane, and to evaluate the tectonic relationship between the Alxa block and the NCC.

2. Geological setting

The Alxa block is bounded by the Ordos block to the east, by the Qilian orogenic belt to the south, by the Tarim craton to the west, and by the Central Asian orogenic belt to the north (Yang et al., 1988) (Fig. 1).

The Precambrian lithology of the Alxa block is composed of a crystalline basement and a sedimentary cover. The crystalline basement consists of the Archean Diebusige group and the Paleo-proterozoic Alxa group. The Diebusige group is composed of high-grade metamorphic supracrustal rocks with deposition age ~2.7 Ga and metamorphic ages from 2.7 to 2.5 Ga to 2.0 to 1.9 Ga (Geng et al., 2007). The Paleo-proterozoic Alxa group is composed of meta-clastic sedimentary rocks and meta-carbonatites. It is present mainly in the Yabulaishan area along the northern margin of the Alxa block (NMBGMR, 1991; Li, 2006). The sedimentary cover includes the Meso- to Neo-Proterozoic strata. It is present in the northern and southern margins of the Alxa block. The Mesoproterozoic strata are further divided into the lower Nuoergong group and the overlying Bayinxibie group, which are well exposed in the Yabulaishan area, the northern margin of the Alxa block. The Nuoergong Group is interpreted to be beach or delta-facies deposits, with a total thickness of 6700 m; the Bayinxibie Group is further divided into lower and upper parts, with a total thickness of 1340 m. The lower part is composed of alternating layers of clastic rocks and carbonate rocks whereas the upper part is composed of carbonate rocks (NMBGMR, 1991; Li, 2006). The Neoproterozoic Wulanhxaxia Group is composed of neritic-facies clastic sedimentary rocks with high calcium and sulfur contents, with a total thickness of 1520 m. The detrital zircon $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1098–2125 Ma have been obtained from the siltstone of this group (Li, 2006). The Meso- to Neo-proterozoic meta-sedimentary rocks in the Longshoushan area in the southern margin of the Alxa block are collectively referred to as the Longshoushan group (Gong et al., 2011, 2014).

The Langshan terrane is located in the northeastern margin of the Alxa block. The exposed lithologic units in Langshan include

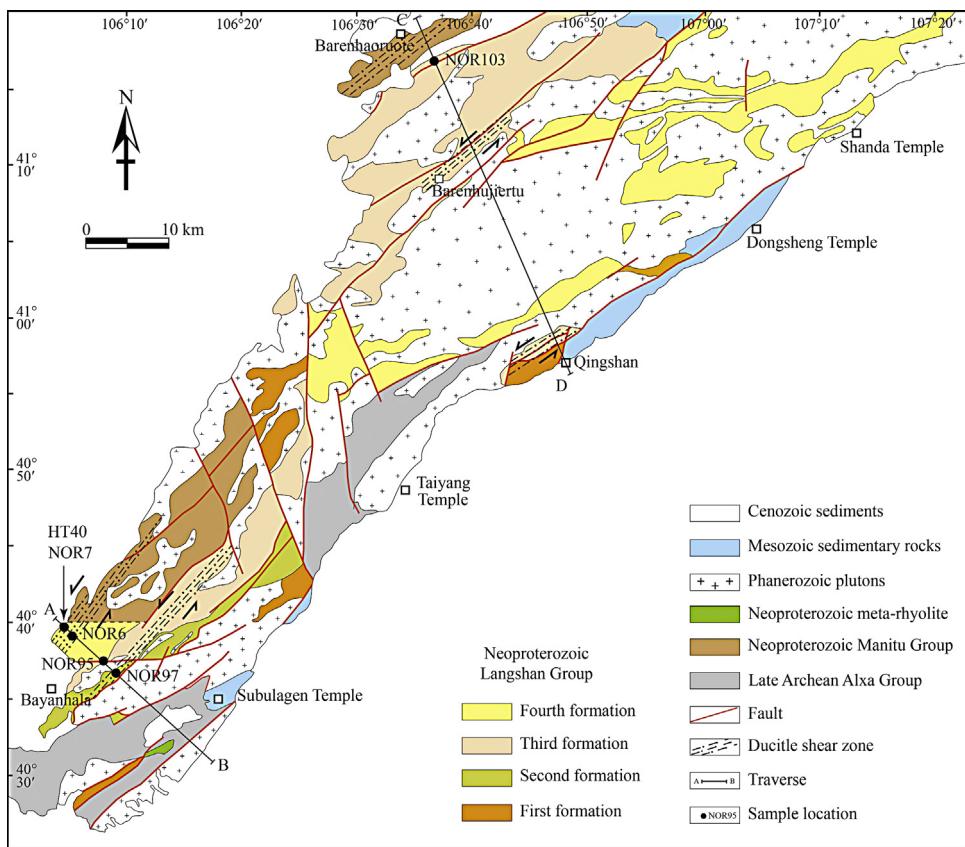


Fig. 2. Geological map of the Langshan terrane and the northeastern Alxa block.

the Paleoproterozoic Alxa group, Proterozoic Langshan Group, Mesozoic sedimentary rocks and Phanerozoic granitic intrusions. The Paleoproterozoic Alxa group is composed of amphibolite- to granulite-facies gneisses including garnet-biotite gneiss, amphibolite and minor marble (Yang et al., 1988). The Alxa group is unconformably overlain by the Proterozoic Langshan Group, which is composed of greenschist-facies clastic rocks, carbonate and minor meta-volcanic interlayers (Peng et al., 2005). The Alxa group is folded to form a NE-trending tight syncline. The Mesozoic sedimentary rocks, including conglomerate, sandstone and siltstone are present locally. Multiple episodes of Phanerozoic felsic magmatism in the Langshan area took place at the Caledonian, Hercynian, Indonina and Early Yanshanian (Fig. 2).

A series of NE-trending ductile shear zones occur parallel to the strike of the Langshan terrane, separating the Alxa block from the rest of the NCC. The foliation in the shear zones steeply dips to the northwest or the southeast whereas the associated lineation gently plunges to the northeast or the southwest. The kinematic indicators in the shear zones such as asymmetric boudinage structures and asymmetric rotated porphyroclasts, and the associated foliation and lineation indicate sinistral strike-slip shearing (Gong, 2014).

Zhang et al. (2013) recognized two phases of ductile deformation in the Langshan terrane. These authors interpreted the $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 351 Ma and 250 Ma obtained for the metamorphosed rocks as the ages of the east-to-west thrusting caused by the collision between the NCC and the Alxa block in the late Devonian and the sinistral strike-slip shearing caused by the collision between the NCC and the Yangtze block in the late Permian, respectively. However, the younger $^{40}\text{Ar}/^{39}\text{Ar}$ age of 250 Ma may have resulted from the intrusion of the 290–260 Ma granite plutons in the area (Geng and Zhou, 2012; Zhang et al., 2009b, 2010b).

Furthermore, the collision between the NCC and the Yangtze block likely occurred in the late Middle Triassic, not at 250 Ma (Meng and Zhang, 2000; Ratschbacher et al., 2003; Li et al., 2007a,b; Hu et al., 2012a,b). Gong (2014) obtained two $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 379.05 ± 4.68 Ma and 356.69 ± 2.50 Ma for muscovite crystals from the deformed rocks with lineation and interpreted these as the deformation ages of the sinistral strike-slip shearing in the Langshan ductile shear zone.

3. The Langshan Group

From bottom to top, the Langshan group consists of four formations (Figs. 2 and 3). The First Formation is further divided into top and bottom members, with a total thickness of 1590 m. The top member is mainly composed of two-mica quartz schist with minor amphibole marbles whereas the bottom member is composed of metamorphosed sandstone, biotite quartz schist with minor amphibolite and quartzite. The Second Formation is mainly composed of crystalline limestone and carbonaceous sericite quartz phyllite, and interbedded metamorphosed volcanic rocks (Fig. 4c-f), with a total thickness of 1560 m. The Third Formation is a major base metal ore-bearing layer and has a total thickness of >1540 m. The top member of the Third Formation is composed of carbonaceous slate (Fig. 4b), carbonaceous sericite-bearing crystalline limestone and interbedded calcite quartzite and graphite-bearing metamorphosed quartz sandstone. The bottom member is mainly composed of sericite-bearing quartz schist, phyllite, phyllitic slate, carbonaceous slate, and interbedded metamorphosed sandstone and calcite two-mica slate. The Fourth Formation has a total thickness of 2400 m. Its top member is mainly composed of actinolite schist, amphibolite slate, quartz tremolite marbles and interbedded quartz schist. Its bottom

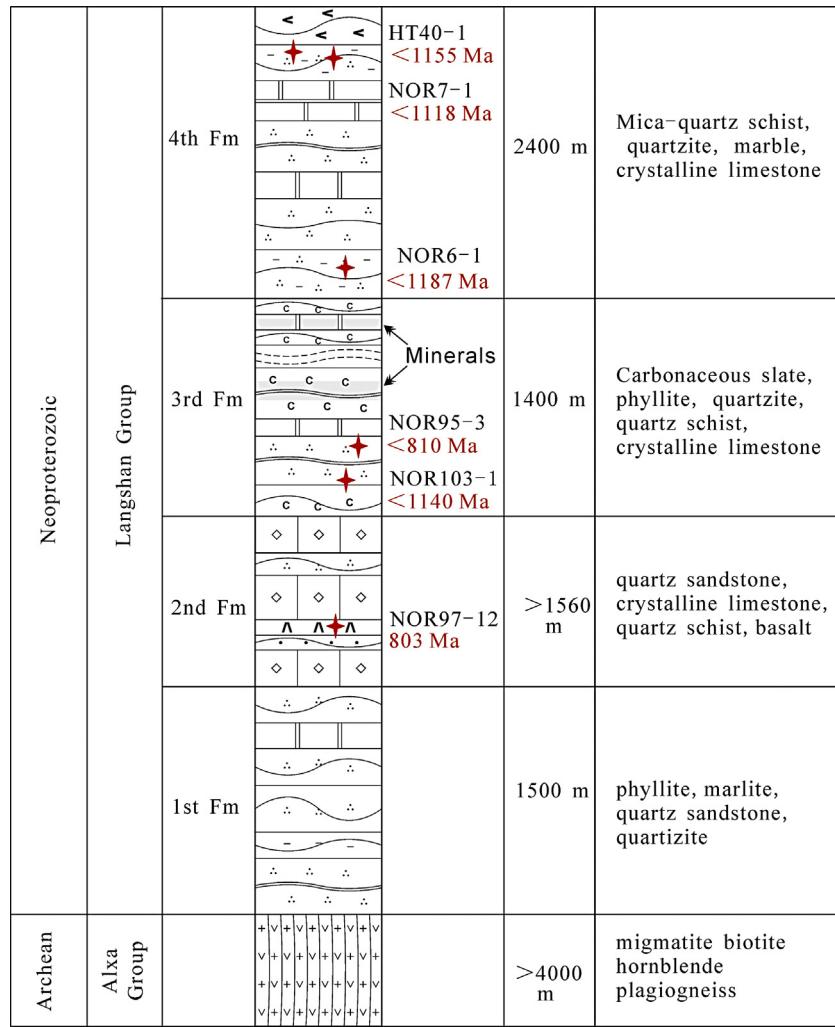


Fig. 3. Stratigraphy, sample locations and minimum zircon U–Pb ages.

member is mainly composed of metamorphosed fine-grained siltstone, mica quartz schist (Fig. 4a), quartz schist and interbedded crystalline limestone and sericite slate (Fig. 3).

4. Analytical method

Zircon separation was carried out in a commercial laboratory in Langfang, Hebei. Whole rock samples were crushed to 200 mesh. Zircon grains in the samples were separated by elutriation and magnetic separation. The zircon crystals for further analysis were selected manually under a stereomicroscope and mounted in epoxy resin disks. The zircon mounts were polished. The images of the selected zircon grains were taken under reflected light, transmitted light and cathodoluminescence. The images were used for target selection for in situ analysis.

Zircon in situ U–Pb isotope analysis was conducted in the Isootope Laboratory of the Tianjin Institute of Geology and Mineral Resources by Laser Ablation Multicollector Inductively Coupled Plasma Mass Spectrometry (LA-MC-ICP-MS). The Neptune (Thermo Fisher) Multicollector Inductively Coupled Plasma Mass Spectrometer and the UP193-FX ArF excimer laser ablation system with a laser wavelength of 193 nm, a pulse width of 5 ns, and a continuously tunable pulse frequency of 1–200 Hz were used. The diameter of laser beam was 35 μm . The laser energy density and frequency were 10–11 J/cm² and 8–10 Hz, respectively. The laser-ablated material was transported into the ICP system, using

He as the carrier gas. The U and Pb in the samples were ionized by the high-temperature ($>8000^\circ\text{C}$) plasma and their isotope ratios were determined simultaneously. The TEMORA and GJ-1 international standards were used for calibration (Black et al., 2003; Jackson et al., 2004). The ICPMSDataCal software from Liu et al. (2009, 2010) and the Isoplot software from Ludwig (Ludwig, 2003) were used for the data reduction. Common lead correction was applied using ^{208}Pb (Andersen, 2002). The NIST612 international standard was used as standard for Pb, U and Th concentrations. The receiver set-ups were: L4, ^{206}Pb ; L3, ^{207}Pb ; L2, ^{208}Pb ; C, 219.26; H2, ^{232}Th ; and H4, ^{238}U . The speeds of the cooling gas, the assistant gas, Ar (carrier gas), and He (carrier gas) were 16 L/min, 0.75 L/min, 0.968 L/min, and 0.86 L/min, respectively. The RF power was 1251 W. The integration time was 0.131 s. The signal collection time was 60 s plus 20 s for the blank.

5. Samples and analytical results

Six rock samples from three formations of the Langshan Group were analyzed for zircon U–Pb isotopes using the LA-ICP-MS method. Sample NOR95-12 is a meta-volcanic rock collected from the Second Formation. Sample NOR95-3 and NOR103-1 are meta-sedimentary rocks collected from the Third Formation. Sample NOR6-1, NOR7-1 and HT40-1 are meta-sedimentary rocks collected from the Fourth Formation (see Fig. 2 for locations). Most of the

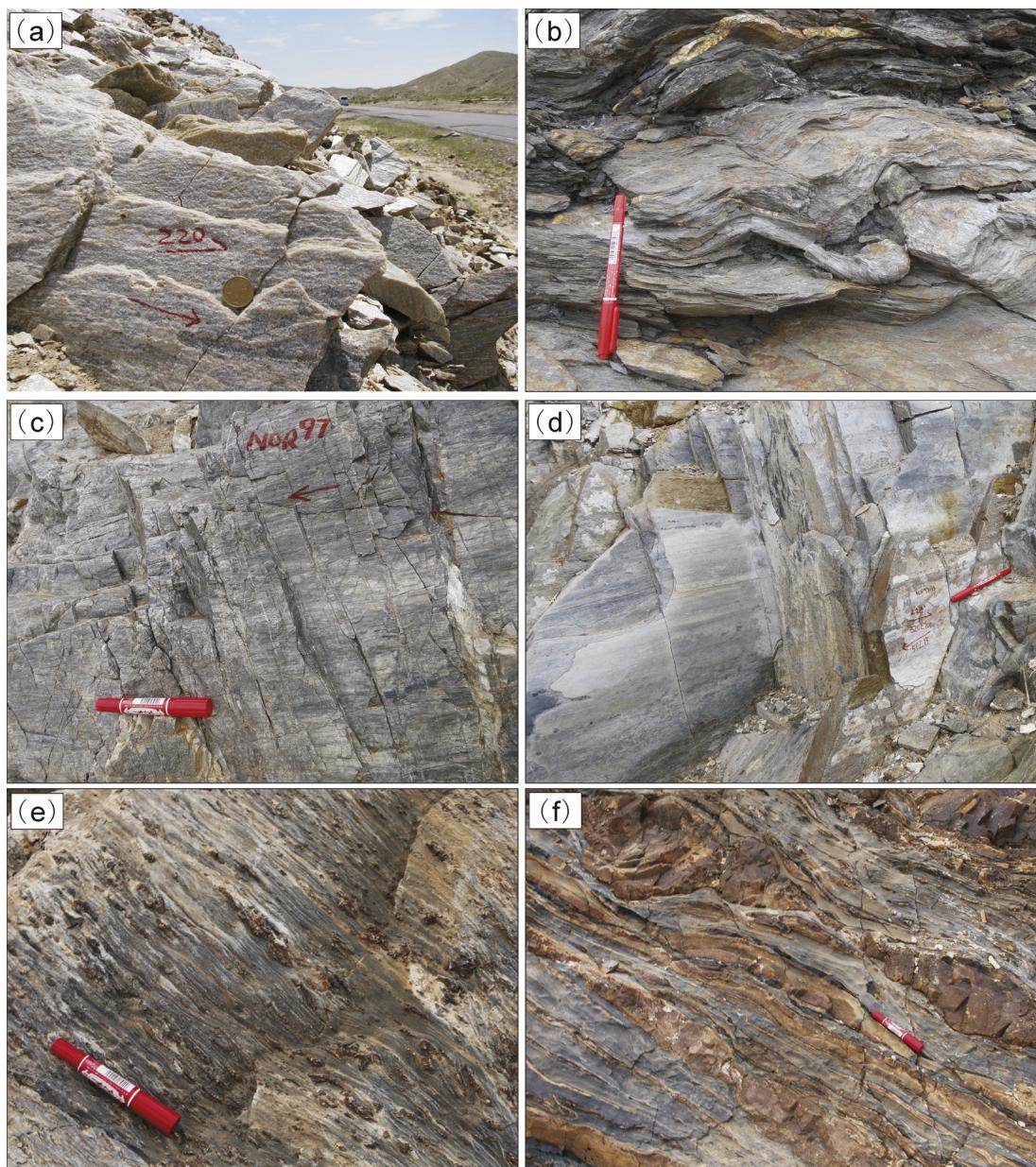


Fig. 4. Outcrop photos of the Langshan Group in the Langshan area. (a) Mica-quartz schist with sub-horizontal lineation; (b) carbonaceous slate; (c) meta-volcanic rocks; (d) meta-sandstone; (e–f) chert-limestone.

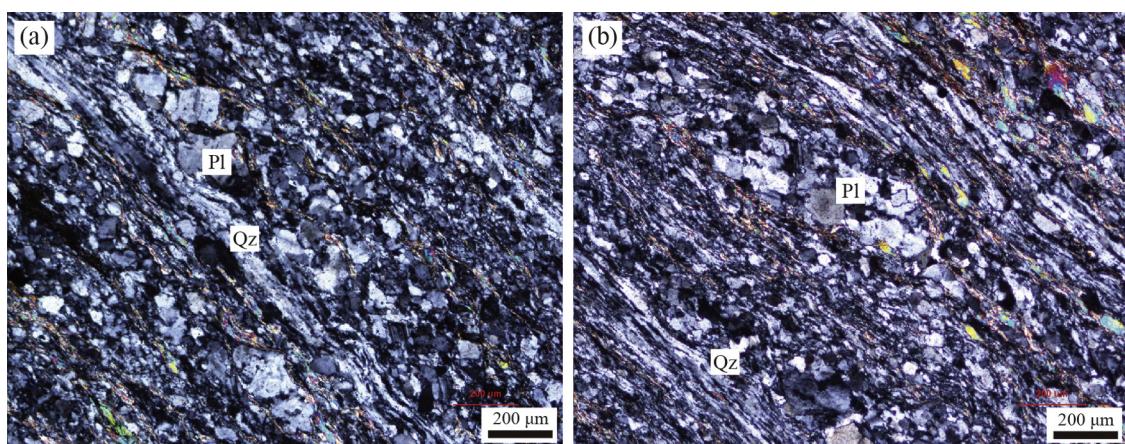


Fig. 5. Photomicrographs of the mylonitic meta-volcanic rock sample from the Second Formation of Langshan Group. Abbreviations: Qz = quartz; Pl = plagioclase.

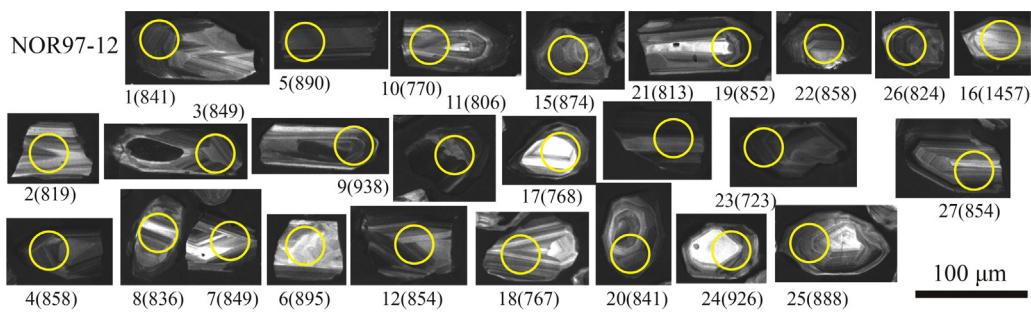


Fig. 6. Cathodoluminescence (CL) images of dated zircons from the meta-volcanic rock sample from the Langshan Group. The circles are the locations of the laser beam, "23(723)" represents the "grain number ($^{206}\text{Pb}/^{238}\text{U}$ ages)".

Table 1

Zircon LA-ICP-MS U-Pb data for a meta-volcanic rock sample from the Langshan group in the Langshan terrane.

Test point	Elemental data	$^{232}\text{Th}/^{238}\text{U}$ Isotopic ratios						Ages (Ma)							
		Pb	U	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ
NOR97-12 (GPS Coordinate: N40°36'52.3"E 106°10'13.1")															
1	42	329	0.1406	0.1316	0.0013	1.2175	0.0160	0.0671	0.0006	797	8	809	11	841	19
2	36	240	0.6494	0.1314	0.0017	1.2037	0.0188	0.0664	0.0008	796	10	802	13	819	25
3	39	292	0.2112	0.1320	0.0012	1.2260	0.0181	0.0674	0.0007	799	8	813	12	849	23
4	39	257	0.6444	0.1338	0.0013	1.2482	0.0182	0.0676	0.0007	810	8	823	12	858	21
5	62	391	0.9512	0.1325	0.0014	1.2552	0.0173	0.0687	0.0006	802	9	826	11	890	19
6	16	105	0.5730	0.1322	0.0013	1.2553	0.0295	0.0689	0.0017	800	8	826	19	895	52
7	23	161	0.4983	0.1339	0.0012	1.2431	0.0199	0.0674	0.0010	810	8	820	13	849	31
8	33	236	0.4004	0.1341	0.0013	1.2377	0.0202	0.0669	0.0009	811	8	818	13	836	28
9	46	334	0.4185	0.1301	0.0013	1.2616	0.0167	0.0703	0.0006	789	8	829	11	938	19
10	24	170	0.2794	0.1349	0.0013	1.2065	0.0194	0.0649	0.0009	816	8	804	13	770	30
11	95	592	0.8763	0.1321	0.0012	1.2018	0.0144	0.0660	0.0004	800	7	801	10	806	13
12	26	190	0.2168	0.1356	0.0015	1.2629	0.0179	0.0675	0.0008	820	9	829	12	854	23
13	27	197	0.2394	0.1344	0.0012	1.2071	0.0173	0.0651	0.0007	813	7	804	12	778	22
14	22	163	0.2796	0.1312	0.0012	1.2339	0.0186	0.0682	0.0009	795	7	816	12	875	27
15	33	249	0.2155	0.1327	0.0012	1.2477	0.0168	0.0682	0.0007	803	7	822	11	874	21
16*	26	113	0.3420	0.2164	0.0042	2.7298	0.0438	0.0915	0.0010	1263	25	1337	21	1457	22
17	18	127	0.3175	0.1348	0.0013	1.2044	0.0232	0.0648	0.0013	815	8	803	15	768	42
18*	22	171	0.3765	0.1210	0.0013	1.0811	0.0191	0.0648	0.0011	737	8	744	13	767	34
19	29	217	0.2395	0.1331	0.0014	1.2385	0.0163	0.0675	0.0006	806	8	818	11	852	19
20	32	240	0.2706	0.1312	0.0011	1.2142	0.0162	0.0671	0.0006	795	7	807	11	841	20
21	54	423	0.1095	0.1344	0.0012	1.2267	0.0148	0.0662	0.0004	813	7	813	10	813	13
22	22	164	0.2794	0.1320	0.0013	1.2317	0.0184	0.0677	0.0009	799	8	815	12	858	27
23*	42	328	1.9202	0.1031	0.0012	0.9015	0.0161	0.0634	0.0007	632	8	653	12	723	25
24	13	85	0.5399	0.1344	0.0018	1.2954	0.0317	0.0699	0.0019	813	11	844	21	926	57
25	21	157	0.3210	0.1317	0.0013	1.2458	0.0213	0.0686	0.0011	797	8	822	14	888	34
26	40	305	0.1556	0.1338	0.0013	1.2281	0.0159	0.0665	0.0006	810	8	813	11	824	18
27	26	190	0.3282	0.1345	0.0014	1.2522	0.0173	0.0675	0.0008	814	9	824	11	854	24
28*	53	181	0.5966	0.2571	0.0039	3.5480	0.0542	1.001	0.0007	1475	22	1538	24	1626	12
29	27	204	0.2401	0.1294	0.0013	1.2149	0.0216	0.0681	0.0012	785	8	807	14	871	38
30	29	217	0.2224	0.1341	0.0012	1.2147	0.0178	0.0657	0.0008	811	7	807	12	796	26
31	26	190	0.3408	0.1320	0.0022	1.2037	0.0216	0.0661	0.0011	799	13	802	14	811	35

* Uncalculated data.

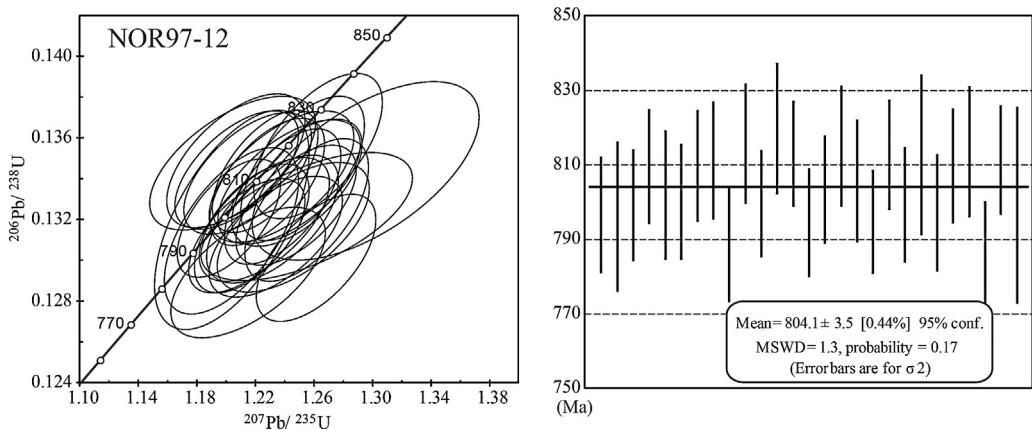


Fig. 7. Zircon U-Pb concordia diagram for the meta-volcanic rock sample from the Second Formation of the Langshan Group.

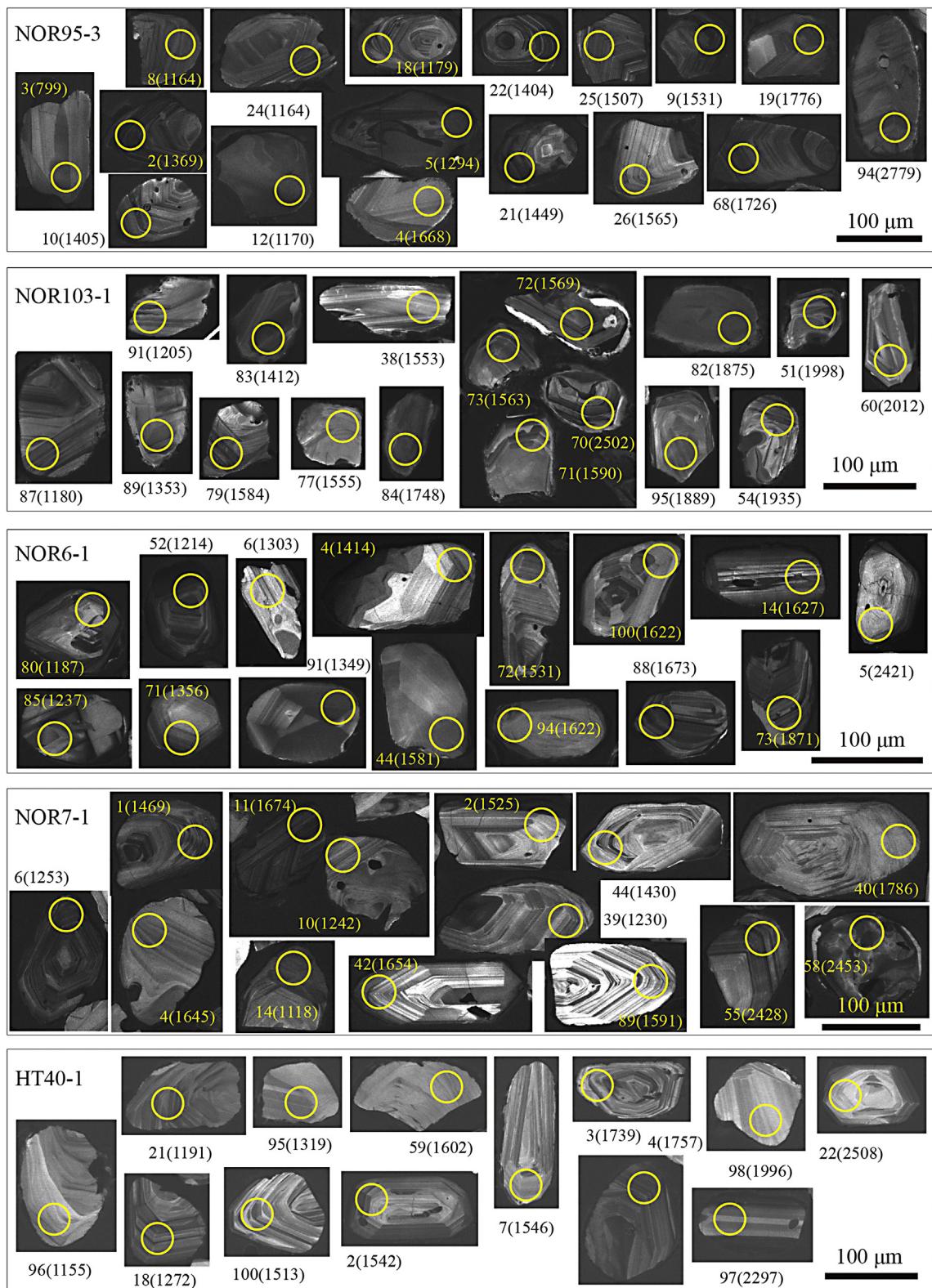


Fig. 8. Representative CL images of dated detrital zircons from the meta-sedimentary rocks of the Langshan Group.

U-Pb ages of the zircon grains from the meta-volcanic rock are younger than 1.0 Ga. The $^{206}\text{Pb}/^{238}\text{U}$ ages are used to represent the crystallization ages of these zircon crystals. The zircon crystals from the meta-sedimentary rocks are older than 1.0 Ga, therefore the $^{207}\text{Pb}/^{206}\text{Pb}$ ages are used to represent the crystallization ages of these zircon crystals.

5.1. Volcanic rock sample from the Second Formation

5.1.1. Sample description

The meta-volcanic rock sample (NOR97-12) is characterized by a porphyroblastic-lepidogranoblastic-mylonitic texture (Fig. 5). The phenocrysts are mainly K-feldspar (15%), plagioclase (5–10%)

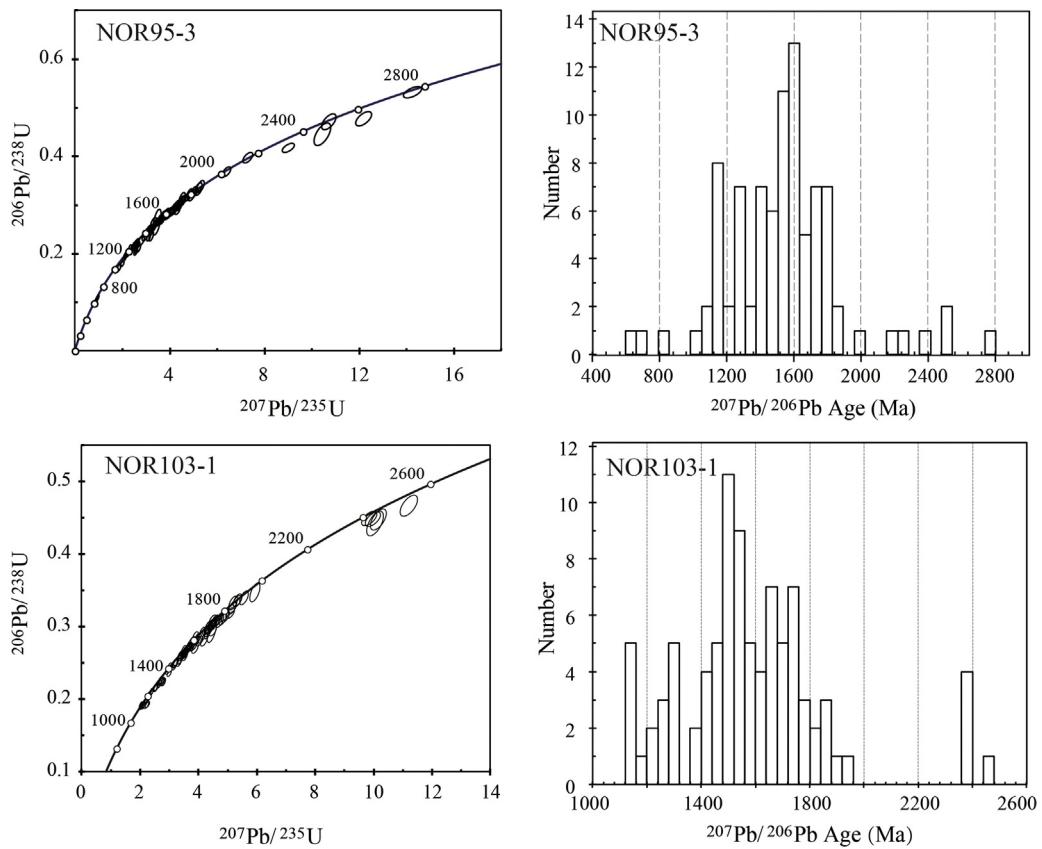


Fig. 9. Concordia diagrams and histograms for the dated detrital zircons from the meta-sedimentary rocks of the Third Formation of the Langshan Group.

and quartz (10%). The matrix (60–65%) is composed of quartz, feldspar and muscovite. The porphyroblastic minerals tend to occur together to form a porphyroblastic banding surrounded by fine-grained quartz, biotite. The texture and mineral assemblages indicate a felsic volcanic rock as the protolith prior to ductile deformation and associated, which have experienced low-grade metamorphism. The mylonitic texture is indicated by foliation and lineation deformed quartz with undulose extinction and elongated muscovite and feldspar crystals formed by low-grade metamorphism.

The cathodoluminescence (CL) images show that the zircon crystals from sample NOR97-12 are transparent and colorless or light brown. The sizes of the zircon grains are between 50 μm and 100 μm in length, with a length-to-width ratio of 1:1–3:1. Most of the zircon crystals have clear oscillatory zonings. Only a few of the zircon grains have inherited cores (Fig. 6).

5.1.2. Age data

The U–Pb data for 31 zircon crystals with oscillatory zoning from the meta-volcanic rock sample (NOR97-12) are listed in Table 1. All of these analyses are concordant within 90–110%. Among them, two analyses (#16 and #28) give much older $^{206}\text{Pb}/^{238}\text{U}$ ages (1263 ± 25 Ma and 1475 ± 22 Ma) than the rest, which are interpreted to be inherited zircon crystals. And another two analyses (#18 and #23) give little younger $^{206}\text{Pb}/^{238}\text{U}$ ages (737 ± 8 Ma and 632 ± 8 Ma). The similar 27 concordant analyses collectively yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 804.1 ± 3.5 Ma ($1\sigma, n=27$, MSWD = 1.3). We interpret this age to be the eruption age of the felsic volcanic rocks in the Second Formation of the Langshan group.

5.2. Detrital zircon U–Pb age compositions of the meta-sedimentary rocks

The detrital zircon grains from the meta-sedimentary rocks of the Langshan Group are mostly $>80 \mu\text{m}$ in length. They are characterized by elongated or stubby shape, with a length-to-width ratio >1.5 . Most of the zircon separates are complete grains with simple zoning patterns. Only a small amount of the zircon separates have irregular zoning patterns such as a thin overgrown margin of possibly metamorphic origin (Fig. 8). We analyzed all of the zircon grains except those with visible fractures and inherited cores.

5.2.1. Sample descriptions and detrital zircon ages of the Third Formation

Both samples from the Third Formation of the Langshan Group (NOR95-3 and NOR103-1) are mylonitic quartzites containing >90% quartz. The porphyroblasts in the samples are coarse-grained quartz with diameter up to 600 μm and undulose extinction. The matrix of both samples is composed of fine-grained quartz.

A total of 96 zircon grains are randomly selected from sample NOR95-3 for zircon U–Pb isotope analysis. The majority of them (90) give concordant ages. Among them, 75 zircon grains give U–Pb ages ranging from 1000 to 1950 Ma with a prominent peak at 1600 Ma and two minor peaks at 1180 Ma and 1800 Ma. Two zircon grains are much older, ~ 2490 Ma. In addition, three other grains from the sample have much younger ages, one has a U–Pb age of ~ 800 Ma and the other two have a U–Pb age of ~ 634 Ma. The age of 810 Ma is similar to the age of the volcanic rock sample (NOR97-12) from the Langshan Group (Fig. 7). The 634 Ma zircon grains are likely derived from cross-contamination during zircon separation

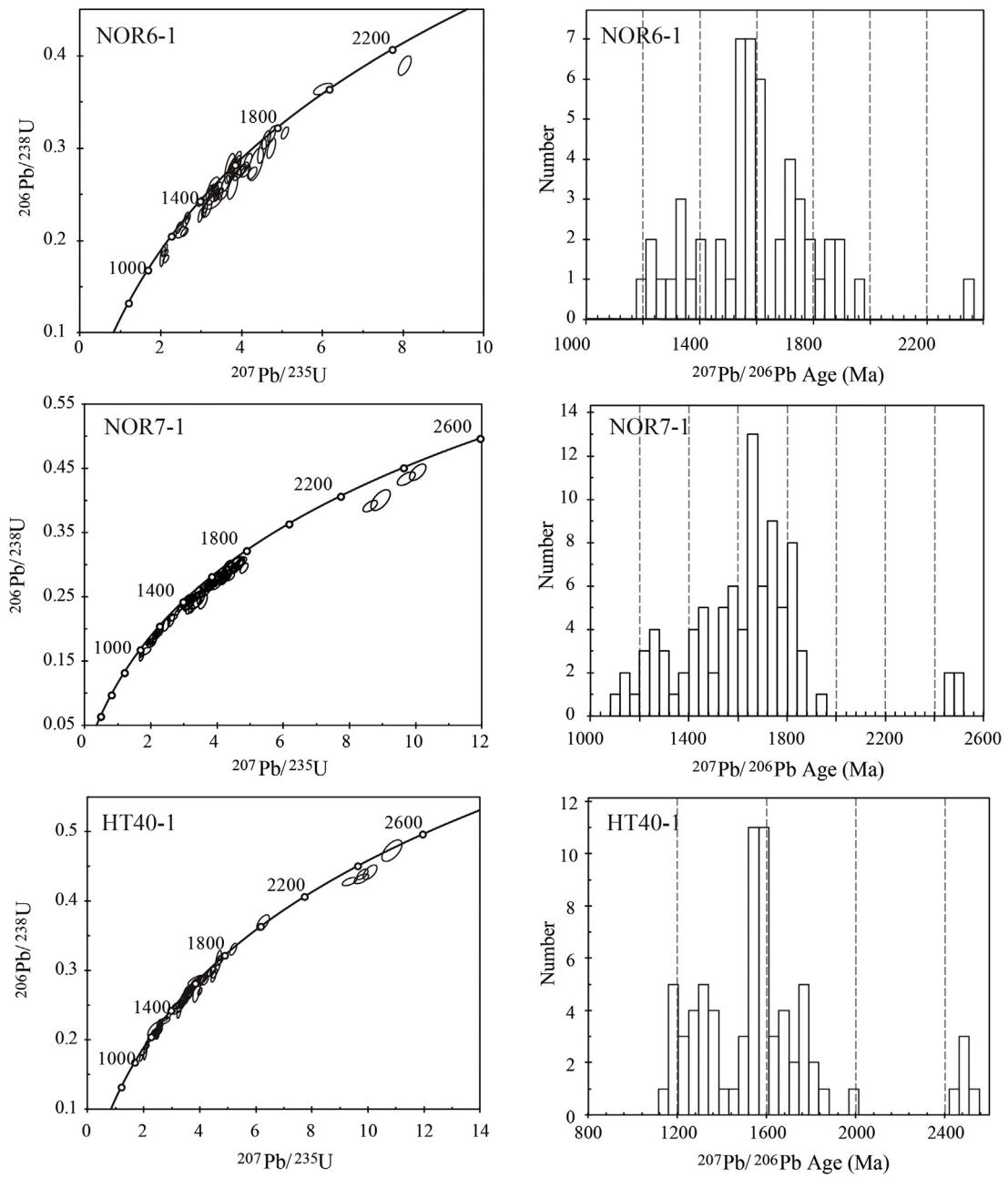


Fig. 10. Concordia diagrams and age distribution patterns of the dated detrital zircons from the meta-sedimentary rocks of the Fourth Formation of the Langshan Group.

because this age is much younger than the deposition age of the sedimentary rock. Thus, the minimum detrital zircon age for this sample (NOR95-3) is 810 Ma (Supplementary data Table 1).

A total of 96 zircons randomly selected from sample NOR103-1 are analyzed for U-Pb isotopes. The majority of the zircon grains (90) give concordant ages from 1122 to 2597 Ma. The results show a prominent peak at 1500 Ma plus several minor peaks at 1140 Ma, 1310 Ma, 1730 Ma, 1880 Ma and 2490 Ma (Fig. 9). The minimum detrital zircon age for this sample (NOR103-1) is 1122 Ma (Supplementary data Table 1).

5.2.2. Sample descriptions and detrital zircon ages of the Forth Formation

Sample NOR6-1 is a garnet bearing two-mica quartz schist with columnar crystalloblastic texture. It is composed of quartz (60%), muscovite (5–10%), biotite (5–10%), garnet (5%) and minor plagioclase. The elongated biotite and muscovite grains are oriented to

form a characteristic schistose texture. The garnet occurs as porphyroclastic grains. A total of 104 zircon grains were randomly selected for U-Pb isotope analysis. Only 37 of them give concordant ages ranging from 1187 to 2342 Ma. The results show a prominent peak at 1590 Ma, two moderate peaks at 1330 Ma and 1720 Ma, and three minor peaks at 1230 Ma, 1880 Ma and 2340 Ma (Fig. 10). The minimum detrital zircon age for this sample (NOR6-1) is 1187 Ma (Supplementary data Table 2).

Sample NOR7-1 is a muscovite-quartzite schist with columnar crystalloblastic texture. It is composed of quartz (>80%) and muscovite (15–20%). The diameter of quartz is <300 μm . The elongated muscovite grains are oriented to form a characteristic schistose texture. A total of 106 zircon grains randomly selected were analyzed for U-Pb isotopes. A significant amount of them (72) give concordant ages varying from 1118 to 2499 Ma. They show a prominent peak at 1660 Ma, two moderate peaks at 1260 Ma and 2480 Ma, and several minor peaks at 1140 Ma, 1460 Ma, 1580 Ma, 1740 Ma, and

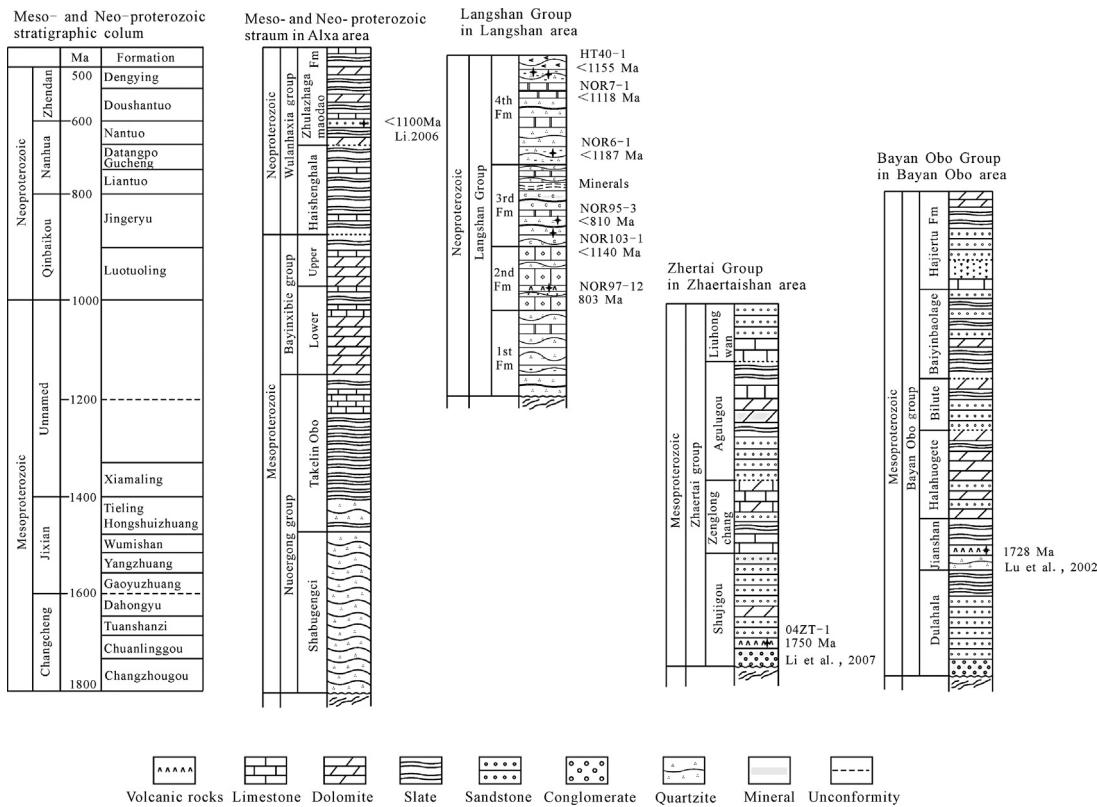


Fig. 11. Stratigraphic and age comparison between the Langshan Group, the Zhaertai Group, the Bayan Obo Group and the Huade Group.

1820 Ma (Fig. 10). The minimum detrital zircon age for this sample (NOR7-1) is 1118 Ma (Supplementary data Table 2).

Sample HT40-1 is a muscovite-quartz schist with columnar crystalloblastic texture. It is composed of quartz (80–85%) and well oriented mica (15–20%). A total of 100 zircons randomly selected were analyzed for U–Pb isotopes. A significant amount of them (74) give concordant ages varying from 1155 to 2523 Ma. The results show a prominent peak at 1580 Ma and several moderate peaks at ~1180 Ma, 1300 Ma, 1760 Ma and 2520 Ma (Fig. 10). The minimum detrital zircon age for this sample (HT40-1) is 1155 Ma (Supplementary data Table 2).

6. Discussion

6.1. Deposition age of the Langshan Group

The minimum detrital zircon U–Pb ages of the 5 meta-sedimentary rock samples from the Third and Fourth Formations of the Langshan are from 810 to 1187 Ma. The weighted mean U–Pb age of comagmatic zircon crystals from the meta-volcanic rock interbedded in the Second Formation is 804.0 ± 3.5 Ma, which is in agreement with the zircon U–Pb ages of 816.9 ± 4.5 Ma and 805 ± 5.0 Ma for the same type of volcanic rocks that occur further to the east within the Second Formation given by Peng et al. (2010). The minimum detrital zircon ages for the meta-sedimentary rocks plus the ages of the comagmatic zircon crystals from the interbedded meta-volcanic rocks indicate that the deposition age of the Langshan group in the Langshan terrane is Neoproterozoic, the same as the deposition age of the Wulanhaxia Group in the northern margin of the Alxa block (Li, 2006).

The “Zhaertai–Bayan Obo–Huade” Mesoproterozoic rift system in the northern margin of the NCC consists of the Zhaertai group, Bayan Obo Group and Huade Group. The deposition ages of these groups have been studied previously. Li et al. (2007) reported a

zircon U–Pb age of 1743 Ma for the mafic volcanic rocks interbedded in the Zhaertai group and a minimum detrital zircon age of 2500 Ma for the associated quartz sandstone (Fig. 11). These data indicate that the deposition age of the Zhaertai group is ~1750 Ma. Lu et al. (2002) obtained a U–Pb age of 1728 ± 5 Ma for a single zircon crystal from the basalt interbedded in the lower part of the Bayan Obo Group. Yang et al. (2012) reported a whole-rock $^{207}\text{Pb}/^{206}\text{Pb}$ isochron age of 1649 ± 45 Ma for the carbonate in the upper part of the Bayan Obo Group. The youngest concordant age of detrital zircon grains from a meta-sandstone sample collected from the base of the Huade Group is 1758 ± 7 Ma (Hu et al., 2009). These data, together with our new data for the Langshan Group, indicate that the Langshan Group is not a part of the Mesoproterozoic “Zhaertai–Bayan Obo–Huade” rift system but rather a younger, Neoproterozoic rift system (Peng et al., 2010) (Fig. 11).

6.2. Comparison of detrital zircon age patterns between the Alxa block and the NCC

The age distributions of detrital zircons from Precambrian sedimentary rocks in different regions in the Alxa block and the NCC are compared in Fig. 12. The detrital zircons from 5 meta-sedimentary rock samples from the Langshan Group show 5 prominent age peaks at 1.35 Ga, 1.6 Ga, 1.75 Ga, 2.1 Ga and 2.5 Ga (Fig. 12a). The zircon crystals from the Paleo- to Neo-proterozoic Longshoushan Group (paragneiss and sandstones) in the southern part of the Alxa block, show 3 age peaks at 1.0 Ga, 2.0 Ga and 2.5 Ga (Fig. 12c) (Tung et al., 2007; Gong et al., 2011, 2014). The detrital zircon crystals from the Neoproterozoic Wulanhaxia Group sandstone in the northern margin of the Alxa block show 2 age peaks of 1.1 Ga and 1.6 Ga (Fig. 12b) (Li, 2006). The detrital zircon crystals from the NCC, including those from the Neoproterozoic sandstone, the Cambrian sandstone and the Ordovician sandstone in the Zhuozishan area of the western NCC (Darby and Gehrels, 2006), the Mesoproterozoic

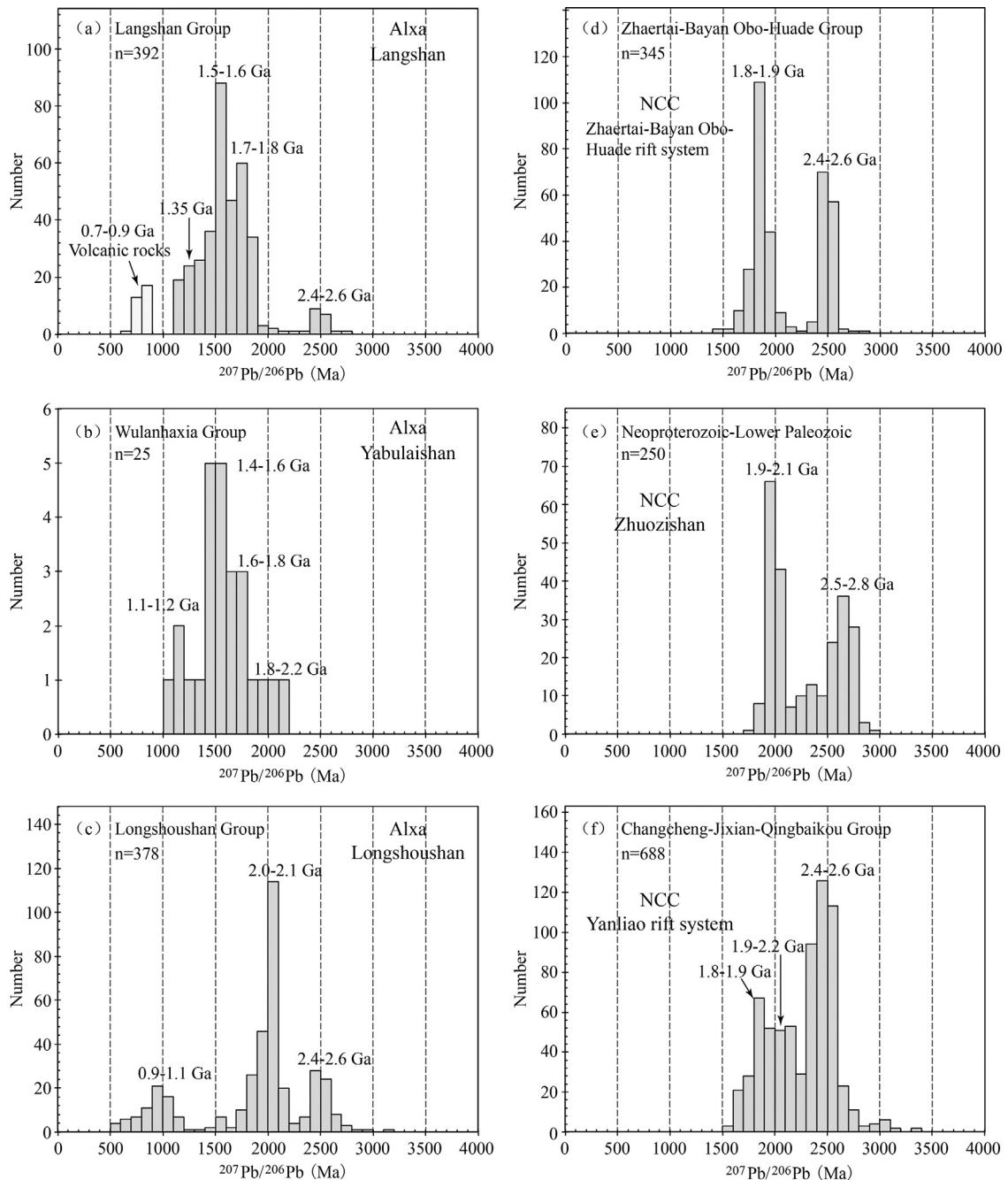


Fig. 12. Comparison of Precambrian detrital zircon U-Pb age patterns between the Alxa block and the NCC.

sandstones of the Bayan Obo Group (Yang et al., 2012) and the Huade Group (Hu et al., 2009) in the northern NCC, and the Meso- to Neo-proterozoic sandstones of the Changcheng-Jixian-Qingbaikou Group in the southeastern NCC (Wan et al., 2011; Ying et al., 2011), show 2 prominent age peaks at 1.8–1.9 Ga and 2.5 Ga (Fig. 12d–f). The older age peaks of the detrital zircons from the Precambrian sedimentary rocks in the Alxa block and the NCC are similar, which indicate that these two blocks have similar history of crustal growth in the Precambrian. The Meso- to Neo-proterozoic detrital zircon ages are absent in the current data sets for the NCC. This is because the deposition ages of the source rocks, i.e., the Changcheng Group and Xiamaling Formation are older than the Mesoproterozoic and Neoproterozoic, respectively (Fig. 12f).

The older and younger age peaks of detrital zircon crystals from the Langshan Group are similar to those for the NCC and the Alxa

block, respectively. Detrital zircons with ages varying from 1.5 to 1.7 Ga are present in the Langshan Group as well as in the NCC but not in the Alxa block based on the current data sets for Precambrian sedimentary rocks. It is possible that these detrital zircon crystals were derived from the igneous rocks in the Mesoproterozoic “Zhaertai-Bayan Obo-Huade” rift system in the northern margin of the NCC.

The Meso- to Neo-Proterozoic detrital zircon crystals are also absent in the Neoproterozoic and early-Paleozoic strata in the Zhuozishan area located in the western margin of the NCC adjacent to the Alxa block. The 1.95 Ga Khondalite belt may have provided most of the detrital materials for the Neoproterozoic and early-Paleozoic sedimentary rocks in the Zhuozishan area. No Meso- to Neo-proterozoic felsic igneous rocks has been found in this Paleoproterozoic orogenic belt. This may explain the lack of detrital

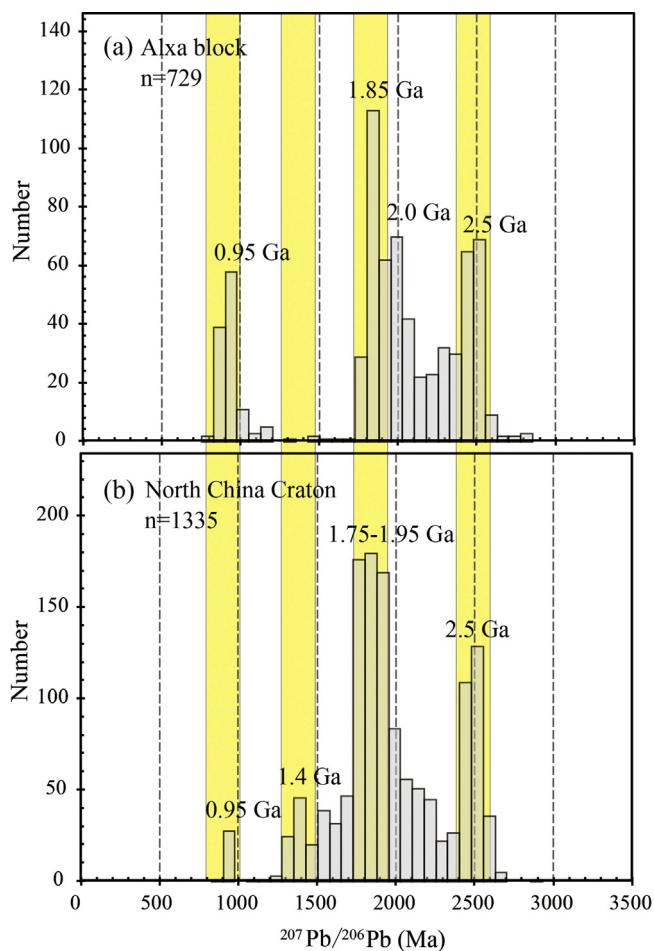


Fig. 13. Comparison of zircon U-Pb ages of igneous rocks in the Alxa block and in the NCC.

zircon crystals with Meso- to Neo-proterozoic ages in the Neo-proterozoic and early-Paleozoic strata in the Zhuozishan area. In contrast, the detrital materials of the Langshan group could have come from the Khondalite belt, the “Zhaertai-Bayan Obo” rift system and the Alxa block, resulting in more complex detrital zircon age patterns.

6.3. Comparison of zircon ages of igneous rocks in the Alxa block and the NCC

In order to determine the geological significance of the detrital zircon age patterns of the Langshan Group and the tectonic relationship between the Alxa block and the NCC in the Precambrian, we have compiled the zircon ages for the igneous rocks in the Alxa block (729 analyses) (Dan et al., 2012; Zhang et al., 2013a,b; Geng and Zhou, 2010) and in the western part of the NCC (1335 analyses) (Zhao et al., 2004a,b; Kroner et al., 2006; Wan et al., 2006a,b, 2013; Li et al., 2007a,b; Gao et al., 2007, 2008; Zhang et al., 2007; Su et al., 2008, 2010; Zhao et al., 2008; He et al., 2009; Yin et al., 2009, 2011; Fan et al., 2010; Li et al., 2009, 2010, 2011; Diwu et al., 2011; Peng et al., 2011a,b; Hu et al., 2013a,b; Liu et al., 2013). The data sets show that the detrital zircon age peaks at 2.5 Ga and 2.1 Ga for the Langshan group are broadly matched by the magmatic zircon age peaks at 2.6–2.4 Ga and 2.1–1.8 Ga for the Alxa block and the NCC (Fig. 13). The magmatic events at 2.6–2.4 Ga are regarded as evidence for the crustal growth from the late-Archean to early-Proterozoic (Kroner et al., 1998) or the cratonization of the NCC in the Neoarchean (Zhai

and Santosh, 2011). The 2.1–1.8 Ga magmatic event is coupled by high pressure-ultra high pressure metamorphism, high temperature metamorphism and crustal partial melting in the Khondalite belt and the Trans-North China orogenic belt (Yin et al., 2009, 2011, 2014; Wan et al., 2013).

The age peaks of 1.6 Ga and 1.75 Ga for the detrital zircon crystals from the Langshan Group are broadly matched by the age peaks of 1.5–1.8 Ga for the zircon crystals from the igneous rocks in the NCC. The corresponding magmatic events have been found in the NCC, such as the rift-related volcanic rocks and mafic dykes, i.e., the Xiong'er volcanic belt in the southern margin of the NCC (He et al., 2009; Zhao et al., 2004a,b), the Dahongyu and Tuanshanzi volcanic belts in the northern margin of the NCC, and the Taihang-Lüliang and Miyun-Beitai mafic dyke swarms in the central part of the NCC (Wang et al., 2004; Peng et al., 2012). Lack of detrital zircon record for these events in the Alxa block can be explained by the presence of the 1.95 Ga khondalite belt between the Alxa block and the NCC.

The 1.35 Ga igneous rocks have only been found in the northern NCC. They occur as diabases and are thought to be related to the breakup of the Columbia supercontinent (Zhang et al., 2009a,b). The detrital zircon crystals with ages close to 1.35 Ga from the Langshan Group may have derived from the associated felsic igneous rocks that are yet to be found in the NCC.

The 0.9–0.8 Ga magmatic event recorded in the Langshan group are also shown by the detrital zircon crystals from the Alxa block and the NCC. The duration of such event appears to overlap the assemblage and breakup of the Rodinia supercontinent at 1.3–0.9 Ga and about 825–740 Ma, respectively (Dalziel, 1991; Hoffman, 1991; Moores, 1991; Li et al., 1999, 2003, 2008). The occurrence of the ~810 Ma felsic volcanic rock in the Langshan Group may be used as evidence for the development of a Neoproterozoic rift in this area. Contemporaneous igneous rocks and gneisses rocks have been found in the Alxa block. Granitic gneisses with zircon U-Pb ages varying from 971 Ma to 845 Ma are present in the Yabulaishan area, the northern part of the Alxa block (Geng et al., 2002; Li, 2006; Tung et al., 2007). Mafic-ultramafic intrusions such as the Hadeng intrusion which has a K-Ar age of 1056 Ma are also present in this area (Wang et al., 1994). In the central part of the Alxa block, a mafic-ultramafic intrusion with Sm-Nd isochron age of 773 ± 11 Ma (Li et al., 2004a,b) and granitoids formed at 921–9041 Ma (Geng and Zhou, 2010, 2011) have been found in the Beidashan and Youqi areas, respectively. In the southern part of the Alxa block, the Jinchuan ultramafic intrusion with a zircon U-Pb age of 830 Ma occurs in the Longshoushan area (Li et al., 2004a,b; Zhang et al., 2010a).

Furthermore, Neoproterozoic igneous rocks have also been found in different parts of the NCC, such as the magmatic events of 1300–1000 Ma and 800–650 Ma in the northern margin of the NCC (Zhai and Liu, 2003; Zhao et al., 2011), the 925–900 Ma mafic dykes in the central and eastern part of the NCC and the northern Korean Peninsula (Peng et al., 2011a,b), felsic magmatism at 1400 Ma and 900–800 Ma inferred from detrital zircon crystals from the eastern NCC (Hu et al., 2012a,b; Zhai and Liu, 2003; Zhai and Santosh, 2011; Zhai, 2011, 2013), the 800–650 Ma mafic dyke swarms in the western part of the NCC (Zhai, 2013). Clearly, both the Alxa block and the NCC were affected by the assembly and breakup of the Rodinia supercontinent (Zhai, 2013).

7. Conclusions

- (1) The Langshan Group in the northeastern margin of the Alxa block formed in Neoproterozoic based on the zircon age of 804.1 ± 3.5 Ma for the meta-volcanic rocks and the minimum detrital zircon ages of 1187–810 Ma for the meta-sedimentary rocks.

- (2) The detrital zircon age patterns indicate that the detrital materials of the Langshan Group came from both the Alxa block and the NCC, supporting the interpretation that the Alxa block and the NCC were together in Neoproterozoic.
- (3) Our new data indicate that the Neoproterozoic rifting occurs across the boundary between the Alxa block and the NCC, which further support the interpretation that these two blocks were together in the Neoproterozoic.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.precamres.2014.08.013>.

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