Discovery of ~4.0 Ga detrital zircons in the Changdu Block, North Qiangtang, Tibetan Plateau

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Using *in situ* zircon dating by LA-ICP-MS and MC-ICP-MS, detrital zircon of 3981 ± 9 Ma age was found in metamorphic rocks of the Ningduo Rock Group, Changdu Block of Northern Qiangtang. This is the oldest age record that has been found in the Qiangtang area. This finding also constitutes the third zircon locality in China with an age older than 3.9 Ga. Thus, the discovery provides new information for the study of Hadean crust. In addition, we found 3.51–3.13 Ga, ~2440 Ma, ~1532 Ma, ~982 Ma and ~618 Ma age peaks from 100 test spots. The younger ages of ~982 Ma and ~618 Ma correspond to the formation of the Rodinian super-continent and the Pan-African event, respectively. These findings suggest a close relationship between these zircons and the Gondwanan super-continent. The age of ~618 Ma defines the lower limit on the deposit time of the protolith for the garnet-mica-quartz schist in the Ningduo Rock Group. Zircons with an age of ~982 Ma generally display a negative $\varepsilon_{\text{Hf}}(t)$ and a two-stage Hf model with concentrated ages around 1933–2553 Ma. This pattern indicates that the source area of the Ningduo Rock Group underwent a significant separation of depleted mantle into the crust during the Paleoproterozoic Era. However, zircons with ages of 2854–3505 Ma also show a negative $\varepsilon_{\text{Hf}}(t)$ and a two-stage Hf model with a concentration of ages around 3784–4316 Ma. These results demonstrate that the source area of the Ningduo Rock Group contains a residual amount of ancient (Hadean) crustal materials. This paper provides new information on the relationship between the basement of the Qiangtang area and the Paleoproterozoic basements of the Gangdese and Himalayan regions, which constrains the northern boundary of Gondwana.

Changdu Block, Ningduo Rock Group, Hadean, detrital zircons, LA-ICP-MS, Hf isotopes

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Exploring the formation and early evolution of the Earth has been an important part of Earth science research. This type of research has involved a series of important scientific studies [1], including identification of when the first continent formed, the nature of this material, and whether recycling between crust and mantle existed during the early evolution of the Earth. Complex and diverse geological processes over time have resulted in a limited distribution of rocks formed during the Hadean (4.56–3.85 Ga) [2,3]. Until now, crustal rocks with age of more than 3.8 Ga only have

been discovered in Greenland [4,5], Canada [6,7], Anshan in China [8–10] and Eastern Antarctica [11–13]. The oldest rocks that have been found on Earth are from the Acasta gneiss of the Wopmay orogenic belt in Canada, and they have been dated to ~4016 Ma [14]. Although there are limited records of rocks surviving from early Earth, abundant ancient zircon residues have been found within younger geologic bodies [15]. After a long exploration, a series of detrital zircons with ages of ≥ 3.8 Ga have been discovered in the northeastern Bavaria region in Germany [16], northern Wyoming, USA [17], the Yilgarn craton of Western Australia [18], the San Francisco craton in Brazil [19], the

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high Himalayan region to the west of Nepal [20], and north of Kazakhstan [21]. Undoubtedly, this information has provided an excellent set of data to investigate the evolution of crustal rocks formed during early Earth.

In recent years, important progress has been made in the search for and study of extremely ancient rock materials in China. Since the discovery of the TTG rocks of 3.8 Ga in the Anshan area at the end of the last century, several detrital zircons with ages of ≥ 3.8 Ga have been reported, including in Qianxi County in the Hebei Province [1,22,23], Pulan County in Tibet [24,25], Yichang in the Hubei Province [26], Liangdang County in the Gansu Province [27], and Pingle-Beiji in southeast Guangdong Province [28]. The discovery of the oldest Chinese zircons of 4.1 Ga in Pulan County in the Himalayan Orogeny, and in Liangdang County in North Qinlin orogenic belt, significantly contributed to research of ancient Earth materials.

Using LA-ICP-MS, we obtained detrital zircon of 3981 ± 9 Ma in the Ningduo Rock Group of the Changdu Block, northern Qiangtang area, Tibetan Plateau. This is the oldest age that has been recorded in the Qiangtang area, the hinterland of Tibet, and is the third oldest zircon suite in China, after the discoveries in Tibet and Qinling. These findings significantly contribute to the study of the formation and evolution of the early crust and for investigating the nature of the basement of Qiangtang.

1 Regional geological setting

The study area is located in the Changdu Block of northern Qiangtang in Tibet, and lies between the Xijinwulan-Jinshajiang and Bangonghu-Nujiang suture zones in western Yushu County, Qinghai Province (Figure 1). The Changdu Block is a narrow, NE-trending belt situated along the south of the Bayankala orogenic belt. Because of the Mesozoic-Cenozoic cover and the fractured dislocation of Precambrian basement rocks toward the NW-SE, they are scattered as faulted blocks, mainly consisting of the Ningduo and the Xionsong rock groups. The "Southwest Regional Stratigraphy" project has provided a revision of Precambrian stratigraphic sequences of this region, and concluded that the Xionsong and Ningduo rock groups are synonymous [29], such that the "Xionsong Rock Group" (named in Mangkang County-Batang County) now belongs in the Ningduo Rock Group. Consequently, the basement of the Changdu Block is composed of only the Ningduo Rock Group, which is distributed mainly in Duocai, Zhiduo County, Qinghai Province; Longbao and Xiaosumang, Yushu County; the Jinshajiang region in western Gongjue County-Mangkang County; and eastern Jiangda County-Batang County on the border between Tibet and Sichuan.

This paper focuses on the Ningduo Rock Group in Longbao (Zanie), Yushu County, Qinghai Province. The Ningduo Rock Group in this area appears as a narrow belt

located between the Xiewu Ophiolite mélangé zone and the Longbao ophiolite mélangé zone, and mainly consists of high-grade greenschist to low-grade amphibolite facies metamorphic rocks, such as biotite plagioclase gneiss, garnet-mica quartz schist, quartzite, granulite with amphibolite schist, and chlorite-amphibole schist. The occurrence of these rock types is at $170^\circ \angle 62^\circ$. The protolith mainly consists of sedimentary clastic rocks, basic-intermediate volcanic rocks, and carbonate rock formations with high maturity. The age of the Ningduo Rock Group has long been disputed. Previous surveys have classified the Qinghai Province into the upper Paleozoic. The 1:200000 regional geological survey [30,31] inferred that the Ningduo Rock Group should be placed in the Paleo-Mesoproterozoic. This suggestion is based on zircon U-Pb ages of 2200 ± 140 Ma from two-mica plagioclase gneiss in Xiariduo, 1870 ± 280 Ma from biotite plagioclase gneiss in the Changkeqing area, and 1780 ± 150 Ma and 1680 ± 309 Ma from gneissic biotite granite in Dasumang and Xiaosumang. However, the 1:250000 regional geological survey of Zhiduo and Qurougaka obtained a single zircon with ages of 709 ± 66 Ma [32] and $835\text{--}915$ Ma [33], which are considered to be the metamorphic age of the Ningduo Rock Group. Based on the above isotopic ages, rock associations, metamorphism, non-layered deformation characteristics, and regional stratigraphic correlations, we tentatively placed the Ningduo Rock Group in the Meso-Neoproterozoic [34].

Two ophiolite mélangé zones extend along the NW-SE portion of the study region. Both are dismembered from the Tongtianhe ophiolite mélangé zone in the 1:250000 regional geological survey of Yushu [35]. Regionally, these are equivalent to part of the Xijinwulan-Jinshajiang suture zone. Following later tectonic events, the Ningduo Rock Group was strongly fractured and foliated, and integrated into a mélangé belt of the Longbao ophiolite in form of rock blocks. The northwest-trending faults are well-developed in this region, and constitute boundaries among different stratal units. A great number of diabase-babbro dykes are found in the northwest. They intruded the epimetamorphic clastic rocks with medium basic to medium acidic volcanic lava and volcanoclastic rocks of the Yiji Formation in the early Devonian.

2 Isotope dating

2.1 Sample collection

The detrital zircons used for isotope dating were collected in the western part of a N-S trending valley, about 45 km away from northwest Yushu County in the Qinghai Province ($33^\circ 14' 27.5''\text{N}$, $96^\circ 35' 24''\text{E}$, 4520 m). The sample collected from the Ningduo Rock Group was a garnet-mica quartz schist (sample No. 07ND-1, about 28 kg). It was pale gray, mainly with a scaly granular texture, schistose structure, crumpled deformation, and kink phenomenon

Figure 1 Schematic map of the Longbao area in Yushu County, Changdu Block, North Qiangtang (from 2004 geological survey map at a scale of 1:250000, Yushu sheet). 1, Quaternary; 2, Tuotuohe Formation of Paleogene age; 3, Batang Group of Late Triassic age; 4, Bolila Formation of Late Triassic age; 5, Jilong Formation of Middle Triassic age; 6, Xiewu Ophiolite mélange of Triassic age; 7, Bayankalashan Group of Middle-Late Triassic age; 8, Hantaishan Group of Permian-Triassic age; 9, Gadikao Formation of Permian age; 10, Nuoribagaribao Formation of Permian age; 11, Longbao Ophiolite mélange of Carboniferous-Permian age; 12, Yiji Formation of early Devonian age; 13, Ningduo Rock Group of Meso-Neoproterozoic age; 14, Triassic quartz diorite; 15, Gabbro-diorite; 16, faults or inferred faults; 17, ductile shear zones; 18, road; 19, study area; 20, sampling locations and control numbers; ① suture of Kangxiwa-Muzitage-Maqin-Mianxian-Lueyang; ② suture of Xijinwulan-Jinshajiang; ③ suture of Bangonghu-Nujiang; ④ suture of Yaluzangbujiang.

developed in the mica minerals. The minerals included mainly biotite (24%±), muscovite (20%±), quartz (45%±), and a small amount of garnet (10%±) and zircon (<1%). The protolith consisted of clastic sedimentary rocks.

2.2 Analytical methods

The selection of a single mineral zircon was accomplished in the Langfang Laboratory, Hebei Bureau of Geology and Mineral Resources, Minister of Land and Resources. The sample (07ND-1) was crushed to pass through a 20–30 mesh. About 180 grains of zircon were obtained after flotation and magnetic separation. A total of 120 zircons with no

cracks or inclusions were selected under a binocular microscope for further tests. These samples were embedded into epoxy and polished to expose the internal structures of zircon grains. Before zircon U-Pb dating with LA-ICP-MS and MC-ICP-MS, reflected and transmitted light microscopy and cathodoluminescence (CL) image analyses were undertaken.

Zircon CL images were taken at the State Key laboratory of Continental Dynamics, Northwest University. The micrographs of the internal structures of zircons were produced with a Cathode-fluorescent spectrometer (Mono CL3+) manufactured by Gatan in the United States.

The zircon U-Pb and Lu-Hf isotopic compositions were

analyzed at the State Key Laboratory of Continental Dynamics, Northwest University. The test spots from 07ND-1-01 to 07ND-1-60 were undertaken by LA-ICP-MS, using 30 μm laser beam ablation. However, the spots from 07ND-1-1b to 07ND-1-68b were tested by MC-ICP-MS, with 44 μm laser beam ablation. The isotope ratios and element contents were calculated with Glitter software (Ver4.0, Macquarie University). According to the method of Andersen [36], isotopic ratio corrections were conducted to eliminate the effects of common lead. Based on the average crustal Pb isotopic composition given by Stacey, we corrected the isotopic ratio and common lead. Concordia age calculations and mapping were achieved with Isoplot (Ver3.0) [37]. Additional detailed equipment characteristics and analytical

procedures are found in [38–40].

2.3 Zircons

Most zircons collected from the garnet-mica quartz schist (07ND-1) in the Ningduo Rock Group were rounded (some of the defects may have been caused by mechanical damage during sample grinding), with great difference in size (60–180 μm) and color variations (from light brown, light smoky gray, light yellow, light pink to colorless). These variations indicate a multi-source for these detrital zircons.

From the CL images, it is clear that the majority of the zircons appeared rounded and had developed internal zonation (Figure 2), a characteristic of origination from a magma

Figure 2 CL images of the detrital zircons with ages (a) >3100 Ma and (b) <3100 Ma. The circles indicate the test spots, the unit of the measured age is Ma, using $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ for age measurements >1000 Ma and <1000 Ma.

source. A few zircons (14b, 26b, 27b, 68b) developed fuzzy and wide internal zonation, which may have been caused by later alterations. Individual zircons (2b, 42b, 66b) had mottled structures, and some (13, 50b, 44b) had a kernel. Some zircons with ages >900 Ma (5, 25, 26, 47, 50, 44b, 66b) were surrounded by dark overgrowths, revealing that they never underwent strong tectono-thermal events. The No. 49 (Figure 2(a)) zircon appeared rounded and showed a well-developed core, mantle and rim structure, which indicates multi-growth.

2.4 Zircon U-Pb dating

Of the 128 total test spots for the detrital zircons collected from the garnet-mica quartz schist of the Ningduo Rock Group, 28 spots (4, 7, 28, 30, 35, 39, 40, 46, 48, 53, 57, 59, 3b, 6b, 13b, 17b, 24b, 28b, 29b, 32b, 33b, 39b, 41b, 46b, 51b, 53b, 54b, 67b) were rejected because of the over proportion value of ^{204}Pb and low concordia degree (including <90 and >110). Thus, 100 valid test spots remained (Table 1).

There were a few ancient detrital zircons in the garnet-mica quartz schist of the Ningduo Rock Group (07ND-1), and the oldest zircon (No. 49) appeared with a core-mantle-rim structure. The $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3981 ± 9 Ma was tested in the core. The test spot was located below and close to the concordia line in the graph (Figure 3(a)), and the concordia degree was 94, which implies slight loss of radiogenic lead. In addition, there were four ancient $^{207}\text{Pb}/^{206}\text{Pb}$ ages of the detrital zircons: (3505 ± 18 – 3127 ± 10 Ma [No. 22b, 13, 50b, 50]).

The zircon U-Pb concordia diagram (Figure 3(a)) and the chart of age frequency distribution (Figure 3(b)) showed that the concordia ages concentrate in four groups: 1200–850 Ma, with a peak age of about 982 Ma. Most of the test spots in this group were located in or adjacent to the concordia line, and most of the zircons in this group were rounded, and had developed internal oscillatory zonation (Figure 2(b)), with higher Th/U ratios (generally in 0.31–4.67). This information suggests that these zircons came from a magma source that experienced the Grenville tec-

tono-magmatic events. Another $^{206}\text{Pb}/^{238}\text{U}$ age group was 700–530 Ma, and the peak age was ~618 Ma. These samples had rounded to angular zircons with developing zonation (Figure 2(b)), and higher Th/U ratios (0.38–5.92). In addition, the $^{207}\text{Pb}/^{206}\text{Pb}$ ages were found to be around 2600–2300 Ma and 1700–1400 Ma, and the age peaks were ~2440 Ma and ~1532 Ma. These zircons were rounded, had wide developing internal zonation, and higher Th/U ratios (0.33–1.23 and 0.23–2.50). From these results, it can be concluded that these zircons came from a source that experienced tectono-magmatic events occurring about 618, 2440 and 1532 Ma BP.

2.5 Hf isotopes

There were 68 test spots obtained for the Lu-Hf isotope test on zircons from the garnet-mica quartz schist of the Ningduo Rock Group. A total of 18 spots (3b, 5b, 6b, 13b, 17b, 23b, 24b, 28b, 29b, 32b, 33b, 39b, 41b, 46b, 51b, 53b, 54b, 67b) were rejected because of low confidence in the data caused by low Hf contents. Thus, 50 valid test spots remained (Table 2). The low $^{176}\text{Lu}/^{177}\text{Hf}$ ratio (mostly <0.002) in all zircons showed that there was lower accumulation of radiogenic Hf after their crystallization. The data on the $^{176}\text{Hf}/^{177}\text{Hf}$ ratios can be divided into four groups (Figure 4(a)). Firstly, zircons with ages concentrating around ~2440 Ma show low $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (0.280456–0.281269) and negative $\varepsilon_{\text{Hf}}(t)$ (–3.2 to –25.6). The two-stage model ages $T_{\text{DM}2}$ (3039–4584 Ma) were all greater than their crystal ages. Secondly, zircons with ages around 1532 Ma also displayed low $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (0.281313–0.281826), and their $\varepsilon_{\text{Hf}}(t)$ (–0.4 to –18.4) were all negative except for one, 0.7. The two-stage model ages $T_{\text{DM}2}$ (2296–2284 Ma) were all greater than their crystal ages. Thirdly, zircons formed during Grenville time had high $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (0.281406–0.282441). The $\varepsilon_{\text{Hf}}(t)$ and the two-stage model ages $T_{\text{DM}2}$ yielded 27.9 to 9.8 and 1234 to 3533 Ma. Fourthly, zircons with ages concentrated around ~618 Ma revealed low $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (0.281637–0.282023) and negative $\varepsilon_{\text{Hf}}(t)$ (–13.0 to –32.4). The two-stage model ages $T_{\text{DM}2}$ yielded

Figure 3 Concordia graph (a) and frequency chart (b) for detrital zircons in the garnet-mica quartz schist of the Ningduo Rock Group.

Table 1 Isotopic LA-ICP-MS and MC-ICP-MS ages of detrital zircons from garnet-mica quartz schist (07ND-1) in the Ningduo Rock Group, Changdu Block, northern Qiangtang

Sample No.	Isotopic ratios						Isotopic age (Ma)						Isotopic contents (x10 ⁻⁶)						Th/U concordance (%)					
	²⁰⁷ Pb/ ²⁰⁶ Pb			²⁰⁶ Pb/ ²³⁸ U			²⁰⁸ Pb/ ²³² Th			²⁰⁷ Pb/ ²³⁵ U			²⁰⁴ Pb			²⁰⁶ Pb				²⁰⁷ Pb			²³⁸ U	
	ratio	1σ	ratio	1σ	ratio	1σ	ratio	1σ	ratio	1σ	ratio	1σ	age	1σ	age	1σ	age	1σ		age	1σ	age		1σ
07ND-1-01	0.1080	0.0012	4.678	0.057	0.3142	0.0036	0.0805	0.0009	1765	10	1763	10	1761	18	1565	16	28.63	2586.18	2051.16	2468.97	8234.79	1027.05	8.02	100
07ND-1-02	0.0728	0.0009	1.891	0.024	0.1884	0.0022	0.0537	0.0006	1008	11	1078	8	1113	12	1058	11	<12.58	1027.30	484.09	583.08	3219.89	688.90	4.67	110
07ND-1-03	0.1533	0.0018	9.429	0.117	0.4459	0.0051	0.1198	0.0013	2383	9	2381	11	2377	23	2288	24	<12.38	650.14	578.23	534.01	1424.29	186.43	7.64	100
07ND-1-05	0.0946	0.0011	3.250	0.040	0.2492	0.0028	0.0771	0.0009	1519	10	1469	10	1434	15	1501	16	10.20	909.86	415.51	259.72	1194.34	478.12	2.50	94
07ND-1-06	0.0634	0.0008	1.062	0.014	0.1215	0.0014	0.0404	0.0004	721	12	735	7	739	8	800	9	<7.40	578.43	152.62	271.68	2554.82	638.08	4.00	101
07ND-1-08	0.0600	0.0007	0.833	0.011	0.1008	0.0012	0.0300	0.0003	620	13	615	6	619	7	597	7	11.22	534.43	117.86	115.79	1540.02	727.60	2.12	101
07ND-1-09	0.0570	0.0007	0.675	0.009	0.0859	0.0010	0.0257	0.0003	493	13	524	6	531	6	513	6	9.16	451.77	90.89	268.42	4431.38	748.22	5.92	101
07ND-1-10	0.0673	0.0008	1.278	0.016	0.1377	0.0016	0.0389	0.0004	847	11	836	7	832	9	772	8	35.86	2303.00	512.62	687.94	7304.20	2347.07	3.11	100
07ND-1-11	0.0942	0.0011	3.339	0.041	0.2569	0.0029	0.0762	0.0008	1513	10	1490	10	1474	15	1484	16	10.68	1917.57	522.82	367.55	2075.77	1082.35	1.92	97
07ND-1-12	0.0658	0.0008	1.150	0.015	0.1268	0.0015	0.0384	0.0004	800	12	777	7	769	8	762	8	<3.59	430.19	78.75	172.69	1954.39	497.40	3.93	99
07ND-1-13	0.2961	0.0033	28.925	0.352	0.7084	0.0080	0.1662	0.0018	3450	8	3451	12	3452	30	3108	32	<3.65	4101.39	3255.15	238.48	629.68	857.77	0.73	100
07ND-1-14	0.0772	0.0009	1.541	0.019	0.1447	0.0016	0.0422	0.0005	1126	11	947	8	871	9	835	9	13.14	1278.19	255.38	335.29	3520.18	1322.28	2.66	92
07ND-1-15	0.0673	0.0010	0.878	0.013	0.0947	0.0011	0.0390	0.0004	846	15	640	7	583	6	773	9	<3.28	165.67	27.90	76.68	877.52	264.74	3.31	91
07ND-1-16	0.0711	0.0009	1.583	0.020	0.1615	0.0018	0.0459	0.0005	961	12	964	8	965	10	906	10	8.69	1072.93	179.63	345.18	3404.38	1026.63	3.32	100
07ND-1-17	0.0700	0.0010	1.551	0.023	0.1606	0.0019	0.0453	0.0005	929	14	951	9	960	10	896	10	<3.35	357.51	57.29	97.50	978.82	347.51	2.82	101
07ND-1-18	0.0734	0.0009	1.903	0.024	0.1880	0.0021	0.0534	0.0006	1025	11	1082	8	1111	12	1052	11	3.99	1124.39	183.72	200.43	1716.06	942.67	1.82	108
07ND-1-19	0.0622	0.0008	0.950	0.012	0.1108	0.0013	0.0321	0.0004	681	12	678	6	677	7	639	7	5.49	784.15	105.80	62.37	892.21	1127.03	0.79	100
07ND-1-20	0.0660	0.0008	1.039	0.014	0.1141	0.0013	0.0401	0.0005	806	12	723	7	697	7	795	9	6.56	665.92	92.97	87.08	1001.85	938.44	1.07	96
07ND-1-21	0.0765	0.0010	2.167	0.030	0.2053	0.0023	0.0580	0.0007	1109	12	1170	10	1204	13	1139	13	<2.39	257.02	38.84	63.35	510.46	207.37	2.46	109
07ND-1-22	0.0889	0.0011	2.874	0.037	0.2345	0.0027	0.0711	0.0008	1401	11	1375	10	1358	14	1388	15	11.78	739.43	127.02	101.36	668.48	527.27	1.27	97
07ND-1-23	0.0723	0.0009	1.785	0.023	0.1791	0.0020	0.0524	0.0006	994	12	1040	8	1062	11	1032	12	9.85	632.10	86.56	48.65	436.87	595.93	0.73	107
07ND-1-24	0.0709	0.0008	1.771	0.022	0.1810	0.0020	0.0451	0.0005	955	12	1035	8	1073	11	891	10	2.96	1532.93	201.98	97.57	1021.29	1443.26	0.71	104
07ND-1-25	0.1185	0.0014	4.177	0.053	0.2556	0.0029	0.0993	0.0011	1544	55	1475	20	1427	16	1418	16	<2.00	944.71	204.10	81.21	386.85	636.02	0.61	92
07ND-1-26	0.0715	0.0009	1.661	0.022	0.1685	0.0019	0.0460	0.0005	972	12	994	8	1004	11	910	10	<1.91	467.89	58.82	45.85	470.53	482.82	0.97	103
07ND-1-27	0.0838	0.0011	2.226	0.031	0.1926	0.0022	0.0546	0.0006	1289	12	1189	10	1135	12	1074	12	<1.75	181.42	26.03	85.32	758.77	171.16	4.43	95
07ND-1-29	0.0690	0.0009	1.631	0.021	0.1714	0.0019	0.0486	0.0006	899	12	982	8	1020	11	958	11	5.32	998.90	115.36	37.56	370.21	1049.69	0.35	104
07ND-1-31	0.1069	0.0014	4.139	0.055	0.2807	0.0032	0.0776	0.0009	1748	11	1662	11	1595	16	1511	17	<1.75	333.29	56.23	65.45	406.32	221.60	1.83	91
07ND-1-32	0.0724	0.0009	1.883	0.025	0.1887	0.0021	0.0475	0.0006	996	12	1075	9	1114	12	938	11	<1.91	487.30	54.04	25.65	259.15	481.84	0.54	104
07ND-1-33	0.0738	0.0010	1.540	0.021	0.1514	0.0017	0.0462	0.0005	1035	12	946	8	909	10	912	10	4.18	441.98	49.72	53.23	558.21	555.83	1.00	96
07ND-1-34	0.0683	0.0009	1.253	0.017	0.1331	0.0015	0.0403	0.0005	876	13	825	8	805	9	799	9	3.22	505.41	52.31	60.17	721.95	727.40	0.99	98
07ND-1-36	0.0706	0.0009	1.588	0.022	0.1630	0.0018	0.0457	0.0005	947	13	965	8	973	10	903	10	<1.47	467.46	48.27	33.32	353.74	563.39	0.63	101
07ND-1-37	0.1038	0.0013	3.970	0.053	0.2773	0.0031	0.0726	0.0009	1694	11	1628	11	1578	16	1417	17	<1.66	1124.78	171.20	27.71	183.86	803.14	0.23	93
07ND-1-38	0.0786	0.0011	1.762	0.025	0.1625	0.0019	0.0457	0.0005	1163	13	1032	9	971	10	902	10	1.84	190.55	21.41	42.34	450.90	234.19	1.93	94
07ND-1-41	0.0581	0.0009	0.761	0.012	0.0950	0.0011	0.0290	0.0004	533	16	575	7	585	6	577	7	<1.18	215.13	16.95	40.90	689.26	471.03	1.46	102
07ND-1-42	0.0700	0.0009	1.599	0.022	0.1657	0.0019	0.0431	0.0005	929	13	970	8	988	10	853	10	<0.88	884.03	83.14	34.89	395.19	1119.24	0.35	102
07ND-1-43	0.0779	0.0010	2.182	0.030	0.2030	0.0023	0.0565	0.0007	1145	12	1175	10	1191	12	1112	13	<1.00	646.25	67.02	68.84	595.02	672.95	0.88	104
07ND-1-44	0.0620	0.0010	0.773	0.013	0.0904	0.0010	0.0255	0.0003	675	17	581	7	558	6	509	6	<1.31	167.08	13.66	32.98	632.77	393.98	1.61	96
07ND-1-45	0.0764	0.0011	2.140	0.032	0.2031	0.0023	0.0569	0.0007	1106	14	1162	10	1192	12	1118	14	<0.97	227.35	22.69	15.91	136.83	240.38	0.57	108

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Sample No.	Isotopic ratios										Isotopic age (Ma)										Isotopic contents (×10 ⁻⁶)					Th/U concordc (%)
	²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U		²⁰⁸ Pb/ ²³² Th		²⁰⁶ Pb/ ²³² Th		²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U		²⁰⁸ Pb/ ²³² Th		²⁰⁶ Pb		²⁰⁷ Pb		²³⁸ U			
	ratio	1σ	ratio	1σ	ratio	1σ	ratio	1σ	ratio	1σ	age	1σ	age	1σ	age	1σ	age	1σ	age	1σ	age	1σ	age	1σ		
07ND-1-47	0.0693	0.0010	1.500	0.022	0.1570	0.0018	0.0421	0.0005			908	14	930	9	940	10	833	10	<1.05	231.17	20.40	18.38	214.10	323.70	0.66	101
07ND-1-49	0.4195	0.0056	45.785	0.624	0.7915	0.0089	0.1847	0.0022			3981	9	3905	14	3758	32	3425	38	1.41	2899.48	1523.75	176.29	467.96	817.51	0.57	94
07ND-1-50	0.0918	0.0013	2.384	0.034	0.1883	0.0021	0.0651	0.0008			1172	63	1121	19	1095	12	1090	12	23.66	744.97	95.43	91.42	602.97	885.39	0.68	93
07ND-1-51	0.1047	0.0015	4.052	0.058	0.2807	0.0032	0.0873	0.0011			1640	46	1610	17	1588	17	1583	17	1.47	388.53	49.42	29.41	165.23	318.25	0.52	97
07ND-1-52	0.0774	0.0012	1.108	0.018	0.1039	0.0012	0.0407	0.0006			760	64	657	13	627	7	623	7	<1.10	132.78	12.39	9.33	112.64	295.99	0.38	95
07ND-1-54	0.0780	0.0011	1.947	0.028	0.1809	0.0020	0.0563	0.0007			1108	48	1082	13	1070	11	1068	11	4.31	625.68	58.07	34.96	304.82	812.84	0.38	97
07ND-1-55	0.2411	0.0034	18.816	0.266	0.5661	0.0064	0.1437	0.0018			3127	10	3032	14	2892	26	2713	32	<0.80	635.70	181.01	39.45	134.87	265.89	0.51	92
07ND-1-56	0.0878	0.0013	2.877	0.043	0.2378	0.0027	0.0681	0.0009			1377	13	1376	11	1375	14	1331	16	<1.07	407.59	41.69	42.80	308.83	411.66	0.75	100
07ND-1-58	0.0710	0.0010	1.466	0.022	0.1497	0.0017	0.0440	0.0006			958	14	916	9	899	9	871	11	<0.95	425.18	34.75	18.97	211.67	692.06	0.31	98
07ND-1-60	0.0760	0.0011	1.878	0.028	0.1792	0.0020	0.0479	0.0006			1096	14	1073	10	1062	11	945	12	0.80	447.46	38.62	32.25	323.61	610.96	0.53	97
07ND-1-1b	0.0816	0.0010	1.795	0.020	0.1596	0.0014	0.0665	0.0007			1236	24	1044	7	955	8	1301	13	41.85	372.03	69.62	51.30	179.24	749.17	0.24	91
07ND-1-2b	0.1591	0.0020	9.271	0.106	0.4227	0.0039	0.1374	0.0015			2446	21	2365	10	2273	18	2602	27	3.10	163.83	33.67	18.62	87.99	120.95	0.73	93
07ND-1-4b	0.0779	0.0011	2.035	0.028	0.1894	0.0018	0.0569	0.0007			1145	29	1127	9	1118	10	1118	13	2.06	92.00	9.22	8.15	90.35	151.52	0.60	98
07ND-1-5b	0.0781	0.0010	1.945	0.022	0.1807	0.0016	0.0590	0.0006			1149	25	1097	8	1071	9	1160	12	1.32	193.87	19.61	16.59	173.33	326.90	0.53	93
07ND-1-7b	0.0703	0.0008	1.654	0.018	0.1707	0.0015	0.0500	0.0005			937	24	991	7	1016	8	987	10	1.56	477.07	43.69	31.10	389.35	866.35	0.45	108
07ND-1-8b	0.0704	0.0008	1.598	0.017	0.1648	0.0015	0.0490	0.0005			939	24	970	7	983	8	967	10	1.71	450.25	41.14	30.48	388.18	844.21	0.46	101
07ND-1-9b	0.1020	0.0012	4.031	0.043	0.2868	0.0026	0.0852	0.0010			1660	22	1640	9	1625	13	1652	19	1.70	343.31	45.89	6.94	52.06	357.20	0.15	98
07ND-1-10b	0.0962	0.0011	3.756	0.040	0.2833	0.0025	0.0803	0.0008			1552	22	1584	9	1608	13	1562	15	1.49	487.32	61.09	39.08	306.34	540.22	0.57	104
07ND-1-11b	0.0800	0.0010	2.211	0.026	0.2006	0.0018	0.0605	0.0007			1197	25	1185	8	1179	10	1187	12	2.00	182.57	19.00	16.76	168.20	275.67	0.61	98
07ND-1-12b	0.0779	0.0010	2.148	0.025	0.2002	0.0018	0.0574	0.0006			1143	25	1165	8	1176	10	1128	12	1.56	204.06	20.66	13.59	143.67	308.67	0.47	103
07ND-1-14b	0.1620	0.0019	10.243	0.106	0.4589	0.0041	0.1219	0.0012			2476	19	2457	10	2435	18	2325	22	2.08	1410.02	278.26	71.59	374.99	1084.95	0.35	98
07ND-1-15b	0.0706	0.0010	1.291	0.017	0.1327	0.0012	0.0395	0.0004			946	29	842	8	803	7	782	9	1.37	170.44	16.29	17.34	267.65	399.03	0.67	95
07ND-1-16b	0.0669	0.0008	0.998	0.011	0.1082	0.0010	0.0384	0.0004			834	25	703	6	663	6	761	8	6.86	655.95	60.86	24.00	295.23	1780.24	0.17	94
07ND-1-18b	0.0754	0.0010	1.841	0.023	0.1772	0.0016	0.0599	0.0007			1079	26	1060	8	1051	9	1175	14	1.35	200.16	19.60	8.64	92.26	354.52	0.26	97
07ND-1-19b	0.0715	0.0009	1.549	0.018	0.1573	0.0014	0.0544	0.0006			971	26	950	7	942	8	1070	11	1.54	275.96	25.51	23.95	274.24	542.42	0.51	99
07ND-1-20b	0.0917	0.0012	3.329	0.039	0.2634	0.0024	0.0765	0.0008			1461	24	1488	9	1507	12	1490	16	1.56	231.92	27.43	22.02	182.54	287.95	0.63	103
07ND-1-21b	0.0758	0.0010	1.772	0.021	0.1697	0.0016	0.0598	0.0007			1089	26	1035	8	1010	9	1175	13	3.79	413.04	39.85	27.66	434.39	823.55	0.53	93
07ND-1-22b	0.3068	0.0036	30.082	0.320	0.7113	0.0065	0.1762	0.0021			3505	18	3490	10	3463	25	3281	35	1.84	1536.12	610.09	10.91	38.74	674.70	0.06	99
07ND-1-23b	0.1535	0.0020	9.685	0.117	0.4578	0.0044	0.1385	0.0015			2385	22	2405	11	2430	19	2622	27	1.03	314.93	58.49	45.24	228.10	295.87	0.77	102
07ND-1-25b	0.0741	0.0011	1.772	0.025	0.1736	0.0017	0.0557	0.0007			1043	30	1035	9	1032	9	1096	13	1.54	111.59	10.66	10.66	118.57	198.95	0.60	99
07ND-1-26b	0.1647	0.0019	10.819	0.118	0.4765	0.0044	0.1747	0.0019			2505	20	2508	10	2512	19	3255	33	9.05	1337.01	282.27	36.17	136.08	882.87	0.15	100
07ND-1-27b	0.0969	0.0014	3.551	0.047	0.2659	0.0026	0.0788	0.0009			1565	26	1539	11	1520	13	1534	17	1.47	116.68	14.55	14.73	116.34	136.20	0.85	97
07ND-1-30b	0.1036	0.0013	4.248	0.049	0.2976	0.0028	0.0863	0.0009			1689	22	1683	9	1680	14	1673	17	1.70	454.76	60.62	81.35	580.11	467.17	1.24	99
07ND-1-31b	0.0744	0.0010	1.726	0.022	0.1682	0.0016	0.0612	0.0008			1053	27	1018	8	1002	9	1201	16	1.39	320.83	31.39	8.95	94.70	644.92	0.15	95
07ND-1-34b	0.0950	0.0016	3.528	0.056	0.2695	0.0027	0.0807	0.0010			1528	31	1534	13	1538	14	1568	19	<1.25	82.79	10.39	13.65	109.90	105.91	1.04	101
07ND-1-35b	0.0971	0.0012	3.805	0.044	0.2842	0.0027	0.0842	0.0009			1569	23	1594	9	1613	13	1633	17	1.75	765.56	95.79	48.19	351.69	825.54	0.43	103
07ND-1-36b	0.0667	0.0011	1.391	0.021	0.1514	0.0015	0.0455	0.0006			827	33	885	9	909	8	900	11	1.36	104.24	8.93	10.12	139.25	217.27	0.64	103
07ND-1-37b	0.0663	0.0010	0.961	0.014	0.1052	0.0010	0.0385	0.0005			814	32	684	7	645	6	764	9	4.94	171.89	18.04	23.63	296.01	495.23	0.60	94
07ND-1-38b	0.0714	0.0019	1.654	0.043	0.1679	0.0019	0.0605	0.0012			970	53	991	16	1001	11	1187	23	<1.40	21.02	2.10	1.74	16.17	42.50	0.38	103

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Sample No.	Isotopic ratios						Isotopic age (Ma)						Isotopic contents (×10 ⁻⁶)						Th/U concordance (%)					
	²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U		²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U		²⁰⁴ Pb		²⁰⁶ Pb		²⁰⁷ Pb			²³² Th		²³⁸ U		
	ratio	1σ	ratio	1σ	ratio	1σ	age	1σ	age	1σ	age	1σ	age	1σ	age	1σ	age	1σ		age	1σ	age	1σ	
07ND-1-40b	0.0713	0.0011	1.800	0.026	0.1831	0.0018	0.0526	0.0007	966	30	1046	9	1084	10	1036	12	<1.45	98.10	9.09	11.00	126.47	159.83	0.79	104
07ND-1-42b	0.1696	0.0022	12.912	0.164	0.5521	0.0054	0.1455	0.0017	2554	22	2673	12	2834	22	2745	31	<2.44	166.15	36.38	20.61	85.37	87.99	0.97	110
07ND-1-43b	0.1567	0.0021	10.399	0.135	0.4812	0.0047	0.1358	0.0016	2421	23	2471	12	2533	21	2573	29	<1.36	145.23	29.02	20.34	91.23	95.15	0.96	105
07ND-1-44b	0.1627	0.0023	11.342	0.156	0.5054	0.0051	0.1372	0.0017	2484	24	2552	13	2637	22	2598	30	1.43	98.04	20.49	16.51	74.66	60.85	1.23	106
07ND-1-45b	0.0679	0.0011	1.233	0.020	0.1318	0.0013	0.0399	0.0005	865	34	816	9	798	8	790	10	<1.46	77.81	6.66	9.04	141.22	184.31	0.77	98
07ND-1-47b	0.0596	0.0011	0.859	0.016	0.1046	0.0011	0.0319	0.0004	588	41	630	9	642	6	635	8	<1.29	55.98	4.29	7.41	144.06	167.24	0.86	102
07ND-1-48b	0.0733	0.0012	1.705	0.028	0.1688	0.0017	0.0542	0.0007	1021	34	1010	10	1005	9	1066	14	1.85	112.66	10.65	13.33	160.86	253.76	0.63	98
07ND-1-49b	0.1045	0.0014	4.079	0.053	0.2832	0.0028	0.0941	0.0011	1705	25	1650	11	1608	14	1818	21	1.67	320.05	42.83	32.54	212.70	353.31	0.60	94
07ND-1-50b	0.2542	0.0033	23.882	0.297	0.6812	0.0066	0.1717	0.0021	3211	20	3264	12	3349	25	3203	35	1.66	1236.38	402.58	55.23	194.53	548.46	0.35	104
07ND-1-52b	0.0802	0.0016	2.122	0.042	0.1918	0.0021	0.0523	0.0007	1202	40	1156	14	1131	11	1030	14	<1.45	60.18	6.40	9.22	109.65	98.39	1.11	94
07ND-1-55b	0.2035	0.0027	15.508	0.204	0.5526	0.0055	0.1487	0.0020	2854	22	2847	13	2836	23	2803	34	<1.42	436.70	113.55	13.56	57.09	249.69	0.23	99
07ND-1-56b	0.0687	0.0011	1.513	0.025	0.1597	0.0016	0.0530	0.0007	888	34	936	10	955	9	1045	14	1.95	297.15	26.93	41.02	522.93	676.03	0.77	102
07ND-1-57b	0.0670	0.0010	1.302	0.020	0.1409	0.0014	0.0420	0.0005	837	32	847	9	850	8	831	10	<1.65	156.86	13.29	48.41	714.01	345.66	2.07	100
07ND-1-58b	0.0589	0.0010	0.824	0.014	0.1014	0.0010	0.0289	0.0004	564	37	610	8	623	6	575	8	<1.45	216.39	16.40	21.39	475.60	726.53	0.65	102
07ND-1-59b	0.1604	0.0024	11.058	0.161	0.4999	0.0052	0.1364	0.0018	2459	25	2528	14	2613	22	2584	33	<1.66	146.78	30.14	15.42	70.18	91.49	0.77	106
07ND-1-60b	0.0723	0.0012	1.758	0.029	0.1762	0.0018	0.0515	0.0007	995	34	1030	11	1046	10	1016	13	<1.43	113.38	10.41	16.40	199.32	203.56	0.98	105
07ND-1-61b	0.0718	0.0012	1.398	0.022	0.1411	0.0015	0.0552	0.0009	979	32	888	9	851	8	1086	17	1.53	171.19	15.44	5.42	67.21	385.01	0.17	96
07ND-1-62b	0.1458	0.0021	8.756	0.123	0.4353	0.0044	0.1326	0.0017	2297	24	2313	13	2330	20	2517	31	<1.38	475.67	88.57	32.19	155.88	350.19	0.45	101
07ND-1-63b	0.1107	0.0017	5.555	0.083	0.3637	0.0037	0.0880	0.0012	1811	27	1909	13	2000	18	1704	23	<1.48	245.22	34.24	14.81	105.58	216.55	0.49	110
07ND-1-64b	0.1654	0.0025	11.770	0.176	0.5157	0.0054	0.1396	0.0019	2511	25	2586	14	2681	23	2642	33	<1.37	110.33	23.29	16.24	73.10	68.62	1.07	107
07ND-1-65b	0.0718	0.0012	1.773	0.029	0.1790	0.0019	0.0537	0.0008	980	33	1036	11	1061	10	1058	14	<1.48	125.88	11.53	10.15	118.08	221.85	0.53	108
07ND-1-66b	0.1563	0.0022	9.862	0.141	0.4572	0.0047	0.1341	0.0018	2416	24	2422	13	2427	21	2544	32	1.60	568.50	113.08	27.98	130.24	392.72	0.33	100
07ND-1-68b	0.1674	0.0024	10.602	0.151	0.4588	0.0047	0.1255	0.0016	2532	24	2489	13	2434	21	2389	30	<0.97	629.30	134.56	44.68	222.08	428.92	0.52	96

07ND-1-1-07ND-1-60 were tested on a LA-ICP-MS, 07ND-1-1b-07ND-1-68b were tested on a MC-ICP-MS, common Pb corrected by Andersen's software. The concordance = (²⁰⁶Pb/²³⁸U)/²⁰⁷Pb×100 if the ²⁰⁶Pb/²³⁸U age>1000 Ma, (²⁰⁶Pb/²³⁸U)/²⁰⁷Pb×100 if the ²⁰⁶Pb/²³⁸U age<1000 Ma.

07ND-1-1-07ND-1-60 were tested on a LA-ICP-MS, 07ND-1-1b-07ND-1-68b were tested on a MC-ICP-MS, common Pb corrected by Andersen's software. The concorde = $(^{206}\text{Pb}/^{238}\text{U})/(^{207}\text{Pb}/^{206}\text{Pb}) \times 100$ if the $^{206}\text{Pb}/^{238}\text{U}$ age > 1000 Ma, $(^{206}\text{Pb}/^{238}\text{U})/(^{207}\text{Pb}/^{235}\text{U}) \times 100$ if the $^{206}\text{Pb}/^{238}\text{U}$ age < 1000 Ma.

Table 2 Lu-Hf isotopes of detrital zircons of garnet-mica schist (07ND-1) in the Ningduo Rock Group in Changdu Block, northern Qiangtang

Sample No.	Age (Ma)	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	2σ	T_{DM1}	T_{DM2}	$f_{\text{Lu/Hf}}$
07ND-1-1b	955	0.03044	0.00116	0.281967	0.000022	-28.5	-8.1	0.8	1816	2320	-0.96
07ND-1-2b	2446	0.01324	0.00052	0.281091	0.000019	-59.4	-5.5	0.7	2972	3294	-0.98
07ND-1-4b	1145	0.03500	0.00132	0.281815	0.000029	-33.8	-9.5	1.0	2036	2551	-0.96
07ND-1-7b	1016	0.02246	0.00083	0.281936	0.000021	-29.6	-7.7	0.7	1843	2339	-0.97
07ND-1-8b	983	0.02092	0.00078	0.281938	0.000019	-29.5	-8.3	0.7	1838	2352	-0.98
07ND-1-9b	1660	0.02991	0.00116	0.281589	0.000023	-41.8	-6.2	0.8	2340	2737	-0.96
07ND-1-10b	1552	0.03797	0.00139	0.281826	0.000021	-33.5	-0.4	0.7	2024	2296	-0.96
07ND-1-11b	1197	0.01957	0.00074	0.281915	0.000022	-30.3	-4.4	0.8	1868	2272	-0.98
07ND-1-12b	1143	0.03628	0.00143	0.281089	0.000028	-59.5	-35.4	1.0	3046	4137	-0.96
07ND-1-14b	2476	0.01407	0.00050	0.280988	0.000022	-63.1	-8.5	0.8	3109	3496	-0.98
07ND-1-15b	803	0.03197	0.00134	0.282441	0.000036	-11.7	5.3	1.3	1158	1363	-0.96
07ND-1-16b	663	0.01068	0.00040	0.280922	0.000020	-65.4	-51.1	0.7	3189	4746	-0.99
07ND-1-18b	1079	0.01905	0.00068	0.281831	0.000031	-33.3	-9.9	1.1	1980	2525	-0.98
07ND-1-19b	942	0.01405	0.00057	0.281406	0.000021	-48.3	-27.9	0.7	2552	3533	-0.98
07ND-1-20b	1461	0.01946	0.00079	0.281544	0.000032	-43.4	-11.8	1.1	2378	2929	-0.98
07ND-1-21b	1089	0.05388	0.00226	0.282343	0.000023	-15.2	7.3	0.8	1329	1458	-0.93
07ND-1-22b	3505	0.01401	0.00053	0.280561	0.000022	-78.2	-0.1	0.8	3678	3784	-0.98
07ND-1-25b	1043	0.06348	0.00232	0.282218	0.000027	-19.6	1.9	1.0	1512	1764	-0.93
07ND-1-26b	2505	0.00446	0.00013	0.280959	0.000021	-64.1	-8.2	0.7	3117	3502	-1.00
07ND-1-27b	1565	0.01349	0.00051	0.281738	0.000024	-36.6	-2.3	0.9	2098	2424	-0.98
07ND-1-30b	1689	0.05765	0.00242	0.281693	0.000033	-38.2	-3.3	1.2	2271	2581	-0.93
07ND-1-31b	1053	0.01302	0.00060	0.281824	0.000023	-33.5	-10.7	0.8	1986	2553	-0.98
07ND-1-34b	1528	0.01774	0.00067	0.281313	0.000022	-51.6	-18.4	0.8	2684	3384	-0.98
07ND-1-35b	1569	0.01893	0.00071	0.281499	0.000023	-45.0	-10.9	0.8	2435	2958	-0.98
07ND-1-36b	909	0.01090	0.00042	0.281865	0.000023	-32.1	-12.3	0.8	1920	2543	-0.99
07ND-1-37b	645	0.02274	0.00088	0.281466	0.000024	-46.2	-32.4	0.8	2491	3592	-0.97
07ND-1-38b	1001	0.01733	0.00069	0.282435	0.000030	-11.9	9.8	1.1	1146	1234	-0.98
07ND-1-40b	1084	0.03725	0.00137	0.281957	0.000024	-28.8	-5.8	0.9	1840	2276	-0.96
07ND-1-42b	2554	0.01301	0.00049	0.280456	0.000031	-81.9	-25.6	1.1	3813	4584	-0.99
07ND-1-43b	2421	0.01125	0.00042	0.280770	0.000029	-70.8	-17.3	1.0	3391	3989	-0.99
07ND-1-44b	2484	0.01408	0.00055	0.281132	0.000024	-58.0	-3.3	0.9	2920	3186	-0.98
07ND-1-45b	798	0.01974	0.00072	0.281941	0.000028	-29.4	-12.2	1.0	1831	2454	-0.98
07ND-1-47b	642	0.00649	0.00029	0.281637	0.000023	-40.1	-26.2	0.8	2223	3205	-0.99
07ND-1-48b	1021	0.01761	0.00066	0.281947	0.000027	-29.2	-7.1	1.0	1820	2304	-0.98
07ND-1-49b	1705	0.00687	0.00027	0.281727	0.000026	-37.0	0.7	0.9	2100	2346	-0.99
07ND-1-50b	3211	0.01212	0.00055	0.280588	0.000023	-77.2	-6.0	0.8	3644	3909	-0.98
07ND-1-52b	1202	0.02107	0.00079	0.282040	0.000031	-25.9	0.1	1.1	1698	1995	-0.98
07ND-1-55b	2854	0.01844	0.00073	0.280509	0.000018	-80.0	-17.4	0.6	3766	4316	-0.98
07ND-1-56b	955	0.03341	0.00130	0.282118	0.000030	-23.1	-2.9	1.1	1611	1991	-0.96
07ND-1-57b	850	0.04760	0.00180	0.281622	0.000025	-40.7	-23.0	0.9	2333	3160	-0.95
07ND-1-58b	623	0.01298	0.00047	0.282023	0.000030	-26.5	-13.0	1.1	1707	2373	-0.99
07ND-1-59b	2459	0.00762	0.00030	0.280568	0.000026	-77.9	-23.5	0.9	3647	4386	-0.99
07ND-1-60b	1046	0.03652	0.00138	0.282071	0.000025	-24.8	-2.6	0.9	1681	2046	-0.96
07ND-1-61b	851	0.01719	0.00076	0.282163	0.000024	-21.5	-3.2	0.9	1527	1933	-0.98
07ND-1-62b	2297	0.02387	0.00093	0.281269	0.000025	-53.2	-3.2	0.9	2762	3039	-0.97
07ND-1-63b	1811	0.04550	0.00179	0.281470	0.000023	-46.0	-7.9	0.8	2546	2955	-0.95
07ND-1-64b	2511	0.01253	0.00057	0.280938	0.000023	-64.9	-9.6	0.8	3181	3589	-0.98
07ND-1-65b	1061	0.02518	0.00093	0.282243	0.000024	-18.7	4.1	0.9	1422	1636	-0.97
07ND-1-66b	2416	0.00762	0.00030	0.280975	0.000021	-63.5	-10.0	0.7	3109	3540	-0.99
07ND-1-68b	2532	0.01384	0.00054	0.280839	0.000020	-68.4	-12.6	0.7	3311	3786	-0.98

Figure 4 Hf isotopic feature (a) and Hf two-stage model ages histogram (b) of detrital zircons from garnet-mica-quartz schist of the Ningduo Rock Group.

values between 2373–3592 Ma. Finally, a few zircons with ages around 2854–3505 Ma showed low $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (0.280509–0.280588) and negative $\epsilon_{\text{Hf}}(t)$ (–0.1 to –17.4), and the T_{DM2} yielded ages from 3784 to 4316 Ma.

3 Discussion

The U-Pb ages of the garnet-mica quartz schist in the Ningduo Rock Group of the Longbao area concentrated in four groups – 2600–2300 Ma, 1700–1400 Ma, 1200–850 Ma and 700–530 Ma – and their peak ages were ~2440 Ma, ~1532 Ma, ~982 Ma and ~618 Ma, respectively. The first peak age of ~982 Ma was consistent with the Grenville orogeny (1190–980 Ma) [41–43] caused by convergence of Rodinia. The second peak age of ~618 Ma was the youngest age of the erosion source area, and was close to the Pan-African Movement (roughly between 600–550 Ma) [44,45]. These results indicate that some of the zircons of the Ningduo Rock Group came from a source that experienced the Pan-African event. These zircons with young ages also constrained the lower limit of the deposition time of this stratum. In other words, these zircons likely formed in the late Neoproterozoic. The zircons with age peaks of ~2440 Ma and ~1532 Ma were rounded, developed wide internal zonation, and had high Th/U ratios. This indicates that they came from a source that experienced tectono-magmatic events that occurred about 2440 Ma and 1532 Ma

ago.

In addition, there were a few ancient detrital zircons with ages older than 3100 Ma, among which is the oldest one with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3981 ± 9 Ma, as well as others with $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 3505 ± 18 Ma, 3450 ± 8 Ma, 3211 ± 20 Ma and 3127 ± 10 Ma. For zircons with ages of 3981 ± 9 Ma, this is the oldest record of the crust that has been discovered in the Qiangtang area, and it also is the third oldest zircon that has been discovered in China, after that in Tibet and Qinling. These results indicate that there residual Hadean signatures are preserved in Northern Qiangtang. This information is crucial to studies of crustal rocks and evolution of early Earth.

Zircon U-Pb dating and Hf isotopic analyses have provided important information regarding the study of the growth and recycling of continental crust [46,47]. Hf model ages indicate that the age of the magma source in the Qiangtang area is the growth age of the crust, at the time it separated from the depleted mantle. However, most zircons did not form directly via mantle differentiation from parent magma. Thus, in this case, the two-stage model of ages is more closely related to the growth age of the crust. The Hf isotopic results indicate that zircons with ages of ~982 Ma produced a negative $\epsilon_{\text{Hf}}(t)$, and the two-stage model of ages yielded an age of about 1933–2553 Ma, which verifies that there may have been initial crust in the Paleoproterozoic in the source area of the Ningduo Rock Group. A few zircons with ages around 2854–3505 Ma also showed a negative $\epsilon_{\text{Hf}}(t)$, and the T_{DM2} yielded ages within 3784–4316 Ma. This information indicates that the source area of the Ningduo Rock Group was much older (Hadean) crust than the residue, which is consistent with the zircon age of 3981 ± 9 Ma. These results probably indicate that there were crustal materials of the initial formation stage of the Earth in the Changdu Block of Northern Qiangtang. It is difficult to confirm from the source area of these zircons, but based on the two-stage model of ages and the negative $\epsilon_{\text{Hf}}(t)$, their source may have been TTG rocks that intruded into the crust after separating from the depleted mantle during the Hadean.

Presently, there is great controversy regarding whether Precambrian basement existed in Qiangtang. Most researchers have believed that the basement of the Qiangtang consists of two-layered Proterozoic metamorphic rocks [48–51]. Nonetheless, Wang et al.[52] indicated that there probably was an Archean continental core in the Qiangtang area. Based on combined data sets of zircon U-Pb and Rb-Sr isotopic ages (318–384 Ma) and a field survey of the Qiangtang area, Li [53] suggested that the main time of formation of the epimetamorphic rocks in central Qiangtang was that of the late Carboniferous. However, the 1:250000 regional geological survey obtained some ages for Jiningian in Eastern Qiangtang. In recent years, SHRIMP U-Pb ages of cumulate gabbros have revealed age clusterings around 438 ± 11 Ma [54], which is useful for determination of the Ordovician ophiolite in the hinterland of Qiangtang. Based

on the youngest age of ~618 Ma and regional geological features, we suggest that the Ningduo Rock Group formed in the late Neoproterozoic to Palaeozoic.

It is worth mentioning that detrital zircons with ages of 4.0–4.1 Ga were discovered in Pulan County and Western Nepal in the Himalayas, and a number of ages consistent with Pan-African events were reported [55–57]; whereas, the Himalayan-Gangdese region has been considered to belong to East Gondwana. Based on U-Pb ages and Lu-Hf isotopic studies on metamorphic rocks of the late Neoproterozoic in the Cathaysia Block, Yu et al. [58] obtained many detrital zircon ages for the Grenville (~1.0 Ga), Neoproterozoic, and a few ages in the Eoarchean (~3.8 Ga), Paleoproterozoic (3.3–3.0 Ga), Paleoproterozoic (1.7–1.4 Ga), Mesoproterozoic (1.7–1.4 Ga) and Pan-Africa (0.70–0.54 Ga) intervals. They believed that the source was mainly Eastern India-Eastern Antarctic, and suggested that the southern margin of the South China Block was close to India and Eastern Antarctic in the period of the Rodinian divergence and Gondwanan convergence. Other than the zircon age of 3.98 Ga, many ages in the Grenville (~980 Ma) and Pan-Africa (~618 Ma) intervals were obtained. We speculate that there were similarities between the Changdu Block and Gondwana. Thus, it is important to study the relationship between the basements of Qiangtang and that of the Gangdese and Himalayan areas to further confine the northern boundary of Gondwana.

4 Conclusions

(1) For detrital zircons collected from garnet-mica quartz schist of the Ningduo Rock Group in Changdu Block, northern Qiangtang, ages of 3981 ± 9 Ma and 3505 ± 18 to 3127 ± 10 Ma tested by LA-ICP-MS revealed that there were ancient crustal residues in the Changdu Block.

(2) Detrital zircon ages of the Ningduo Rock Group mainly clustered in four groups — 2600–2300 Ma, 1700–1400 Ma, 1200–850 Ma and 700–530 Ma — with age peaks of ~2440 Ma, ~1532 Ma, ~982 Ma and ~618 Ma, respectively. The first peak at ~982 Ma is consistent with the Grenville orogeny caused by convergence of Rodinia, and the second peak of ~618 Ma is roughly consistent with the Pan-African Movement, which resulted from convergence of Gondwana. These data indicate that there was a relationship between the Changdu Block and Gondwana. This new evidence is of great importance with respect to understanding the relationship between the basement of the Qiangtang and that of Gangdese and Himalayan.

(3) The youngest detrital zircon age was ~618 Ma in the Ningduo Rock Group, which may constrain the lower boundary of the stratum from late Neoproterozoic to early Paleozoic.

(4) Detrital zircons with ages of ~982 Ma were negative in $\varepsilon_{\text{Hf}}(t)$, and the two-stage Hf model of ages yielded about

1933–2553 Ma. These results suggest that the source area of the Ningduo Rock Group was separated into crust from the depleted mantle during the Paleoproterozoic. In other words, there were crustal growth events in the Paleoproterozoic. However, zircons with ages of 2854–3505 Ma showed a negative $\varepsilon_{\text{Hf}}(t)$ and their two-stage Hf models of ages were around 3784–4316 Ma, which demonstrates that there still were much older (Hadean) crustal residues in the source area of the Ningduo Rock Group.

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