Research Article

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Provenance and tectonic significance of the Zhongwunongshan Group from the Zhongwunongshan Structural Belt in China: insights from zircon geochronology

<https://doi.org/10.1515/geo-2020-0003>

Received Aug 06, 2018; accepted Dec 15, 2019

Abstract: The Zhongwunongshan Structural Belt (ZWSB) locates between the Olongbruk Microblock of North Qaidam and the South Qilian Block in China, and it has important implication for understanding the tectonic significance of North Qaidam. Nowadays, there are few discussion on the Caledonian tectonothermal events of the Zhongwunongshan Structural Belt, and there exist different opinions on provenance and tectonic environment of the Zhongwunongshan Group in the ZWSB and its adjacent North Qaidam. In this study, a comprehensive analysis of the detrital zircon geochronological research was carried out on the Zhongwunongshan Group. The detrital zircon U-Pb dating results showed two major populations. The first was Neoproterozoic (966–725 Ma) with a $\epsilon_{\text{Hf}}(t) = -15.9$ to 9.5, and the other was late Early Paleozoic (460–434 Ma) with a $\epsilon_{\text{Hf}}(t) = -9.6$ to -3.1 . In combination with previous research, the dominated provenances were found to be the Neoproterozoic granitic gneiss of the Yuqia-Shaliuhe HP-UHP metamorphic belt and the late Early Paleozoic granite of the Tanjianshan ophiolite-volcanic arc belt in North Qaidam. The Zhongwunongshan Group was deposited in the back-arc sedimentary basin related to the Caledonian collisional orogeny during Middle Silurian–Early Devonian (434–407.9 Ma).

Keywords: North Qaidam, Zhongwunongshan Structural Belt, detrital zircon, provenance, back-arc basin, Caledonian

1 Introduction

The Zhongwunongshan Structural Belt (ZWSB) is a northwest-extending structural belt located between the Olongbruk Microblock of North Qaidam and the South Qilian Block [1, 2] (Figure 1). The ZWSB is separated from the South Qilian Block to the north and the Olongbruk Microblock to the south by the Qinghai Nanshan Fault and the Southern Zhongwunongshan Fault, respectively. It extends westward to the Altun Fault, and divides between the West Qingling and South Qilian in the east. Therefore, the geological position of the Zhongwunongshan Structural Belt is significant. It is generally believed that the Zhongwunongshan Structural Belt is a Hercynian–Indosinian tectonic zone developed on the Caledonian block jointly constructed by the Olongbruk Microblock of the North Qaidam and the South Qilian Block [5–7]. At present, there are few data reported the Caledonian tectonic thermal events and evolution of the ZWSB.

The Zhongwunongshan Group is the most important and widely exposed formation in the ZWSB and adjacent North Qaidam. Therefore, the Zhongwunongshan Group is determined to be the ideal object for the tectonic research of the ZWSB. The previous authors carried out a certain research on Zhongwunongshan Group, and most of them believe that it deposited in the Late Carboniferous rift [8–10]. However, other geologists have had different viewpoints about the tectonic environments and basin types of the Zhongwunongshan Group deposited in. There are two primary views about tectonic environment and basin type: (1) The Zhongwunongshan Group deposited in a stable passive continental margin basin, which irrelevant to plate subduction and collision [7, 10, 11]; and (2) Due to plate subduction and collision, the sediments deposited in the back-arc sedimentary basin along the North Qaidam active continental margin [9, 12, 13]. A consensus in the detritus provenance has also not been reached. Some scholars suggest the provenance was located in the uplift ter-

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Figure 1: (a): Map showing the location of the North Qaidam. (b): Tectonic units of the North Qaidam. (c): Simplified geological map of the study area (modified after [3, 4])

rane along the southern margin of the South Qilian Block to the north [11, 14, 15], but the others hold the opinion that, the southern part of North Qaidam provided sediments northward [9, 13]. Meanwhile, Geologists also held different opinions about the stratigraphic age of Zhongwunongshan Group. Some believed the strata deposited in Late Carboniferous as indicated by the fusulinids and corals [16]. However, the fossils identification were challenged because of their limited occurrence and metamorphic recrystallization.

Clastic rocks contain lots of useful information, including the material composition and tectonic environment of the source area, and the crustal evolution in the early geological history [17, 18]. The zircon geochronology has been widely used to reveal the petrogenesis of clastic rocks [19, 20], and to reconstruct the characteristics and tectonic environment of source areas [20, 22–24]. Since sandstone and mudstone are relatively homogeneous and have high level of trace element, they become the first choice for geochemical and chronological studies [21, 25, 26]. Epimetamorphic clastic rocks have also been widely used to study the petrogenesis and tectonic environments of source areas [20, 27]. Based on the previous research with the new geochronology analysis of the Zhongwunongshan Group

clastic rocks, this paper aims at providing new data to reconstruct the provenance and tectonic setting of Zhongwunongshan Group, and attempting to find the geological records of the Caledonian tectonic thermal events in order to provide a reasonable explanation for the aforementioned problems.

2 Geological background

Recent studies have well demonstrated that the North Qaidam Structural Belt (NQS), bounded by the South Qilian Block to the north and Qaidam Block to the south (Figure 1), is a composite tectonic orogenic belt with multi-stage orogenic processes [2, 28]. The NQS consists of the Shaliuhe-Yuqia high pressure-ultrahigh pressure (HP-UHP) metamorphic belt, the Tanjianshan ophiolite-volcanic arc belt, the Olongbruk Microblock (Figure 1b), from south to north, in view of the significantly diverse geological composition and tectonic evolutionary history [28, 29]. The complex tectonic composition indicates that the sub-tectonic units that make up the NQS underwent different tectonic evolutionary phase predating the pre-

Devonian, including the Paleoproterozoic (2400–1800 Ma) continental crust formation [2, 28]; Neoproterozoic (1030–750 Ma) magmatic activities related to Rodinia supercontinent convergence and breakup [30, 31]; early Paleozoic (542–434 Ma) magmatism and HP-UHP metamorphism by oceanic crust subduction followed by collision associated continental deep-subduction [3, 32]. The continental deep subduction marked the assembly of Olongbruk Microblock and the Qaidam Block. Subsequently, the NQSB evolved into the post-orogenic stage indicated by the rifting molasse of the Upper Devonian Maoniushan Group.

The Shaliuhe-Yuqia HP-UHP metamorphic belt is the northern border separating the Qaidam Block from the NQSB (Figure 1b). The belt is predominantly composed of Neoproterozoic-Early Paleozoic granitic gneiss (1011–434 Ma) and metamorphic supracrustal rock, with minor sporadically exposed eclogite (1000–800 Ma) [29, 33]. The Tanjianshan ophiolite-volcanic arc belt, to the north of HP-UHP metamorphic belt, is dominated by widespread Early Paleozoic intermediate-basic volcanic (486–450 Ma) and pyroclastic rocks with ophiolite complex, which are intruded by granitic intrusive rocks (465–434 Ma) [4, 34] (Figure 1b). The Olongbruk Microblock has an early Paleoproterozoic crystalline basement including the ~2400 Ma Delingha granitic gneiss and the ~1800 Ma Khondalite-like supracrustal rocks (Figure 1b). Above the basement are a series of unmetamorphosed sedimentary successions that were discontinuously deposited from late Paleoproterozoic to Cenozoic [4, 8, 11, 34–36].

This study focuses on the ZWSB and the adjacent North Qaidam (Figure 1b). The ZWSB widely outcrops the Upper Carboniferous Zhongwunongshan Group comprising carbonate dominated sedimentary successions with some volcanic interlayers, which are overlain by Permian-Triassic shallow marine clastic rocks and carbonates [6, 8, 14] (Figure 1c). The Zhongwunongshan Group have been further subdivided into two lithostratigraphic units. The lower section is predominately composed of gray green phyllite and sandy slate, with minor medium-basic volcanic layers and limestone lenses, which were deposited in the neritic shelf environment. The upper unit mainly consists of gray white banded limestone and dolomitic limestone with gray green intermediate-basic volcanic interlayers, typically formed in sublittoral platform environment (Figure 2).

In this study, two samples (KDLG1505 and BLG1505) were collected from the sandstones of Zhongwunongshan Group exposed in the Baluogenguole (BLG) and Kendelonggou (KDLG) areas (Figure 1c), respectively.

3 Analytical Methods

3.1 Zircon geochronology analysis

The detrital zircons were separated using a conventional heavy liquid and magnetic separation techniques, and then further purified by handpicking under a binocular stereoscope. Subsequently, the grains were mounted in epoxy, and polished to expose the cores of the grains. Cathodoluminescence (CL) images were obtained for all zircons prior to analysis, in order to characterize the internal structures and to choose potential sites for in situ U-Pb dating and Lu-Hf analyses.

This zircon U-Pb dating was conducted in the Key Laboratory of Metallogeny and Mineral Assessment of the Ministry of Nature Resources, which is located at the Institute of Mineral Resources of the Chinese Academy of Geological Sciences. The zircon geochronology was performed by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS), on a Finnigan Neptune equipped with Newwave UP213 laser ablation system, with an ablation spot diameter of 30 μm , frequency of 10 Hz, and energy density of approximately 2.5 J/cm². Helium was used as the carrier gas. Zircons SRM610, Plesovice, and 91500 were used as the external standards for correcting the mass discrimination and isotope fractionation. The detailed analytical conditions are described in [37]. An ICPMSDataCal program was used for the data processing [38], and the Concordia diagrams were obtained using an Isoplot4.0 routine [39]. Therefore, in this study a maximum of 80 individual zircon grains were selected randomly from each of the samples. Among the 80 grains, we excluded zircon age analyses with >10% discordance for interpretation. We report the ages derived from $^{206}\text{Pb}/^{238}\text{U}$ for < 1000 Ma and $^{207}\text{Pb}/^{206}\text{Pb}$ for ≥ 1000 Ma. Visualization of U-Pb zircon ages is achieved using Isoplot 4.0 [39] and Density Plotter program [40].

3.2 Zircon Hf isotope analysis

The Zircon in situ Lu-Hf analysis was completed in the State Key Laboratory of Continental Tectonics and Dynamics of the Institute of Geology, Chinese Academy of Geological Sciences, utilizing a Neptune Plus MC-ICP-MS instrument, and a Complex pro.193 nm laser-ablation system. The ablation spot diameter was 44 μm . The global zircon standard GJ-1 was taken as the reference material, and the analytical points were the same as those of the U-Pb dating. The detailed operating conditions for the LA-MC-ICP-

Figure 2: Stratigraphic column of the Zhongwunongshan Group

MS and calibration strategy followed those used by [41]. The LA-MC-ICP-MS analyses of the zircon standard GJ-1 during the analytical process achieved the $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282015 ± 8 (2σ , $n = 10$), which was identical to the literature values within error [42].

4 Results

4.1 Zircon U-Pb dating

The zircon grains from sample BLG1505 range in size from 50 to 100 μm with length/width ratios of 2:1–1:1. These zir-

cons generally display sub-angular to rounded morphology. In CL images, most zircon grains have clear oscillatory zonings, with few zircons showing weak zoning or being structureless (Figure 3). All dated zircons show high Th/U ratios of 0.26–2.05, low LREE/HREE (<1) ratios and REE+Y content ($<1\%$), positive Ce and negative Eu anomalies (Table 1), which jointly indicate a magmatic origin [43, 44]. The sample BLG1505 yields 67 concordant U-Pb ages varying from 2456 Ma to 634 Ma with one major age cluster (Table 1, Figure 4a). The most prevailing age cluster of 925–725 Ma contains 53 data and defines two age peaks at 831 Ma and 804 Ma. Additionally, few zircons of Paleo- and Meso-

Figure 3: Cathodoluminescence images (CL) of the representative analyzed detrital zircons and their corresponding U-Pb ages from the Zhongwunongshan Group sandstone samples (BLG1505 and KDLG1505). The open circles represent the positions of ablation pits

proterozoic age are also present, with subordinate peaks at 2398 Ma and 1746 Ma (Figure 4b).

The detrital zircons, in sample KDLG1505, are sub-angular to sub-rounded shapes with length/width ratios of 2:1–1:1. Except for the No. 29 and No. 30 analytical points, the majority of zircons shows well-developed oscillatory zoning or plate internal structure (Figure 3), with Th/U ratios greater than 0.1 (0.26–2.42). Besides, these zircons have similar REE concentration features with sample BLG1505, indicating the magmatic origin [44] (Table 1). Sixty-nine concordant zircon U-Pb ages of 2688–420 Ma were obtained from 69 zircon grains (Table 2, Figure 4c). These concordant ages are mainly grouped into two distinct age populations of 460–434 Ma and 966–726 Ma, defining dominant peaks at 456 Ma with 21 data, and secondary peaks of 828 Ma, 730 Ma and 956 Ma with 24 data

(Figure 4d). About one-third of the grains are older than 1500 Ma with peaks at 2540 Ma and 1799 Ma.

4.2 Zircon Hf isotopic analysis

Zircon Lu-Hf isotopic analysis were carried out on samples KDLG1505 and BLG1505 with completed zircon U-Pb dating. The related results are listed in Table 3. For samples KDLG1505 and BLG1505, the detrital zircons of the Zhongwunongshan Group were found to be dominated by late Early Paleozoic and Neoproterozoic (Table 2, Figure 4). The Hf isotopic analysis results indicated that the vast majority of the zircons had negative $\epsilon_{\text{Hf}}(t)$ (Figure 5). Such $\epsilon_{\text{Hf}}(t)$ distribution characteristics confirmed that the detrital zircons of the Zhongwunongshan Group were mainly sourced from crustal recycling. However, some zircons

Figure 4: U-Pb Concordia diagrams and age histograms of the detrital zircons from the Zhongwunongshan Group sandstone samples (BLG1505 and KDLG1505)

Figure 5: Plot of zircon Hf isotopes vs. crystallization age from the Zhongwunongshan Group sandstones

with positive $\epsilon\text{Hf}(t)$ in BLG1505 proved a depleted mantle source existed (Table 3, Figure 5). The zircons of the Zhongwunongshan Group in the eastern section of the study area had two major U-Pb age populations of 460–434 Ma and 966–726 Ma (Figure 4d). Also, the corresponding $\epsilon\text{Hf}(t)$ were calculated at -9.6 to -3.1 , and -15.9 to -0.8 , respectively, with the exception of the No.21 point which had an $\epsilon\text{Hf}(t)$ of 3.8 (Figure 5). The two-stage model ages (T_{DM}^c) were between 1621 Ma and 2029 Ma, and between 1581 Ma and 2815 Ma respectively. The averages were determined to be 1864 Ma and 2362 Ma, respectively (Table 3). In the western section of the study area, the zircons had a major U-Pb age population of 925–725 Ma (Figure 4d); $\epsilon\text{Hf}(t)$ between -11.9 and 9.5 (Figure 5); and average T_{DM}^c of 1692 Ma, which was lower than that of the Neoproterozoic zircons in the eastern section.

Table 1: Microelement eigenvalues of zircons from the Zhongwunongshan Group sandstones

Sample Spot	$\sum$ REE+Y	δ Eu	δ Ce	LREE/HREE	Sample Spot	$\sum$ REE+Y	δ Eu	δ Ce	LREE/HREE
Sample BLG1505					Sample KDLG1505				
BLG1505-1	984.65	0.30	154.39	0.10	KDLG1505-01	872.27	0.84	1.13	0.43
BLG1505-2	2242.89	0.48	56.63	0.03	KDLG1505-02	870.60	0.23	56.28	0.04
BLG1505-3	1227.22	0.36	18.87	0.03	KDLG1505-03	1237.64	0.40	78.44	0.08
BLG1505-4	3122.88	0.31	5.58	0.02	KDLG1505-04	1364.93	0.36	3.68	0.13
BLG1505-6	935.13	0.50	1.37	0.11	KDLG1505-06	1165.79	0.32	3.50	0.15
BLG1505-7	1891.89	0.67	7.39	0.02	KDLG1505-07	1454.27	0.24	4.65	0.04
BLG1505-8	1956.24	0.36	85.73	0.05	KDLG1505-08	957.66	0.23	56.28	0.04
BLG1505-9	2541.56	0.60	12.42	0.04	KDLG1505-09	2154.00	0.28	4.97	0.05
BLG1505-10	1732.07	0.70	57.82	0.02	KDLG1505-10	1296.68	0.36	3.68	0.13
BLG1505-11	1137.40	0.50	33.45	0.02	KDLG1505-11	2154.00	0.28	4.97	0.05
BLG1505-12	3328.52	0.25	208.57	0.04	KDLG1505-12	3307.58	0.11	1.05	0.12
BLG1505-14	1479.85	0.49	46.33	0.03	KDLG1505-14	914.13	0.23	56.28	0.04
BLG1505-15	3899.46	0.16	1.07	0.09	KDLG1505-15	655.49	0.27	26.48	0.04
BLG1505-16	836.95	0.30	26.55	0.06	KDLG1505-16	1574.60	0.12	69.11	0.03
BLG1505-17	852.27	0.52	76.20	0.14	KDLG1505-17	1508.14	0.44	11.42	0.06
BLG1505-18	3793.98	0.10	14.83	0.04	KDLG1505-18	1099.85	0.25	58.76	0.04
BLG1505-19	1901.71	0.41	98.29	0.03	KDLG1505-19	1724.24	0.14	1.33	0.10
BLG1505-20	1471.52	0.11	132.46	0.04	KDLG1505-20	956.39	0.25	58.76	0.04
BLG1505-22	2451.73	0.88	10.12	0.03	KDLG1505-21	2239.38	0.11	1.00	0.10
BLG1505-23	4735.18	0.49	6.95	0.01	KDLG1505-22	1237.64	0.40	78.44	0.08
BLG1505-25	7874.87	0.38	75.37	0.03	KDLG1505-23	984.18	0.19	2.61	0.04
BLG1505-28	1536.70	0.23	19.74	0.09	KDLG1505-24	1358.25	0.39	4.30	0.16
BLG1505-29	2272.13	0.08	5.10	0.01	KDLG1505-25	2239.38	0.11	1.00	0.10
BLG1505-32	3145.49	0.58	6.29	0.06	KDLG1505-26	1436.78	0.46	22.59	0.07
BLG1505-33	3498.16	0.19	14.17	0.04	KDLG1505-27	927.26	0.32	1.64	0.20
BLG1505-34	2030.05	0.20	17.03	0.02	KDLG1505-28	1547.05	0.40	78.44	0.08
BLG1505-35	3027.49	0.11	1.72	0.04	KDLG1505-29	12019.09	8.48	0.76	0.10
BLG1505-36	839.41	0.60	11.94	0.03	KDLG1505-30	14048.07	4.49	0.60	0.01
BLG1505-39	580.31	0.23	40.26	0.07	KDLG1505-31	1225.84	0.17	43.46	0.01
BLG1505-40	1876.54	0.10	1.51	0.07	KDLG1505-32	1182.91	0.17	1.36	0.14
BLG1505-41	2089.35	0.15	1.48	0.06	KDLG1505-33	914.13	0.23	56.28	0.04
BLG1505-42	1063.46	0.41	109.51	0.02	KDLG1505-34	1086.01	0.20	2.90	0.05
BLG1505-43	1908.81	0.13	33.69	0.03	KDLG1505-35	2110.92	0.28	4.97	0.05

Table 1: ...continued

Sample Spot	$\sum$ REE+Y	δ Eu	δ Ce	LREE/HREE	Sample Spot	$\sum$ REE+Y	δ Eu	δ Ce	LREE/HREE
BLG1505-44	2143.49	0.47	3.70	0.03	KDLG1505-36	2632.39	0.11	2.53	0.09
BLG1505-45	1678.47	0.15	4.02	0.03	KDLG1505-40	1243.55	0.37	14.64	0.06
BLG1505-47	2685.93	0.31	242.71	0.03	KDLG1505-41	957.66	0.23	56.28	0.04
BLG1505-48	672.32	0.20	84.41	0.06	KDLG1505-42	1086.07	0.13	7.95	0.03
BLG1505-50	1268.37	0.80	50.15	0.10	KDLG1505-43	1200.39	0.13	7.95	0.03
BLG1505-51	5687.00	0.29	4.16	0.03	KDLG1505-44	1301.33	0.17	43.46	0.02
BLG1505-52	1647.42	0.51	1.83	0.08	KDLG1505-45	2261.70	0.28	4.97	0.05
BLG1505-53	2787.27	0.67	8.64	0.08	KDLG1505-46	2046.30	0.28	4.97	0.05
BLG1505-54	4354.37	0.58	1.04	0.80	KDLG1505-47	966.36	0.23	56.28	0.04
BLG1505-55	3269.21	0.62	1.14	0.43	KDLG1505-49	1332.37	0.39	4.30	0.16
BLG1505-56	3138.72	0.23	7.90	0.03	KDLG1505-50	1245.17	0.17	1.36	0.14
BLG1505-57	870.63	0.81	38.01	0.04	KDLG1505-51	1034.29	0.20	2.90	0.05
BLG1505-58	1916.87	0.57	22.75	0.03	KDLG1505-52	1346.12	0.17	20.68	0.04
BLG1505-60	1606.86	0.28	3.85	0.05	KDLG1505-53	1637.92	0.36	3.68	0.13
BLG1505-61	1332.75	0.37	36.83	0.03	KDLG1505-55	1221.72	0.32	2.86	0.24
BLG1505-62	1985.51	0.63	2.80	0.03	KDLG1505-56	784.81	0.20	53.91	0.03
BLG1505-63	1788.09	0.47	50.54	0.02	KDLG1505-58	1508.14	0.44	11.42	0.06
BLG1505-64	2791.14	0.26	1.21	0.06	KDLG1505-59	1440.29	0.13	5.60	0.04
BLG1505-65	1131.07	0.07	1.11	0.22	KDLG1505-60	1456.91	0.22	98.12	0.03
BLG1505-66	1240.06	0.15	33.60	0.03	KDLG1505-61	1648.08	0.03	23.06	0.01
BLG1505-67	2157.51	0.38	11.21	0.02	KDLG1505-62	668.87	0.27	26.48	0.04
BLG1505-68	1624.76	0.20	21.89	0.04	KDLG1505-64	1130.44	0.12	128.36	0.06
BLG1505-69	1825.65	0.26	5.89	0.08	KDLG1505-65	2027.76	0.32	3.71	0.09
BLG1505-70	1275.80	0.02	36.87	0.03	KDLG1505-67	842.27	0.32	1.28	0.42
BLG1505-71	991.14	0.44	9.89	0.03	KDLG1505-68	2606.20	0.03	20.30	0.01
BLG1505-72	1867.45	0.12	1.52	0.09	KDLG1505-69	1109.86	0.33	36.85	0.06
BLG1505-73	1629.06	0.19	26.61	0.04	KDLG1505-70	1365.42	0.48	183.22	0.09
BLG1505-74	832.37	0.62	104.84	0.04	KDLG1505-71	628.30	0.29	1.75	0.09
BLG1505-75	1125.07	0.45	101.16	0.05	KDLG1505-72	2280.25	0.21	26.12	0.03
BLG1505-76	2615.70	0.46	53.32	0.02	KDLG1505-74	1657.44	0.15	9.50	0.04
BLG1505-77	2792.51	0.39	87.72	0.05	KDLG1505-75	846.18	0.13	55.96	0.03
BLG1505-78	1583.42	0.07	141.86	0.03	KDLG1505-76	3222.01	0.11	1.01	0.12
BLG1505-79	1942.86	0.36	77.16	0.14	KDLG1505-77	1282.74	0.10	23.30	0.02
BLG1505-80	1452.64	0.60	1.89	0.34	KDLG1505-78	1729.99	0.42	9.52	0.02

Table 1: ...continued

Sample Spot	$\sum$ REE+Y	δEu	δCe	LREE/HREE	Sample Spot	$\sum$ REE+Y	δEu	δCe	LREE/HREE
					KDLG1505-79	2018.77	0.11	9.96	0.01
					KDLG1505-80	956.39	0.25	58.76	0.04

Table 2: LA-ICP-MS U-Pb analyses of zircons from the Zhongwunongshan Group sandstones

Sample Spot	ω_B/ppm		Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$		Isotopic ratio		$^{206}\text{Pb}/^{238}\text{U}$		$^{207}\text{Pb}/^{206}\text{Pb}$		Apparent age (Ma)		$^{206}\text{Pb}/^{238}\text{U}$	
	Th	U		1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ			
Sample BLG1505															
BLG1505-1	268	223	1.2	0.1522	0.0033	8.0457	0.1883	0.3829	0.0047	2372	31	2236	21	2090	22
BLG1505-2	78	69	1.13	0.0714	0.0057	1.3228	0.0939	0.1374	0.0031	970	163	856	41	830	18
BLG1505-3	253	388	0.65	0.0676	0.002	1.2823	0.0392	0.1378	0.0017	857	63	838	17	832	9
BLG1505-4	245	414	0.59	0.066	0.002	1.2356	0.037	0.1359	0.0017	807	68	817	17	822	9
BLG1505-6	28	41	0.68	0.0713	0.0049	1.3309	0.0913	0.1376	0.0029	969	141	859	40	831	16
BLG1505-7	159	348	0.46	0.0678	0.002	1.0042	0.0299	0.1076	0.0017	861	140	706	15	659	10
BLG1505-8	111	102	1.09	0.0751	0.0049	1.3863	0.0814	0.1358	0.0029	1072	99	883	35	821	16
BLG1505-9	261	418	0.62	0.0658	0.0053	0.9304	0.0708	0.1034	0.0026	1200	164	668	37	634	15
BLG1505-10	83	110	0.75	0.0745	0.0036	1.4032	0.0647	0.1378	0.0018	1054	98	890	27	832	10
BLG1505-11	65	111	0.58	0.0649	0.0024	1.2199	0.0493	0.1366	0.0026	769	78	810	23	826	15
BLG1505-12	423	354	1.2	0.0667	0.0017	1.2643	0.0353	0.1374	0.0021	829	52	830	16	830	12
BLG1505-14	45	56	0.8	0.0692	0.0039	1.1009	0.0592	0.119	0.003	906	117	754	29	725	17
BLG1505-15	342	548	0.62	0.0659	0.0019	1.253	0.0372	0.1377	0.0018	806	61	825	17	832	10
BLG1505-16	336	255	1.32	0.0673	0.0025	1.2903	0.0524	0.1381	0.0022	856	77	841	23	834	12
BLG1505-17	390	373	1.05	0.1576	0.0026	9.4864	0.1874	0.4342	0.0055	2431	28	2386	18	2325	24
BLG1505-18	965	742	1.3	0.0654	0.0014	1.2533	0.0296	0.1381	0.0018	787	44	825	13	834	10
BLG1505-19	110	111	0.99	0.0663	0.0027	1.2711	0.0557	0.138	0.0021	815	85	833	25	833	12
BLG1505-20	150	172	0.87	0.1586	0.0032	9.6778	0.222	0.4395	0.0059	2440	35	2405	21	2348	26
BLG1505-22	340	500	0.68	0.0641	0.002	1.0949	0.0374	0.1232	0.0022	743	67	751	18	749	12
BLG1505-23	381	1440	0.26	0.0978	0.0018	3.7797	0.0783	0.2782	0.0035	1583	33	1588	17	1582	18
BLG1505-25	854	933	0.92	0.0679	0.0013	1.2997	0.0292	0.1377	0.0016	878	38	846	13	831	9
BLG1505-28	1938	1367	1.42	0.0675	0.0014	1.2793	0.0311	0.1366	0.0018	854	43	837	14	825	10
BLG1505-29	113	334	0.34	0.0681	0.0021	1.2887	0.0413	0.1368	0.002	872	95	841	18	827	11
BLG1505-32	753	718	1.05	0.0701	0.0017	1.3323	0.0346	0.1375	0.0016	931	53	860	15	831	9
BLG1505-33	419	372	1.13	0.0694	0.0018	1.3259	0.0372	0.1383	0.0016	909	54	857	16	835	9
BLG1505-34	297	505	0.59	0.0683	0.0015	1.3012	0.033	0.1376	0.0017	880	46	846	15	831	10
BLG1505-35	92	222	0.42	0.0709	0.0023	1.3504	0.0455	0.1378	0.0019	967	67	868	20	832	10
BLG1505-36	26	65	0.41	0.0716	0.0032	1.3391	0.0603	0.1373	0.0025	976	91	863	26	829	14
BLG1505-39	301	293	1.03	0.0681	0.0018	1.2997	0.0398	0.1377	0.002	872	54	846	18	832	11
BLG1505-40	135	138	0.98	0.0706	0.0025	1.3408	0.0495	0.1378	0.0018	946	72	864	21	832	10

Table 2: ...continued

Sample Spot	ω_B/ppm		Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$		1σ	Isotopic ration		$^{206}\text{Pb}/^{238}\text{U}$		1σ	$^{207}\text{Pb}/^{206}\text{Pb}$		1σ	Apparent age (Ma)		$^{206}\text{Pb}/^{238}\text{U}$		1σ
	Th	U		$^{207}\text{Pb}/^{235}\text{U}$	1σ		$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ		$^{206}\text{Pb}/^{238}\text{U}$	1σ						
BLG1505-41	142	126	1.13	0.069	0.0025	0.0025	1.311	0.0491	0.1379	0.0022	0.0022	898	68	851	22	833	12	12	
BLG1505-42	75	141	0.53	0.065	0.0025	0.0025	1.2316	0.0498	0.1372	0.0021	0.0021	772	75	815	23	829	12	12	
BLG1505-43	248	342	0.72	0.0652	0.0017	0.0017	1.1359	0.0301	0.126	0.0014	0.0014	783	54	771	14	765	8	8	
BLG1505-44	397	761	0.52	0.0663	0.0013	0.0013	1.267	0.0296	0.1378	0.0016	0.0016	817	41	831	13	832	9	9	
BLG1505-45	186	270	0.69	0.0641	0.002	0.002	1.2264	0.0421	0.1382	0.0019	0.0019	746	67	813	19	835	11	11	
BLG1505-47	228	245	0.93	0.0667	0.0021	0.0021	1.2674	0.0437	0.137	0.0019	0.0019	828	67	831	20	828	11	11	
BLG1505-48	266	220	1.21	0.0651	0.0021	0.0021	1.243	0.0454	0.1373	0.0017	0.0017	776	69	820	21	830	10	10	
BLG1505-50	39	59	0.67	0.1302	0.0039	0.0039	6.6389	0.2058	0.3685	0.0049	0.0049	2102	52	2065	27	2022	23	23	
BLG1505-51	256	335	0.76	0.074	0.0034	0.0034	1.5303	0.0685	0.1522	0.0037	0.0037	1040	94	943	27	913	21	21	
BLG1505-52	467	658	0.71	0.0702	0.002	0.002	1.1767	0.0341	0.1216	0.0022	0.0022	1000	58	790	16	740	13	13	
BLG1505-53	739	1310	0.56	0.1535	0.0033	0.0033	6.3792	0.1957	0.2972	0.0057	0.0057	2385	37	2029	27	1677	28	28	
BLG1505-54	1456	2260	0.64	0.0693	0.0016	0.0016	1.0682	0.0346	0.1104	0.0023	0.0023	906	48	738	17	675	14	14	
BLG1505-55	441	511	0.86	0.0668	0.002	0.002	1.2313	0.0367	0.1328	0.0015	0.0015	831	63	815	17	804	8	8	
BLG1505-56	195	298	0.65	0.0642	0.0024	0.0024	1.1864	0.044	0.1333	0.0018	0.0018	746	50	794	20	807	a	a	
BLG1505-57	205	654	0.31	0.1517	0.0032	0.0032	7.701	0.1715	0.3657	0.0044	0.0044	2365	236	2197	20	2009	21	21	
BLG1505-58	63	115	0.55	0.0716	0.0044	0.0044	1.2472	0.0715	0.1278	0.0021	0.0021	976	121	822	32	775	12	12	
BLG1505-60	191	273	0.7	0.066	0.0026	0.0026	1.2226	0.0469	0.1335	0.0018	0.0018	809	81	811	21	808	10	10	
BLG1505-61	41	51	0.8	0.0844	0.0075	0.0075	1.4496	0.1081	0.1337	0.0034	0.0034	1302	172	910	45	809	20	20	
BLG1505-62	70	91	0.76	0.0709	0.0044	0.0044	1.5008	0.0886	0.1544	0.003	0.003	955	122	931	36	925	17	17	
BLG1505-63	46	64	0.72	0.0735	0.0056	0.0056	1.3289	0.0997	0.1328	0.0033	0.0033	1028	154	858	44	805	19	19	
BLG1505-64	32	41	0.78	0.1035	0.0056	0.0056	3.4637	0.1882	0.2449	0.0048	0.0048	1687	99	1519	43	1412	25	25	
BLG1505-65	50	73	0.7	0.1008	0.0035	0.0035	3.9226	0.1352	0.2822	0.004	0.004	1639	64	1618	28	1603	20	20	
BLG1505-66	60	82	0.74	0.0681	0.0045	0.0045	1.2229	0.0755	0.1334	0.0027	0.0027	872	139	811	34	807	15	15	
BLG1505-67	141	209	0.68	0.0679	0.0038	0.0038	1.2329	0.0602	0.1335	0.0022	0.0022	865	117	816	27	808	13	13	
BLG1505-68	64	118	0.54	0.0797	0.0045	0.0045	1.4206	0.084	0.1304	0.0025	0.0025	1191	113	898	35	790	14	14	
BLG1505-69	328	406	0.81	0.0649	0.0018	0.0018	1.1866	0.0345	0.1322	0.0019	0.0019	770	53	794	16	801	11	11	
BLG1505-70	297	627	0.47	0.1142	0.0015	0.0015	4.7994	0.0715	0.3037	0.0028	0.0028	1866	29	1785	13	1710	14	14	
BLG1505-71	76	143	0.53	0.065	0.0039	0.0039	1.1151	0.0621	0.1261	0.002	0.002	776	121	761	30	766	12	12	
BLG1505-72	162	172	0.94	0.0645	0.0034	0.0034	1.1186	0.0602	0.1248	0.0019	0.0019	767	105	762	29	758	11	11	
BLG1505-73	428	487	0.88	0.0673	0.002	0.002	1.242	0.0402	0.1337	0.0017	0.0017	856	64	820	18	809	10	10	
BLG1505-74	81	124	0.65	0.0647	0.0026	0.0026	1.1824	0.0468	0.1331	0.0022	0.0022	765	87	792	22	805	13	13	
BLG1505-75	92	225	0.41	0.159	0.0033	0.0033	9.9756	0.2137	0.4545	0.0057	0.0057	2456	35	2433	20	2415	25	25	
BLG1505-76	111	130	0.86	0.0671	0.0037	0.0037	1.2004	0.0635	0.1313	0.0024	0.0024	843	117	801	29	795	14	14	
BLG1505-77	740	582	1.27	0.0642	0.0019	0.0019	1.1833	0.0352	0.1334	0.0016	0.0016	748	62	793	16	807	9	9	
BLG1505-78	119	192	0.62	0.0679	0.0052	0.0052	1.1445	0.0872	0.1231	0.0023	0.0023	865	160	775	41	748	13	13	
BLG1505-79	42	70	0.61	0.0816	0.005	0.005	1.7359	0.1124	0.1536	0.0027	0.0027	1236	122	1022	42	921	15	15	
BLG1505-80	758	652	1.16	0.0689	0.0021	0.0021	1.2704	0.0385	0.1333	0.0016	0.0016	895	68	833	17	807	9	9	
Sample KDLG1505																			
KDLG1505-01	790	878	0.9	0.0586	0.001	0.001	0.727	0.0138	0.09	0.0009	0.0009	552	36	555	11	555	6	6	
KDLG1505-02	41	68	0.6	0.177	0.0035	0.0035	12.2597	0.2563	0.5023	0.0052	0.0052	2625	32	2624	55	2624	27	27	

Table 2: ...continued

Sample Spot	ω_B /ppm		Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$		$^{206}\text{Pb}/^{238}\text{U}$		$^{207}\text{Pb}/^{206}\text{Pb}$		Apparent age (Ma)		$^{206}\text{Pb}/^{238}\text{U}$	1σ
	Th	U		1σ	Isotopic ration	1σ	1σ	1σ	1σ	$^{207}\text{Pb}/^{235}\text{U}$	1σ		
KDLG1505-03	541	526	1.03	0.0561	0.0014	0.5541	0.015	0.0716	0.0008	458	57	446	5
KDLG1505-04	386	345	1.12	0.0558	0.0022	0.5469	0.0221	0.071	0.0008	446	87	442	5
KDLG1505-06	324	299	1.08	0.0557	0.0026	0.5447	0.0258	0.0709	0.0008	440	105	442	5
KDLG1505-07	253	388	0.65	0.0676	0.002	1.2823	0.0392	0.1378	0.0017	857	63	832	9
KDLG1505-08	216	178	1.21	0.1838	0.0031	12.3995	0.2285	0.4892	0.0053	2688	28	2567	28
KDLG1505-09	140	346	0.41	0.0651	0.0015	1.123	0.0266	0.1252	0.0013	776	47	760	8
KDLG1505-10	374	269	1.39	0.0559	0.0025	0.5444	0.0245	0.0706	0.0008	448	99	440	5
KDLG1505-11	111	277	0.4	0.064	0.0017	1.0624	0.029	0.1205	0.0013	741	57	733	8
KDLG1505-12	343	749	0.46	0.0709	0.0012	1.5623	0.028	0.1598	0.0017	955	34	956	10
KDLG1505-14	193	386	0.5	0.1583	0.0023	9.9527	0.159	0.4559	0.0049	2438	24	2421	26
KDLG1505-15	85	123	0.69	0.1179	0.0019	5.6393	0.0982	0.347	0.0036	1924	29	1920	20
KDLG1505-16	169	262	0.64	0.0978	0.0016	3.0352	0.054	0.2251	0.0023	1582	30	1309	14
KDLG1505-17	89	277	0.32	0.0564	0.0021	0.5575	0.0216	0.0717	0.0008	469	83	446	5
KDLG1505-18	87	278	0.31	0.1695	0.0025	11.3624	0.1847	0.4861	0.0051	2553	24	2554	27
KDLG1505-19	400	453	0.88	0.0563	0.0015	0.5457	0.0159	0.0703	0.0007	463	61	438	5
KDLG1505-20	146	215	0.68	0.1366	0.002	7.5941	0.1211	0.4032	0.0041	2184	26	2184	22
KDLG1505-21	353	666	0.53	0.071	0.0011	1.5708	0.0257	0.1606	0.0016	956	31	960	10
KDLG1505-22	420	453	0.93	0.0558	0.0014	0.5462	0.0142	0.0711	0.0007	443	55	443	5
KDLG1505-23	272	409	0.66	0.0665	0.0012	1.2489	0.0235	0.1363	0.0014	821	36	824	9
KDLG1505-24	477	773	0.62	0.0561	0.0012	0.555	0.0125	0.0717	0.0008	458	48	446	5
KDLG1505-25	822	1014	0.81	0.0714	0.001	1.5729	0.024	0.1599	0.0017	968	27	956	10
KDLG1505-26	111	225	0.49	0.0566	0.0027	0.5569	0.0271	0.0714	0.0008	474	105	445	5
KDLG1505-27	136	220	0.62	0.0564	0.0027	0.552	0.0263	0.071	0.0008	467	104	442	5
KDLG1505-28	790	878	0.9	0.0586	0.001	0.727	0.0138	0.09	0.0009	552	36	555	6
KDLG1505-29	92	1054	0.09	0.0699	0.001	1.4749	0.0229	0.1531	0.0016	924	28	919	10
KDLG1505-30	136	898	0.15	0.1126	0.0015	4.2313	0.0659	0.2725	0.0029	1842	25	1553	17
KDLG1505-31	302	481	0.63	0.0659	0.0012	1.175	0.0232	0.1294	0.0013	802	38	784	8
KDLG1505-32	107	304	0.35	0.056	0.0162	0.5377	0.1544	0.0696	0.0009	454	640	434	5
KDLG1505-33	102	195	0.52	0.1615	0.0024	8.4156	0.1353	0.3779	0.0038	2472	25	2066	21
KDLG1505-34	965	742	1.3	0.0654	0.0014	1.2533	0.0296	0.1381	0.0018	787	44	834	10
KDLG1505-35	229	150	1.53	0.064	0.0024	1.0639	0.0403	0.1205	0.0013	743	80	733	8
KDLG1505-36	319	881	0.36	0.0797	0.0011	1.7772	0.0279	0.1616	0.0016	1191	28	966	10
KDLG1505-40	656	648	1.01	0.0563	0.0013	0.5506	0.0129	0.0709	0.0007	465	50	442	5
KDLG1505-41	269	695	0.39	0.1742	0.0027	10.4835	0.1796	0.4364	0.0046	2599	26	2335	25
KDLG1505-42	218	125	1.75	0.0679	0.0021	1.3418	0.0485	0.1432	0.0021	867	65	863	13
KDLG1505-43	41	51	0.8	0.0783	0.0068	1.57	0.1347	0.1457	0.0039	1155	173	877	22
KDLG1505-44	237	337	0.7	0.0657	0.0012	1.1946	0.0236	0.1319	0.0013	796	39	799	8
KDLG1505-45	1411	637	2.22	0.0645	0.0011	1.0997	0.0199	0.1236	0.0013	758	35	751	8
KDLG1505-46	332	154	2.15	0.0643	0.0025	1.0568	0.0422	0.1193	0.0013	750	82	726	8
KDLG1505-47	266	541	0.49	0.1707	0.0023	9.906	0.1598	0.4208	0.0047	2565	23	2264	25

Table 2: ...continued

Sample Spot	ω_B/ppm	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$		Isotopic ratio		$^{206}\text{Pb}/^{238}\text{U}$		$^{207}\text{Pb}/^{206}\text{Pb}$		Apparent age (Ma)		$^{206}\text{Pb}/^{238}\text{U}$	
Th	U		1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ
KDLG1505-49	267	391	0.68	0.0565	0.0016	0.5761	0.0171	0.0739	0.0008	474	64	462	14	460
KDLG1505-50	178	261	0.68	0.0561	0.0026	0.5451	0.0267	0.0705	0.0008	456	102	442	22	439
KDLG1505-51	429	339	1.27	0.0674	0.0014	1.2778	0.0288	0.1376	0.0014	849	42	836	19	831
KDLG1505-52	82	78	1.05	0.1376	0.0024	6.5832	0.1296	0.347	0.004	2197	30	2057	40	1920
KDLG1505-53	110	219	0.5	0.0588	0.0013	0.6957	0.0167	0.0857	0.001	561	48	536	13	530
KDLG1505-55	372	456	0.82	0.0556	0.0026	0.5483	0.026	0.0717	0.0012	435	136	444	17	447
KDLG1505-56	37	153	0.24	0.1521	0.0044	9.2775	0.3286	0.4395	0.0101	2369	49	2366	32	2348
KDLG1505-58	324	554	0.58	0.0554	0.0023	0.5455	0.0231	0.0714	0.0011	428	94	442	15	444
KDLG1505-59	99	143	0.7	0.0706	0.0038	1.353	0.0684	0.1398	0.0027	946	111	869	30	844
KDLG1505-60	65	106	0.62	0.0707	0.0043	1.2933	0.0811	0.1342	0.0031	950	125	843	36	812
KDLG1505-61	89	159	0.56	0.0618	0.0041	0.5957	0.0415	0.0701	0.0016	733	144	475	26	436
KDLG1505-62	32	76	0.43	0.1185	0.0045	5.7298	0.2059	0.3509	0.0061	1944	101	1936	31	1939
KDLG1505-64	65	124	0.52	0.1112	0.0038	5.1238	0.1714	0.3327	0.0061	1820	62	1840	28	1851
KDLG1505-65	141	145	0.98	0.065	0.0036	1.0661	0.0553	0.1196	0.0025	772	117	737	27	728
KDLG1505-67	172	219	0.79	0.0574	0.004	0.5676	0.04	0.0712	0.0014	506	152	456	26	443
KDLG1505-68	104	187	0.56	0.0524	0.004	0.4916	0.0371	0.0674	0.0014	306	179	406	25	420
KDLG1505-69	345	383	0.9	0.0555	0.0023	0.5542	0.0239	0.0713	0.0012	435	89	448	16	444
KDLG1505-70	402	407	0.99	0.0572	0.0028	0.5649	0.0259	0.0714	0.001	498	112	455	17	445
KDLG1505-71	142	264	0.54	0.0686	0.0026	1.2796	0.0475	0.1343	0.0019	887	79	837	21	812
KDLG1505-72	373	470	0.79	0.0653	0.0022	1.1107	0.0383	0.122	0.0016	783	72	758	18	742
KDLG1505-74	78	123	0.64	0.1232	0.0038	6.2775	0.196	0.3664	0.0058	2003	55	2015	27	2013
KDLG1505-75	71	195	0.36	0.0729	0.003	1.5292	0.0647	0.1507	0.0023	1013	83	942	26	905
KDLG1505-76	437	301	1.45	0.0753	0.0028	1.6259	0.0638	0.1554	0.0025	1076	69	980	25	931
KDLG1505-77	102	239	0.43	0.0707	0.0033	1.3061	0.0616	0.1332	0.0024	950	94	848	27	806
KDLG1505-78	30	41	0.73	0.1151	0.0054	5.2916	0.2536	0.3334	0.0064	1883	85	1868	41	1855
KDLG1505-79	75	141	0.53	0.0807	0.0027	2.0223	0.0668	0.1801	0.0022	1215	67	1123	22	1068
KDLG1505-80	88	185	0.48	0.1448	0.0036	7.6864	0.179	0.3822	0.0042	2287	43	2195	21	2087

Table 3: Hf isotopic compositions of zircons from the Zhongwunongshan Group sandstones

Sample	U-Pb Age (Ma)	$\frac{^{176}\text{Yb}}{^{177}\text{Hf}}$	$\frac{^{176}\text{Lu}}{^{177}\text{Hf}}$	2σ	$\frac{^{176}\text{Hf}}{^{177}\text{Hf}}$	2σ	$\epsilon_{Hf}(0)$	$\epsilon_{Hf}(t)$	T_{DM}^C
Sample BLG1505									
BLG1505-01	2372	0.014893	0.000503	0.000008	0.281265	0.000023	-53.3	-0.95	2960
BLG1505-02	830	0.034457	0.001056	0.000039	0.282392	0.000027	-13.43	4.34	1446
BLG1505-03	832	0.020833	0.000634	0.000002	0.28227	0.000022	-17.75	0.27	1704
BLG1505-04	822	0.054682	0.001565	0.000026	0.2824	0.000022	-13.16	4.16	1452
BLG1505-06	831	0.018978	0.000557	0.000003	0.28253	0.000025	-8.57	9.5	1120

Table 3: ...continued

Sample	U-Pb Age (Ma)	$\frac{^{176}\text{Lu}}{^{177}\text{Hf}}$	2σ	$\frac{^{176}\text{Hf}}{^{177}\text{Hf}}$	2σ	$\epsilon_{\text{Hf}}(0)$	$\epsilon_{\text{Hf}}(t)$	T_{DM}^{C}
BLG1505-07	659	0.033059	0.001168	0.000058	0.000023	-13.29	0.74	1542
BLG1505-08	821	0.037872	0.00114	0.000028	0.000024	-15.11	2.4	1561
BLG1505-10	832	0.040049	0.001355	0.000015	0.000022	-9.79	7.86	1225
BLG1505-11	826	0.02147	0.000714	0.000007	0.000023	-14.8	3.05	1523
BLG1505-12	830	0.097608	0.003171	0.000059	0.00002	-12.58	4.02	1467
BLG1505-14	725	0.049159	0.001682	0.000156	0.000028	-13.41	1.79	1527
BLG1505-15	832	0.051351	0.001449	0.000066	0.000027	-22.72	-5.15	2045
BLG1505-17	2431	0.02254	0.00073	0.000003	0.000024	-55.29	-1.97	3068
BLG1505-18	834	0.077842	0.002077	0.000018	0.000027	-28.92	-11.66	2455
BLG1505-19	833	0.022269	0.00071	0.000003	0.000025	-13.24	4.8	1421
BLG1505-20	2440	0.017897	0.000506	0.000002	0.000019	-63.1	-9.27	3519
BLG1505-22	749	0.02431	0.000792	0.000016	0.000025	-16.22	-0.09	1663
BLG1505-23	1583	0.062695	0.001971	0.000062	0.000022	-38.57	-5.47	2634
BLG1505-25	831	0.100069	0.003164	0.00004	0.000026	-9.64	6.98	1280
BLG1505-28	825	0.018694	0.000616	0.000008	0.000026	-27.61	-9.73	2327
BLG1505-29	827	0.019528	0.00055	0.000023	0.000019	-22.44	-4.48	2000
BLG1505-32	831	0.036456	0.001106	0.000002	0.000026	-16.54	1.21	1644
BLG1505-33	835	0.040226	0.001201	0.000007	0.000026	-14.72	3.07	1530
BLG1505-34	831	0.026978	0.000853	0.00001	0.000025	-21.39	-3.5	1941
BLG1505-35	832	0.049137	0.001592	0.00002	0.000025	-9.52	8	1217
BLG1505-36	829	0.014769	0.000522	0.000049	0.000021	-18.87	-0.86	1773
BLG1505-39	832	0.008091	0.000247	0.000001	0.000027	-26.53	-8.3	2242
BLG1505-40	832	0.038534	0.001343	0.000065	0.000025	-18.37	-0.75	1768
BLG1505-41	833	0.039793	0.001258	0.000039	0.000028	-17.77	-0.06	1727
BLG1505-42	829	0.030067	0.001048	0.000023	0.000025	-9.33	8.43	1187
BLG1505-43	765	0.032088	0.001025	0.000015	0.000026	-21.04	-4.69	1965
BLG1505-44	832	0.060327	0.00168	0.000023	0.000024	-18.34	-0.9	1777
BLG1505-45	835	0.025155	0.000839	0.000011	0.000025	-21.7	-3.73	1959
BLG1505-47	828	0.046628	0.001702	0.000024	0.000027	-12.8	4.54	1430
BLG1505-48	830	0.009163	0.000271	0.000001	0.000026	-30.01	-11.85	2463
BLG1505-50	2102	0.007978	0.000196	0.000003	0.000023	-58.16	-11.48	3398
Sample KDLG1505								
KDLG1505-02	2625	0.010742	0.000327	0.00001	0.000023	-62.23	-3.86	3331
KDLG1505-03	446	0.019216	0.000612	0.000009	0.000021	-13.88	-4.26	1696

Table 3: ...continued

Sample	U-Pb Age (Ma)	$\frac{^{176}\text{Lu}}{^{177}\text{Hf}}$	2σ	$\frac{^{176}\text{Hf}}{^{177}\text{Hf}}$	2σ	$\epsilon_{\text{Hf}}(0)$	$\epsilon_{\text{Hf}}(t)$	T_{DM}^c
KDLG1505-04	442	0.019617	0.000607	0.000031	0.000021	-15.53	-5.98	1802
KDLG1505-06	442	0.015493	0.000484	0.000015	0.000026	-19.08	-9.48	2023
KDLG1505-07	832	0.013424	0.000359	0.000012	0.000021	-29.36	-11.2	2424
KDLG1505-08	2688	0.047057	0.001472	0.000005	0.000028	-62.32	-4.6	3425
KDLG1505-09	760	0.049388	0.001607	0.000047	0.000027	-29.95	-14.01	2545
KDLG1505-10	440	0.017338	0.000533	0.000003	0.000026	-19.13	-9.6	2029
KDLG1505-11	733	0.017129	0.000497	0.000012	0.000022	-23.28	-7.35	2108
KDLG1505-12	956	0.018144	0.000532	0.000007	0.000024	-21.56	-0.75	1864
KDLG1505-13	439	0.021354	0.000672	0.000009	0.000021	-14.74	-5.27	1755
KDLG1505-14	2438	0.0212	0.000651	0.000022	0.000024	-47.76	5.87	2593
KDLG1505-15	1924	0.017898	0.00052	0.000014	0.000025	-42.48	-0.2	2570
KDLG1505-16	1582	0.046345	0.001719	0.000076	0.000028	-34.23	-0.84	2349
KDLG1505-17	446	0.040986	0.001226	0.000023	0.000025	-17.59	-8.16	1941
KDLG1505-18	2553	0.017914	0.000595	0.000008	0.000025	-53.54	2.77	2871
KDLG1505-19	438	0.027397	0.000829	0.000025	0.000022	-16.58	-7.16	1875
KDLG1505-20	2184	0.021474	0.000679	0.000034	0.000025	-52.53	-4.7	3045
KDLG1505-21	960	0.057063	0.001823	0.000071	0.000027	-16.27	3.81	1581
KDLG1505-22	443	0.015489	0.000483	0.000006	0.000024	-12.71	-3.09	1621
KDLG1505-23	824	0.05065	0.001531	0.000043	0.00002	-30.32	-12.98	2529
KDLG1505-24	446	0.03988	0.001225	0.000039	0.000026	-14.08	-4.62	1720
KDLG1505-25	956	0.053563	0.001465	0.000019	0.000024	-33	-12.83	2617
KDLG1505-26	445	0.036234	0.001077	0.000012	0.000022	-16.95	-7.47	1898
KDLG1505-27	442	0.01839	0.000546	0.000005	0.000024	-16.33	-6.76	1853
KDLG1505-28	555	0.027264	0.000786	0.000013	0.000027	-20.52	-8.58	2052
KDLG1505-30	1842	0.029848	0.00085	0.000005	0.000023	-41.08	-1.04	2559
KDLG1505-31	784	0.058477	0.001719	0.000023	0.00003	-28.1	-11.71	2419
KDLG1505-32	434	0.02181	0.000654	0.000013	0.000021	-18.73	-9.38	2010
KDLG1505-33	2472	0.027235	0.000883	0.000008	0.000025	-63.68	-9.74	3572
KDLG1505-34	834	0.043409	0.001189	0.000005	0.000026	-31.94	-14.21	2612
KDLG1505-35	733	0.055346	0.001726	0.000011	0.000028	-25.75	-10.43	2300
KDLG1505-36	966	0.011427	0.00034	0.000006	0.000023	-37	-15.87	2815
KDLG1505-40	442	0.019077	0.000597	0.000011	0.000021	-15.82	-6.26	1820
KDLG1505-42	877	0.049528	0.001589	0.000013	0.00003	-25.98	-7.54	2228
KDLG1505-43	1152	0.01379	0.000446	0.000007	0.000021	-32.26	-7.1	2409

Table 3: ...continued

Sample	U-Pb Age (Ma)	$\frac{^{176}\text{Yb}}{^{177}\text{Hf}}$	$\frac{^{176}\text{Lu}}{^{177}\text{Hf}}$	2σ	$\frac{^{176}\text{Hf}}{^{177}\text{Hf}}$	2σ	$\epsilon_{\text{Hf}}(0)$	$\epsilon_{\text{Hf}}(t)$	T_{DM}^c
KDLG1505-44	799	0.045299	0.001299	0.000012	0.281855	0.000025	-32.44	-15.52	2667
KDLG1505-45	751	0.080713	0.002377	0.000026	0.281896	0.00003	-30.97	-15.59	2637
KDLG1505-46	726	0.087725	0.00254	0.000021	0.281989	0.00003	-27.69	-12.93	2450
KDLG1505-47	2565	0.047276	0.001282	0.000049	0.28114	0.000023	-57.73	-2.36	3195
KDLG1505-49	460	0.018305	0.000567	0.000021	0.282323	0.000021	-15.88	-5.93	1813
KDLG1505-50	439	0.044257	0.001376	0.000035	0.282259	0.000029	-18.15	-8.91	1983
KDLG1505-51	831	0.029402	0.000888	0.00001	0.282014	0.00003	-26.81	-8.96	2282
KDLG1505-52	2197	0.015031	0.000448	0.000003	0.281306	0.000025	-51.84	-3.34	2972
KDLG1505-53	530	0.030277	0.000878	0.000002	0.282029	0.00003	-26.28	-14.94	2432

5 Discussion

5.1 Sources of detritus

The zircon U-Pb age histogram of the clastic samples showed two major populations (460–434 Ma and 966–725 Ma), which illustrated that the zircons of the Zhongwunongshan Group were mainly derived from Neoproterozoic and late Early Palaeozoic detritus source rocks (Figure 4). The Neoproterozoic granitic gneiss with similar formation ages was found in the Yuqia-Shaliuhe HP-UHP metamorphic belt, located on the southern margin of the NQSB [3, 27]. Due to the continental collision between the Olongbruk Microblock and the Qaidam Block, the most important Neoproterozoic tonalite-monzonitic granites were formed, and intruded into the Yuqia-Shaliuhe HP-UHP metamorphic belt during the Jinningian period (1000–800 Ma) [28, 29, 36, 45]. In addition, the Hf isotopic results showed that the Neoproterozoic zircons from the sample KDLG1505 also had similar model age (2815–1581 Ma, with a peak of 2362 Ma), and a similar origin (dominated by ancient crust melting) as the Neoproterozoic Shaliuhe granitic gneiss in the eastern section of the Yuqia-Shaliuhe HP-UHP metamorphic belt [2, 46]. However, since the two-stage model age (T_{DM}^C) of sample BLG1505 in the western section was lower than that in the eastern section, the $\epsilon\text{Hf}(t)$ was found to be significantly higher (Table 2, Figure 5). These results indicated that the Neoproterozoic detritus source rock in the western section may have been mixed with depleted mantle. A previous survey revealed that eclogite which developed in the Xitieshan granitic gneiss of the western section was originally the oceanic ridge basalt, with crystallization ages of 1000–800 Ma and positive $\epsilon\text{Nd}(t)$ [47, 48]. It confirmed that the Neoproterozoic granite gneiss in the west may have been formed during a crust-remelting process, and mixed with depleted mantle, which caused the model age T_{DM}^C to be below the normal value in the east [49, 50]. Therefore, in the Yuqia-Shaliuhe HP-UHP metamorphic belt of North Qaidam, the Neoproterozoic granitic gneiss can likely be one of the major detritus source for the Zhongwunongshan Group.

The detrital zircon U-Pb age histogram also showed that the late Early Paleozoic detritus source rocks within the age population of 460–434 Ma were another major source of the Zhongwunongshan Group (Figure 4). However, the zircons in this age range only appeared in the eastern section of the study area. It was indicated that the detritus source rocks were slightly different between the eastern and western sections of the study area. The Hf isotopic analysis showed that the late Paleozoic detri-

tus source rocks were mainly derived from the remelted magma of the lower crust reservoir (Figure 5). A previous survey indicated the sustained oceanic crust subduction occurred when the Qaidam block northward dived beneath the Olongbruk Microblock during the Late Ordovician [36, 63]. Due to the rapid subduction, the thickened lower continental crust melting took place which formed the active epicontinental arc tonalite-granodiorite (450–440 Ma) in the Tanjianshan ophiolite-volcanic arc belt [3, 12, 28, 51]. As the only Early Paleozoic continental arc granites within the age population in the study area, the Tomorit quartz diorite-monzogranite series approaching to the south of Ulan was another source for the Zhongwunongshan Group.

5.2 Age of the Zhongwunongshan Group

Because the deposition age of sedimentary formation must be younger than the youngest detrital zircon, which can be regarded as the maximum deposition age for this formation [52–54]. This approach has been successfully applied to the time determination for sedimentary strata, especially to successions where biostratigraphy cannot be used [55, 56].

In this study, the $^{206}\text{Pb}/^{238}\text{U}$ age of the youngest detrital zircon (KDLG1505-32) of the Zhongwunongshan Group is 434 ± 5 Ma (Table 2), and can be regarded as the maximum deposition age of the Zhongwunongshan Group. As the major provenances for the Zhongwunongshan Group, the significant input of detritus materials derived from the Yuqia-Shaliuhe HP-UHP metamorphic belt and the Tanjianshan ophiolite-volcanic arc belt to the south (Figure 1b). The widespread Maonianshan Group in Devonian period of the above source regions was characterized of the youngest detrital zircon age of 407.9 Ma [57], which limited the deposition of the Maoniushan Group to be later than the Early Devonian. However, the detrital zircon U-Pb ages of the Zhongwunongshan Group were all older than 407.9 Ma, which indicated the absence of detritus materials of 407.9 Ma in the source regions during the Zhongwunongshan group deposited, and limited the depositional age of that strata to be older than early Devonian (407.9 Ma).

5.3 Tectonic significance

In the period from late Late Neoproterozoic to Middle Ordovician (580–465 Ma), the North Qaidam oceanic crust subducted northward beneath the Olongbruk Microblock, resulted in the formation of the Tanjianshan volcanic is-

land arc [32, 58, 59] and Yuqia-Shaliuhe ultrahigh pressure metamorphic rocks [60, 61]. This subduction also induced compensatory convection of the mantle wedge behind the island arc, and forced deep-seated magma to upwell which resulted in back-arc extension [63].

During the Late Ordovician to Middle Silurian (465–435 Ma), the North Qaidam Ocean closed and the Qaidam Block collided with the Olongbruk Microblock. Due to the rapid subduction, the thickened lower continental crust melting took place which formed the epicontinental arc tonalites-granodiorites (450–440 Ma) in the Tanjianshan ophiolite-volcanic arc belt [3, 12, 28]. At the same time, the back-arc basin to the north of the North Qaidam deposited thick flysch sediments in the ZWSB and the adjacent South Qilian area during the Silurian [63].

The Late Silurian-Early Devonian (435–400 Ma) is an important transition period for the Early Paleozoic tectonic evolution in the North Qaidam. The continuous movement of the asthenosphere with respect to the lithosphere at this stage promoted detachment within the lithosphere and caused partial melting of the subducted continental crust. Meanwhile the alkaline basaltic magma, derived from remelting of deep subduction of the oceanic crust, uplifted and mixed with the continental crust magma. The mixed magma was finally emplaced in both sides of the HP-UHP zone, which formed the Early Devonian gneissic granite with the characteristics of intraplate cracking. The zircons from the gneissic granite yielded a U-Pb isotopic age about 400 Ma [3, 12], marking the completion of the Caledonian collisional orogeny in the NQSB.

In conclusion, the Zhongwunongshan Group was deposited during the period from the late Early Silurian to the early Early Devonian (434–407.9 Ma), when the North Qaidam was in the orogenic stage of the end of the early Paleozoic. Its provenance mainly came from the uplifting and erosion of the Yuqia-Shaliuhe HP-UHP metamorphic belt and the Tanjianshan ophiolite-volcanic island arc belt of the NQSB. Furthermore, the Zhongwunongshan Group was located in the back-arc area to the Early Paleozoic Tanjianshan volcanic island arc belt of North Qaidam. With this information, it suggests that the Zhongwunongshan Group in the ZWSB and adjacent area is obviously dominated by the intense collisional orogeny of the North Qaidam in the end of the Early Paleozoic, which formed in the late Early Paleozoic back-arc basin.

6 Conclusion

Our new data allow the following major conclusions:

1. The detrital zircon U-Pb dating results of the Zhongwunongshan Group showed two major populations. The first was Neoproterozoic (966–725 Ma) with a $\epsilon_{\text{Hf}}(t) = -15.9$ to 9.5, and the other was late Early Paleozoic (460–434 Ma) with a $\epsilon_{\text{Hf}}(t) = -9.6$ to -3.1 . Based on the regional studies, the dominated provenances were found to be the Neoproterozoic granitic gneiss of the Yuqia-Shaliuhe HP-UHP metamorphic belt and the late Early Paleozoic granites of the Tanjianshan ophiolite-volcanic arc belt in the NQSB.
2. In combination with previous research, the youngest detritus zircon ages of 434 Ma suggest that the Zhongwunongshan Group was deposited in the back-arc sedimentary basin associated with the Caledonian collisional orogeny of the NQSB during the Middle Silurian-Early Devonian (434–407.9 Ma).

Acknowledgement: We are grateful to Mr Dongdong Yu, Suyang Jiang and Kai Li for their help during the zircon U-Pb and Lu-Hf analyses. This study was financially supported by the subject of National Key R&D Program of China (subject No.2017YFC0602806) and the National Natural Science Foundation of China (grant number 4157021100).

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