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Late Devonian closure of the North Qilian Ocean: evidence from detrital zircon U–Pb geochronology and Hf isotopes in the eastern North Qilian Orogenic Belt

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The closure age of the North Qilian Ocean, which lay between the Alashan Terrane and Central Qilian Block during the early Palaeozoic, is intensely debated. This article presents a provenance study of detrital materials from three Upper Devonian sedimentary formations in the Pingchuan area of Gansu Province in the eastern North Qilian Orogenic Belt (NQOB), to constrain the tectonic evolution of the belt. U–Pb dating and Lu–Hf isotopic studies were conducted on detrital zircons from samples of sedimentary rocks. Four age populations of U–Pb zircon ages are defined as: 0.5–0.4 Ga (peak at 472 Ma); 0.8–1.3 Ga (peaks at 960 Ma and 1102 Ma); 1.8–2.1 Ga (two prominent peaks at 1963 Ma and 2045 Ma, and two subordinate peaks at 1816 Ma and 2168 Ma); and 2.4–2.5 Ga (peak at 2495 Ma). Zircons with U–Pb age spectra of 1.8–2.1 Ga and their corresponding zHf(t) values are markedly different from those of the North China Block, Dunhuang Terrane, and Central Qilian Block, but have a strong similarity to zircons from the Alashan Terrane. Furthermore, zircons with ages ranging from 1.8 to 2.1 Ga are reported for the first time in early Palaeozoic strata of the eastern NQOB. The presence of Alashan-derived clasts in the Upper Devonian strata in the NQOB indicates that the sediments were deposited after amalgamation between the Alashan and Qilian terranes. Combined with previous geochronological and geochemical data from the early Palaeozoic igneous and sedimentary rocks, we propose that the closure of the North Qilian Ocean occurred in the Late Devonian. The similar age spectra of detrital zircons from sediments of the Alashan, Cathaysia, and Australia imply that the Alashan–Qilian–Qaidam block was probably located in the periphery of Gondwana in the early Palaeozoic.

Keywords: North Qilian Ocean; Alashan Terrane; Late Devonian; detrital zircons; U–Pb age; Hf isotopes

1. Introduction

The Qilian Orogen is located in the northern Tibetan Plateau and is part of the Qinling–Qilian–Kunlun Fold System or the Central China Orogenic Belt (Wu et al. 1993) (Figure 1), in which numerous Neoproterozoic magmatic and metamorphic events might record the amalgamation of the supercontinent Rodinia (Yu et al. 2013). In addition, the Qilian Orogen provides the link between the dominantly collisional terranes to the south (Tibetan Plateau) and the dominantly accretionary belts to the north (Altaid Orogenic belt) and west (Kunlun orogenic belt) (Xiao et al. 2009). The Qilian Orogen is, therefore, a key region for understanding the tectonic evolution of the Central China Orogenic Belt in the Neoproterozoic to early Palaeozoic.


The Alashan Terrane (also called Alxa), which bridges the Mongolian fold belt and the Tarim, Qaidam, is situated at the north of Qilian Orogen. The Alashan Terrane was considered to be the westernmost part of the North China Block (NCB) (e.g. Zhao et al. 2004, 2005; Santosh et al. 2013).
However, palaeomagnetism and geochronological analyses of detrital zircons suggested that the Alashan Terrane was not connected with the NCB prior to the Early to Middle Triassic (Yuan and Yang 2014a, 2014b). Moreover, the Qilian Orogen had affinity with Gondwana from the Neoproterozoic to early Palaeozoic (Tung et al. 2007, 2013). So, the closure age of the North Qilian Ocean (NQO), which is located between the Alashan Terrane and Central Qilian Block (CQB), is crucial to understanding the tectonic attribute of the Alashan Terrane and its palaeogeographic affinity in the early Palaeozoic. However, the closure age of the NQO remains debated. HP/LT metamorphic rocks mainly consisting of blueschist and LT eclogite are considered to be an important indicator of former subduction zones (e.g. Ernst 1971; Zhang JX et al. 2007), and the study of lawsonite-bearing metamorphic rocks is important for understanding the preservation and exhumation of lawsonite in a subduction zone (Zhang LF et al. 2009). Based on $^{40}$Ar/$^{39}$Ar ages of 440–460 Ma obtained for glaucophane and phengite from blueschist in NQO, combined with the presence of Silurian remnant-sea flysch and Devonian molasses, some authors have concluded that the NQO closed at the end of the Ordovician (Liou et al. 1989; Wu et al. 1993; Song 1997; Zhang et al. 1997a; Song et al. 2004; 2005, 2007, 2009, 2013; Liu et al. 2006; Song 2009). However, this interpretation is inconsistent with the following aspects of the NQO: (1) arc-related magmatism did not end in the middle Silurian and (2) the petrology and geochemistry of volcanic clasts from Silurian and Lower–Middle Devonian sedimentary rocks indicate that the sediments are forearc basin fill (Wang and Liu 1976; Yan et al. 2007, 2010; Xiao et al. 2009). These two lines of evidence indicate that the NQO did not close until the Early–Middle Devonian, and resolving these discrepancies may improve our understanding of the regional tectonic setting and the evolution of the Qilian Orogen. A definitive age for the NQO will also aid in reconstructing the basic tectonic framework of Northwest China in the early Palaeozoic.

Figure 1. Sketch map of China showing the tectonic elements and orogenic belts. Several orogenic belts were formed as a result of multiple stage accretion and arc–continent collision events from the early Neoproterozoic to the Palaeozoic; for example, the Central Asian belt (Windley et al. 2007), the Qilian Belt (Wu et al. 1993; Xu et al. 1994; Xiao et al. 2009; Song et al. 2013), and the Qinling belt (Meng and Zhang 2000). The inset boxes show the locations of Figure 2A and Figure 2B.
2. Geological background and sampling

The Qilian Orogen is located to the south of the Alashan Terrane, north of the Qaidam Block, and southwest of the NCB (Figure 1). The Altyn–Tagh Fault is the largest sinistral strike-slip fault in Northwest China and transects the Qilian Orogen and its possible extension, the Altyn Mountains in the Tarim Craton (Yang 1997; Figure 1). The Qilian Orogen is composed of three parts from north to south: the NQOB, the CQB, and the South Qilian Orogenic Belt. These three blocks are separated by fault zones along the northern margin of each block in addition to the Qaidam northern marginal fault zone that marks the southern boundary of the Qilian Orogen (Wang and Liu 1976; Zuo and Liu 1987; Xia et al. 1991; Feng and Wu 1992; Lu et al. 2009).

The NQOB is located at the northern margin of the Qilian Orogenic belt and lies between the Alashan Terrane and the CQB (Figure 2A). It strikes NW–SE and is ~1000 km long. The petrological, metamorphic, and structural characteristics reveal that the NQOB was formed by subduction–collision-related processes in the Neoproterozoic to early Palaeozoic, and the belt contains ophiolites, HP/LT metamorphic rocks, seamounts, Ordovician–Silurian island arc volcanic rocks and granitoid plutons, accretionary prisms, Devonian molasses, and Carboniferous to Triassic sedimentary cover sequences (Wu et al. 1993; Xu et al. 1994; Song 1997; Xia et al. 1998; Zhang JX et al. 1998; Xia et al. 2003b; Xiao et al. 2009; Song et al. 2013).

The ophiolite sequences in the NQOB are distributed along two belts (Song et al. 2013; Fig. 2A). The southern belt extends from Aoyougou in the northwest, via Yushugou and Dongcaobe, to Yongdeng. The northern belt extends from Jiugequan at its westernmost extent, via Biandukou, to Laohushan in the southeast. The ophiolitic gabbros yielded U–Pb ages of 449–550 Ma (Shi et al. 2004; Tseng et al. 2007; Xiang et al. 2007; Xia and Song 2010; Song et al. 2013). Island arc volcanic rocks are widely distributed in the NQOB, which is >800 km long, extending from Baiyinchang in the southeast, via Xidaoliu in Minle County and Shihuigou in Yongdeng County, to Bianmagou in Qilian County at its westernmost extent (Xia et al. 1995a). Geochemical and chronological data indicate the presence of abundant 420–486 Ma subduction-related calc–alkaline magmatic rocks (Xia et al. 1996; Zhang et al. 1997a; Mao et al. 2000; Gehrels et al. 2003; Shi et al. 2004; Wu et al. 2004, 2006, 2011; Wang et al. 2005; Chen 2007; Tseng et al. 2009; Yan et al. 2010).

The blueschist belt of the NQOB contains high-grade blueschist and glaucophane eclogite extending

Figure 2. (A) Sketch maps of the NQOB (modified after Song et al. 2013). (B) Simplified geological map of the study area and adjacent regions in Pingchuan at the eastern end of the NQOB. The star symbol denotes the sampled section. (C) Silurian to Carboniferous stratigraphic section of the eastern NQOB.
discontinuously over a distance of ~500 km (Wu et al. 1993). Based on the petrological, mineralogical, and geochronological studies, the belts are suggested to be one of the oldest ‘cold’ oceanic subduction zones on Earth, with a palaeo-geothermal gradient of 6–7°C km⁻¹ (Zhang et al. 2007; Song et al. 2009, 2013). SHRIMP U–Pb dating of zircons from the eclogitic samples yielded ages of 460–517 Ma (Song et al. 2004, 2006; Zhang et al. 2007; Xia et al., 2012). ⁴⁰Ar/³⁹Ar dating of glaucophane and phengite from lawsonite blueschist gives an isochron age of 380–460 Ma (Liou et al. 1989; Wu et al. 1993; Zhang et al. 1997a; Song et al. 2005; Liu et al. 2006, 2007, 2009, 2013; Lin et al. 2010; Lin and Zhang 2012).

A Silurian sedimentary sequence occurs mainly in the southern part of the Hexi Corridor Belt, but also in the northern margin of the NQOB (Wu et al. 1993). It consists predominately of silty and thin-bedded massive sandstones that are interfingered with conglomerates and calc–alkaline basaltic and andesitic rocks (R.G.S. Gansu 1971; Song 1997). The sedimentary rocks are composed predominantly of terrigenous flysch, perhaps reflecting deposition in a remnant ocean basin (Wu et al. 1993) or in a forearc basin (Yan et al. 2010). Devonian sedimentary rocks are scattered throughout the NQOB and are interpreted as non-marine molasses, resulting from rapid orogeny; they are not metamorphosed and they disconformably overlie the lower Palaeozoic sequences (Huang et al. 1980; Wu et al. 1993). The Devonian strata in the eastern NQOB include the Lower–Middle Devonian Laojunshan Formation and the Upper Devonian Shaliushui Formation (R.G.S. Gansu 1971). In the Pingchuan area, the Upper Devonian Shaliushui Formation (D3sh) is overlain by lower Carboniferous strata across a paraconformity and is overlain by the Lower–Middle Devonian Laojunshan Formation across an angular unconformity. The Shaliushui formation, 89–95 m thick in the study area, is composed of grey to white conglomerate, pebbly coarse sandstones interbedded with purple siltstone at the base, and mauve siltstone and mudstone interbedded with sandstone (BGMRGS 1990). The sandstones contain large-scale, trough-shaped cross-bedding of fluvial facies (BGMRGS 1990). The plant fossils Leptophloeum rhombicum Dawson, Sublepidodendron sp., Sublepidodendron mirabile, Sublepidodendron wusihense, Cordaites sp., Rhodea sp., Lepidodendron sp., Sphenopteris sp. and Asterolamites sp., and the fish fossil Bothriolepidae gen. et sp. indet have been reported from this formation (BGMRGS 1990). Among them, Leptophloeum rhombicum, Sublepidodendron mirabile, and Sublepidodendron wusihense, which are representative plant fossils of the Wutong and Huangjiadeng formations in South China, were endemic species in the Late Devonian (BGMRGS 1990). Importantly, the palaeontological data suggest that the Shaliushui formation was deposited in the Late Devonian. In this study, three sandstone samples (PC-2, PC-3, and PC-5) were obtained from the Upper Devonian Shaliushui formation at Shaliushui village in Pingchuan County, eastern NQOB (Figure 2B and C).

3. Analytical methods

Zircons were separated from crushed samples by conventional heavy liquid and magnetic separation techniques, then hand-picked under a binocular microscope. The zircon grains were mounted in epoxy resin, polished, and coated with gold. All zircons were photographed in transmitted and reflected light to characterize the analysed grains. Cathodoluminescence (CL) images of the grains were made using an electron microscope (Quanta 400 FEG) equipped with a Mono CL3+ system (Gatan, USA), operated at an accelerating voltage of 10 kV and current of 240 µA at the State Key Laboratory of Continental Dynamics at Northwest University, Xi’an, China.

Zircon U–Pb isotopic compositions were analysed at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, using laser ablation inductively coupled plasma mass spectrometry (LA–ICP–MS). These analyses were carried out using a laser spot size of 23 µm at a repetition rate of 8 Hz, which has an energy density of 15 J cm⁻². Zircon ages were calibrated using zircons 91,500 (1062.4 ± 0.6 Ma) and GJ-1 (608.53 ± 0.37 Ma) as the standard and unknown, respectively. Trace-element concentrations were corrected using ²⁹Si as an internal standard and NIST610 as an external standard (Pearce et al. 1997). The zircon 91,500 and glass NIST 610 standards were measured twice before and twice after the analyses of zircons from each sample. Zircons GJ-1 and 91,500 were measured once each after analyses of 10 unknown zircons, and NIST 610 was analysed once after analyses of 20 unknown zircons. The detailed analytical procedures are similar to those described by Xie et al. (2008). Age calculations and plotting of concordia diagrams were performed using the Isoplot program (version 3.0) (Ludwig 2003).

In situ Hf isotope analyses were performed with a Neptune LA–multi-collector–ICP–MS coupled to a 193 nm excimer ArF laser ablation system (GeoLas Plus) at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China. This instrument is a double-multi-collector–ICP–MS that can operate at high mass resolution. The Hf isotope analyses used a laser spot size of 60 µm at a repetition rate of 4 Hz, which has an energy density of 15 J cm⁻² and pulse width of 15 ns. Helium was used as a carrier gas to enhance transport of the ablated material to the mass spectrometer. Initial ¹⁷⁶Hf/¹⁷⁷Hf values were calculated...
with a $176\text{Lu}$ decay constant of $1.865 \times 10^{-11} \text{y}^{-1}$ (Söderlund et al. 2004). Lu–Hf model ages were calculated using a $^{176}\text{Lu}/^{177}\text{Hf}$ ratio for average crust of 0.015, present-day $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of chondritic and depleted mantle of 0.0332 and 0.0384, respectively, and present-day $^{176}\text{Hf}/^{177}\text{Hf}$ ratios for chondritic and depleted mantle of 0.282772 and 0.28325, respectively (Blichert-Toft et al. 1997; Griffin et al. 2004).

CL images were used to avoid inclusion analysis and grain–epoxy boundaries. During U–Pb dating analyses, each mounted zircon grain (>32 µm) was dated from left to right, until either 140 or 150 zircon grains had been dated.

4. Analytical results

The zircon grains were colourless and transparent or brown to light brown in colour. The generally euhedral nature of the zircons suggests that they are derived from nearby rocks. However, some rounded zircons indicate that they have been abraded during long-distance transport or multiphase reworking. In situ U–Pb and Hf isotopic data for detrital zircons from the three samples of the Shaliushui formation are summarized in Supplementary Documents 1 and 2 (see http://dx.doi.org/10.1080/00206814.2014.999357). CL images of representative zircons from all samples are shown in Figure 3. A total of 359 U–Pb ages were obtained that are concordant between 80% and 117% (Figure 4) (Supplementary Document 1). For zircons with ages of >1000 Ma, the $^{207}\text{Pb}/^{206}\text{Pb}$ age is more reliable, whereas for zircons with ages of <1000 Ma, the $^{206}\text{Pb}/^{238}\text{U}$ age is more reliable. Although Hf and U–Pb isotope analyses were conducted separately, Hf isotope analyses were performed at the same sites as those used for U–Pb dating. A total of 321 zircon Hf isotope measurements were carried out (Figure 5; Supplementary Document 2).

![Figure 3. CL images of representative zircons from three samples in the eastern NQOB. The large circles indicate the sites of Hf isotope analyses and the small circles indicate the sites of U–Pb age analyses. The scale bar is 100 µm long.](image-url)
4.1 Sample PC-2

A total of 148 analyses of 140 grains were undertaken for sample PC-2, which yielded 121 concordant analyses with ages from $462 \pm 11$ Ma to $3574 \pm 17$ Ma (Figure 4a and e; Supplementary Document 1). Three populations are evident: 0.4–0.6 Ga (peak at 482 Ma); 1.8–2.1 Ga (prominent peak at 1970 Ma, and two secondary peaks at 1826 Ma and 2166 Ma); and 2.4–2.6 Ga (peak at 2503 Ma). Three grains yielded $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 3104 ± 18 Ma, 3514 ± 17 Ma, and 3574 ± 17 Ma. The dated zircons range in size from 60 to 250 µm and most zircons exhibit oscillatory zoning and are bright in CL images. Zircon Th/U ratios vary between 0.04 and 1.37 (95% of the grains have Th/U > 0.1). The CL images and Th/U ratios indicate that the majority of the detrital zircons have a magmatic origin.

Hf isotope analysis of 116 zircons was undertaken for sample PC-2 (Supplementary Document 2). The 0.4–0.5 Ga zircons have $\varepsilon$Hf(t) values between $-11.6$ and $-7.4$ with the model ages of 1940–2178 Ma. However, the 1.8–2.1 Ga zircons have $\varepsilon$Hf(t) values between $-9.7$ and $+5.0$ with model ages of 2333–3384 Ma, and the 2.4–2.6 Ga zircons have $\varepsilon$Hf(t) values between $-7.1$ and $+5.6$ with model ages of 2751–3447 Ma, indicating that their
parent magmas were derived from 2.7 to 3.3 Ga continental crust.

4.2 Sample PC-3

For sample PC-3, 142 analyses of 140 grains were conducted (Supplementary Document 1), yielding 122 concordant ages from 483 ± 10 Ma to 3357 ± 17 Ma. Three age groups were obtained: 0.4–0.6 Ga (peak at 493 Ma); 1.8–2.1 Ga (two prominent peaks at 1970 Ma and 2054 Ma, and two secondary peaks at 1819 Ma and 2177 Ma); and 2.4–2.6 Ga (peak at 2504 Ma) (Figure 4b and f; Supplementary Document 1). Zircons in sample PC-3 range in size from 70 to 230 µm. Th/U ratios vary from 0.02 to 1.18, and only five zircon grains have Th/U < 0.1. Most zircon grains exhibit oscillatory zoning and high Th/U values, which are typical of a magmatic origin.

In situ Hf isotopic analyses of 101 zircons were undertaken for sample PC-3 (Supplementary Document 2). Zircons with ages of 0.4–0.6 Ga have negative εHf(t) values (−12.2 to −9.4) with model ages of 1942–2234 Ma. The negative εHf(t) values suggest that the parent magmas were produced by crustal reworking. Zircons with ages of 1.8–2.1 Ga have εHf(t) values between −8.0 and +7.5, which correspond to model ages of 2297–3014 Ma. The 2.4–2.6 Ga zircons have εHf(t) values between −0.1 and +6.6 with model ages of 2561–3001 Ma, indicating that their parent magmas were derived from juvenile crust.

4.3 Sample PC-5

A total of 142 analyses of 139 grains were obtained for sample PC-5 (Supplementary Document 1), yielding 116 concordant ages from 436 ± 10 Ma to 3214 ± 22 Ma. Two age populations can be identified: 0.4–0.6 Ga (peak at 469 Ma) and 0.8–1.3 Ga (peaks at 967 Ma and 1109 Ma). Another 10 zircon grains yielded ages of 1613–2487 Ma, accounting for 8.6% of the total. Only one zircon yielded ages older than 3.0 Ga (3214 ± 22 Ma). The Th/U ratios of these zircons range between 0.02 and 1.27, with only two zircons having Th/U < 0.1. Most zircons have oscillatory zoning, and this observation, along with their high Th/U ratios, indicates a magmatic origin.

In total, 104 zircons from sample PC-5 were analysed for Hf isotopes (Supplementary Document 2). The 0.4–0.6 Ga zircons have εHf(t) values between −27.5 and +9.8 with a correspondingly large range in model ages of 830–3257 Ma. The 0.8–1.3 Ga zircons have εHf(t) values between −23.5 and +10.5 with a correspondingly large range of model ages of 1184–3384 Ma, suggesting that the zircons have different origins or host magmas if they are crystallized at a similar time.

5. Discussion

5.1 Provenance analysis

Zircon U–Pb age spectra obtained from the Devonian sedimentary rocks formed near the northern margin of the NQOB generally define five age populations at 0.4–0.5 Ga, 0.8–1.3 Ga, 1.8–2.1 Ga, 2.4–2.7 Ga, and >3.0 Ga (Figure 4d).

Detrital zircon U–Pb ages indicate that samples PC-2, PC-3, and PC-5 have peaks at 482 Ma, 493 Ma, and 469 Ma, respectively. The zircons with U–Pb ages of 0.4–0.5 Ga are typically euhedral, indicating derivation from a nearby source area. Arc-related volcanic and granitic rocks are widely developed in the North Qilian Orogen, ranging in age from 490 to 424 Ma (Xia et al. 1996; Zhang et al. 1997a; Mao et al. 2000; Gehrels et al. 2003; Shi et al. 2004; Wu et al. 2004, 2006, 2011; Wang

Figure 5. Hf isotopic evolution diagram of detrital zircons in Late Devonian rocks from NQOB in this study.
et al. 2005; Chen 2007; Tseng et al. 2009; Zhao et al. 2014). We suggest, therefore, that the 0.4–0.5 Ga detrital zircons (peak at 468 Ma) were likely sourced from the Ordovician volcanic rocks in the NQOB during the Late Devonian.

Neoproterozoic igneous rocks with ages of 0.7–1.0 Ga crop out widely in the North Qilian Orogen and the CQB. Neoproterozoic magmatic rocks in the North Qilian Orogen yield ages from 724 ± 4 Ma to 776 ± 10 Ma (Su et al. 2004; Tseng et al. 2006; He et al. 2010), whereas ages in the CQB range from 790 ± 12 Ma to 943 ± 28 Ma (Guo et al. 2000; Wan et al. 2000, 2003; Tung et al. 2007; Wang et al. 2007). Moreover, numerous Neoproterozoic magmatic and metamorphic events (950–900 Ma) have also been reported in the Altun–Qilian–North Qaidam region that might record amalgamation of the supercontinent Rodinia (Yu et al. 2013). Also, records of extensive 1.0–0.8 Ga magmatic events are reported in the Alashan Terrane: zircon U–Pb ages from 807 ± 4 Ma to 833 ± 35 Ma have been obtained from the Longshoushan pluton in the Jinchuan area at the southern margin of the Alashan Terrane (Li XH et al. 2004; Yang et al. 2005; Tian et al. 2007); and 845–971 Ma gneisses occur in the eastern Alashan Terrane (Geng et al. 2002; Geng and Zhou 2010). These data indicate that the zircons with ages of 0.7–1.0 Ga may have a source in the Qilian Orogenic Belt and/or Alashan Terrane.

Furthermore, detrital zircons reveal U–Pb ages of 1.0–1.3 Ga; however, magmatic events in that age range are rarely reported in the Qilian Orogen and Alashan Terrane, suggesting that the 1.3–1.0 Ga detrital zircons in the NQOB did not originate from the Qilian Orogen or Alashan Terrane.

Geological studies suggest that the Grenvillian Orogeny occurred widely in South Laurentia, the Maud–Namaqua–Natal province of East Antarctica, Southwest Australia, Amazonia, and Africa at 1.0–1.3 Ga (Hoffman 1991; Boger et al. 2000; Jayananda et al. 2000). Yuan and Yang (2014a) suggested that detrital materials with ages of 1.0–1.3 Ga in the Upper Devonian sandstones at the southeastern margin of the Alashan Terrane have a strong affinity with sediments from the Cathaysian Block. Furthermore, petrographic and geochemical studies of Neoproterozoic granitoids from the CQB indicate that the CQB was part of the South China Block in Neoproterozoic time (Tung et al. 2013). We speculate that the 1.0–1.3 Ga detrital zircons from the NQOB have an affinity with the contemporaneous clastic material in the South China Block.

A prominent group of detrital zircons with a U–Pb age of 2.5 Ga has been reported from sedimentary strata in major Gondwanan blocks. However, it is unsound to deduce their provenance based solely on zircon U–Pb age spectra. Zircon Hf isotopic data can also be used as a provenance tool (Hoskin and Ireland 2000; Fedo et al. 2003). In the present study, 2.5 Ga zircons have εHf(t) values between −15 and +6.6, which correspond to Hf crustal model ages of 2561–3946 Ma with a peak at 2.95 Ga and few dates younger than 2.8 Ga (Figure 6d). Detrital zircons with ages of ca. 2.5 Ga from the NCB have Hf isotope model ages mainly in the range of 2.6–2.9 Ga with a peak at 2.75 Ga, implying an important crustal growth event at 2.75 Ga (Li QL et al. 2007; Zheng et al. 2009; Jiang et al. 2010; Diwu et al. 2011; Wan et al. 2011a, 2011b; Wang et al. 2011) (Figure 6b). These results indicate a difference between detrital material in the NQOB and NCB. Moreover, detrital zircon U–Pb chronology and palaeomagnetic studies suggest that the Alashan Terrane migrated towards the NCB after the Early–Middle Triassic (Yuan and Yang 2014a, 2014b). The Hf isotope model ages of the ca. 2.5 Ga detrital zircons in the NQOB are similar to those in the Alashan Terrane, but are different from the Dunhuang Terrane (Zhang et al. 2013a) (Figure 6a and c). These results support a close affinity between the ca. 2.5 Ga detrital zircons from Upper Devonian strata in the NQOB and contemporaneous detritus in the Alashan Terrane.

5.2 Implications for the closure age of the North Qilian Ocean

The closure age of the NQO has been a topic of intense debate. An Ordovician–Silurian closure age has been suggested (e.g. Xia et al. 1996; Song 1997, 2009; Qian et al. 1998; Song et al. 2004, 2005, 2007, 2009, 2013; Yang et al. 2009; Xu et al. 2010a, 2010b) on the basis of, for example, an angular unconformity between the lower Silurian and older strata, suggesting a strong orogenic influence during the early Silurian in the NQOB (Song 1997). However, Lu et al. (2009) argued that the so-called basal conglomerate on the unconformity between the lower Silurian and Upper Ordovician is in fact a set of conglomerates of marine–waterway facies, with well-rounded, poorly sorted, variably cemented gravel of varied composition. In addition, graded bedding is well developed and is indicative of high-density turbidites (Lu et al. 2009). This evidence suggests that the NQO may not have closed until the Late Ordovician.

The results of recent geochemical and isotopic studies on the Silurian sandstones and conglomerates in North Qilian seem to be consistent with a forearc basin model, and the oceanic crust between the Alashan Terrane and CQB was active and continued to the Silurian (Yan et al. 2010). Geochemical studies on the igneous rocks in North Qilian indicate that the Chenjiahe intermediate to acidic granite and alkaline diorite pluton at Laohushan in the Jingtai area has an age of 424 ± 3 Ma (Qian et al. 1998) and has characteristics typical of an island arc setting. In addition, geochemical and chronological studies of granitoid
clasts in the Middle Devonian conglomerates (Laojunshan Formation) indicate that subduction-related island-arc rocks with an age of 425 ± 1.6 Ma were the source of the detrital material (Yan et al. 2007). The arc volcanism took place in the middle Silurian, indicating that subduction had not ceased by that time.

Samples PC-3 and PC-2 record a zircon age population of 1.8–2.1 Ga; ages in this range are rarely reported in early Palaeozoic sedimentary strata in the NQOB. Sample PC-3 yields two prominent peaks at 1970 Ma and 2166 Ma (Figure 4a), and sample PC-2 is characterized by a main peak at 1970 Ma and two secondary peaks at 1826 Ma and 2166 Ma (Figure 4b). The detrital zircons from Precambrian basement in the Qilian Orogen exhibit a U–Pb age spectrum with a peak at 1766 Ma, but this peak is absent in the 1.8–2.1 Ga age spectrum (Tung et al. 2007; Li et al., 2007; He et al. 2010) (Figure 7a), indicating that the 1.8–2.1 Ga detrital material identified in this study was not sourced from the Qilian Orogen.

Recently, detrital and magmatic zircons with ages of 1.8–2.1 Ga have been reported from the Alashan Terrane, the Dunhuang Terrane, and the western part of the NCB (Darby and Gehrels 2006; Dan et al. 2012; Zhang et al. 2013a, 2013b) (Figure 7b–d). The εHf(t) values of 1.8–2.1 Ga zircons in the present study are between −9.7 and +7.5 with a peak at +2.0 (Figure 8d). However, contemporaneous zircons yield εHf(t) values between −13.7 and −5.3 with a peak at −9.0 in the Dunhuang Terrane (Zhang et al. 2013a) (Figure 8a), which is markedly different from those in the NQOB. Detrital zircons in Neoproterozoic–Ordovician strata in the Zhuozishan area at the western margin of the NCB preserve a U–Pb age peak at 1947 Ma and two minor peaks at 1994 Ma and 2047 Ma (Darby and Gehrels 2006) (Figure 7c). Detrital material younger than 1.85 Ga is absent in the NCB, but exists in the NQOB (Figure 7c and e), suggesting different provenances for the clastic material. Moreover, detrital zircon U–Pb chronology and palaeomagnetic studies have shown that the Alashan Terrane was not part of North China by the Late Devonian (Yuan and Yang 2014a, 2014b). These results indicate that the ca. 2.1–1.8 Ga detrital zircons in the NQOB were not sourced from the NCB or the Dunhuang Terrane in the Late Devonian.

Numerous geological and chronological studies have been conducted in the Alashan Terrane. Palaeoproterozoic magmatic events have an age range of 2100–1800 Ma, which can be divided into three stages: the first stage occurred at ca. 2050 Ma (Li JJ et al. 2004; Geng et al. 2009); the second stage at 1900–1950 Ma (Geng et al. 2009, 2010); and the third stage at 1800–1850 Ma (Shen et al. 2005; Zhou et al. 2007; Geng et al. 2010). In the eastern Alashan Terrane, the Bayanwula and Diebusige complexes were overprinted by three metamorphic events.
at ca. 1890 Ma, 1850 Ma (Zhang et al. 2013b), and ca. 1790 Ma (Dan et al. 2012). In this study, the detrital zircon age spectra between 1.8 Ga and 2.1 Ga have a close affinity with the Palaeoproterozoic magmatic event in the Alashan Terrane (Figure 4d). In addition, the εHf(t) values of 1.8–2.1 Ga zircons in the present study are consistent with those of zircons from the Palaeoproterozoic basement of the Alashan Terrane (Figure 8c and d). Therefore, we consider that the 1.8–2.1 Ga detrital zircons in the NQOB

Figure 7. Relative age probability plot comparing the ages of Precambrian basement from: (a) the Qilian Orogen (Li et al. 2007a; Tung et al. 2007; He et al. 2010); (b) the Dunhuang Terrane (Zhang et al. 2013a); (c) western North China Block (Darby and Gehrels 2006); (d) Alashan Terrane (Tung et al. 2007; Yin et al. 2011; Dan et al. 2012; Zhang et al. 2013b); and (e) the detrital zircons in the NQOB (this study).

Figure 8. Histogram of εHf(t) value of 1.8–2.1 Ga detrital zircons in (a) the Dunhuang Terrane (Zhang et al. 2013a); (b) the North China Block (Geng et al. 2011); (c) the Alashan Terrane (Yin et al. 2011; Dan et al. 2012; Zhang et al. 2013b); and (d) the NQOB (this study).
were sourced from the Alashan Terrane in the Late Devonian.

The NQO lay between the CQB and Alashan Terrane. The presence of Alashan-derived clasts in the Upper Devonian strata in the NQOB indicates that the sedimentary sequence was deposited after collision between the Alashan Terrane and the CQB. Further study has shown that the 1.8–2.1 Ga detrital zircons are found only in samples PC-2 and PC-3 from the Upper Devonian Shaliushui formation in the upper part of the sampling profiles (Figure 2C, Figure 4A and B), whereas 1.8–2.1 Ga detrital zircons are absent in sample PC-5 (Figure 2C and Figure 4C) and in samples from the Middle–Upper Devonian (Xu et al. 2010b) (Figure 9B) and pre-Devonian strata in the Qilian Orogenic Belt (Yang et al. 2009; Xu et al. 2010a) (Figure 9c and D). These results suggest that the NQO may have closed during the Late Devonian.

Closure of the NQO in the Late Devonian is also supported by an HP/LT metamorphic event. \(^{40}\)Ar/\(^{39}\)Ar dating of glaucophane and phengite from lawsonite blueschist gives an isochron age range of 380–423 Ma (Wu et al. 1993; Zhang et al. 1997a; Lin et al. 2010; Lin and Zhang 2012), suggesting that subduction of the oceanic crust continued until the Middle Devonian. In addition, the Jinfosi pluton (Rb–Sr age of 419.87 ± 0.4 Ma, Zhang et al. 1995) and Xiaoliugou granodiorite (U–Pb age of 417.7 ± 1.7 Ma, Zhao et al. 2014) were generated probably in a syn-collision setting in the western NQOB. However, geochemical data from the Huangyanghe pluton in the eastern NQOB (which yields an LA–ICP–MS U–Pb zircon age of 383 ± 6 Ma, Wu et al. 2004) indicated that granite was formed in a post-collision environment. These results implied that the closure time of the NQO was probably diachronous, the western NQOB was during the late Silurian, whereas the eastern NQOB was during the late Devonian (Figure 10).

In the late Cambrian to early Silurian, the ocean located in the north of Qaidam block was subducted northwards beneath the Oulongbuluk block that was connected with the CQB by the South Qilian ocean (Xiao et al. 2009). In the early to middle Silurian, the CQB had probably amalgamated with the Oulongbuluk block (Xiao et al. 2009). We therefore propose that the NQO was closed in the Late Devonian, implying that the Alashan Terrane, Qilian Orogen, and Qaidam Block had amalgamated into a consistent block at that time.

Palaeomagnetic study has showed that the Alashan Terrane was not connected with the NCB prior to the Early–Middle Triassic (Yuan and Yang 2014b). However, age spectra of the detrital zircons separated from the Middle to Late Devonian sandstones in the Alashan Terrane have shown affinity with those of sediments in the Cathaysian Block in southeast China (Yuan and Yang 2014a). In addition, paleography and geochemistry study have shown that the CQB might be part of the South China block in Neoproterozoic time (Tung et al. 2013). Palaeontological studies demonstrate that the trilobites in Cambrian strata from the Qilian Orogen have endemic species of the Tarim–Yangtze biogeographic domain (Duan and Ge 2005),

![Figure 9](image_url)  
Figure 9. Relative age probability plot comparing the ages of the NQOB from: (a) Late Devonian (this study); (b) Mid–Late Devonian (Xu et al. 2010b); (c) early Silurian (Yang et al. 2009); and (d) Mid–Late Ordovician (Xu et al. 2010a).
which have a close relationship with trilobites from south China and northwest Queensland in Australia (Zhou et al. 1996). The antiarchian fossils were a type of freshwater fish that are found in the Upper Devonian Zhongning formation in the Alashan Terrane, which have a close affinity with those from south China and New South Wales, Australia (Pan et al. 1987; Jia et al. 2010). Since the South China Block was probably connected with the northwestern margin of Australia (Yang et al. 2004), these results suggest that the Alashan–Qilian–Qaidam block was very probably located in the periphery of Gondwana during the Palaeozoic.

6. Conclusion
Detailed U–Pb geochronology and in situ zircon Hf isotope analyses were conducted on detrital zircons from Upper Devonian sandstone in the eastern NQOB. The results indicate that 0.4–0.5 Ga detrital zircons were sourced from in situ Ordovician volcanic rocks in the NQOB, while detrital zircons dated to 1.0–1.3 Ga have an unknown provenance. Detrital zircons dated to 1.8–2.1 Ga were sourced from Palaeoproterozoic igneous rocks in the Alashan Terrane and are reported for the first time in early Palaeozoic strata of the NQOB. The occurrence of Alashan-derived detritus indicates a post-collision sedimentary environment and records the closure of the NQO. This evidence, combined with previous geochronological and geochemical data from the Palaeozoic igneous rocks, leads us to propose that the eastern NQO closed during the Late Devonian. The Alashan–Qilian–Qaidam block was situated in the periphery of the Gondwanaland during the early Palaeozoic.

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