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ARTICLE

Tectono-magmatic events of the Qilian orogenic belt in northern Tibet: new insights from detrital zircon geochronology of river sands

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ABSTRACT

The Precambrian–Palaeozoic evolution of the Qilian orogen is widely debated due to the complexity of the orogen's structure and the extent of Phanerozoic deformation. In order to identify the tectono-magmatic events of the Qilian orogenic belt, we conducted detrital zircon U-Pb geochronology on river sediments across the orogen. The results indicate that the detrital zircon ages mainly comprise five populations: 220–280 Ma, 400–520 Ma, 800–1000 Ma, 1200–2100 Ma, and 2200–2700 Ma. The sediments in the Central Qilian Block exhibit zircon age peaks at ~1.8 Ga and ~1.0 Ga, which support that the Central Qilian Block successively accreted to the Columbia and Rodinia supercontinents. The sediments in the Quanji Block exhibit zircon age peaks at ~1.8 Ga and ~2.5 Ga, revealing possible affinity of the Quanji Block to the North China Craton prior to the Neoproterozoic. The detrital zircon age population in 400–520 Ma of all the sediments recorded the continental aggregation process among the Quanji, Qaidam, and Central Qilian Blocks. The widespread 200–300 Ma zircon ages in Central Qilian, Quanji, and North Qaidam regions, reflect a tectono-magmatic event which was most likely associated with the low-angle Paleo-Tethys subduction at the southern margin of Qaidam Block. Our results underline that the overlooked Neoarchean to Paleoproterozoic and Permian to Triassic tectono-magmatic events of the Qilian orogenic belt deserves more attention in the future study. The detrital zircon age populations of different river sand samples indicate fairly high variability, highlighting that caution should be exercised while using modern river sand detrital zircon age signatures to track tectono-magmatic history of such complex orogens.

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Detrital zircon; Qilian orogenic belt; Quanji Block; tectonic evolution; Tibetan plateau

1. Introduction

The ~1200 km long, 100–200 km wide Palaeozoic Qilian orogenic belt is located at the northeast margin of Tibetan Plateau and composes the west segment of the central orogenic belt of China (Kunlun-Qilian-Qinling-Dabie-Sulu orogenic belt). The NW-SE trending Qilian orogenic belt has been offset to the northwest by the sinistral Altyn-Tagh fault (Figure 1(b); Wang 1997; Yue and Liou 1999; Bendick *et al*. 2000; Yin *et al*. 2002). The Qilian orogenic belt is considered to record Palaeozoic amalgamation history of east Asia as well as the far-field effect of the Cenozoic collision between India and Eurasia plates (e.g. Zhang and Zhou 2001c; Song *et al*. 2006, 2007, 2009a, 2013; Zhang *et al*. 2007, 2015a; Wang *et al*. 2016b; Allen *et al*. 2017). For this reason, the Qilian orogenic belt has been widely studied over the past decades (Xiao *et al*. 1974, 1978; Wang and Liu 1976; Li *et al*. 1978; Dong and Qiu 1984; Zuo 1986; Zuo and Liu 1987; Xia *et al*. 1991a, 1991b, 1995, 1996, 1998, 1999, 2003, 2016; Xu *et al*. 1994; Feng and He 1995a, 1995b, 1996; Zhang *et al*. 1998a, 1998b, 2007, 2017b; Zhang and Zhou 2001c; Song *et al*. 2003a, 2003b, 2004, 2005, 2006, 2007, 2009a, 2009b, 2010b, 2013, 2014a, 2014b, 2017, 2019b; Zhang and Meng 2006b; Xiao *et al*. 2009; Zuza *et al*. 2013, 2016, 2018; Yang *et al*. 2019).

The Qilian orogenic belt has experienced a protracted multiple-stage tectonic evolution history (Song *et al*. 2017). The orogen can be divided into five subunits based on pre-Mesozoic history, i.e. North Qilian suture zone, Central Qilian Block, South Qilian belt, Quanji Block, and North Qaidam ultrahigh-pressure (UHP) metamorphic belt from north to south (Figure 1(b)), Lu *et al*. 2002b; Pan *et al*. 2002; Chen *et al*. 2013; Song *et al*. 2013). Crustal composing of the Central Qilian Block is thought to have developed as a part of the supercontinent Rodinia (Tseng *et al*. 2006; Song *et al*. 2013, 2014a, 2014b; Wang *et al*. 2015; Xu *et al*. 2015, 2016). The

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The supplemental data for this article can be accessed here.

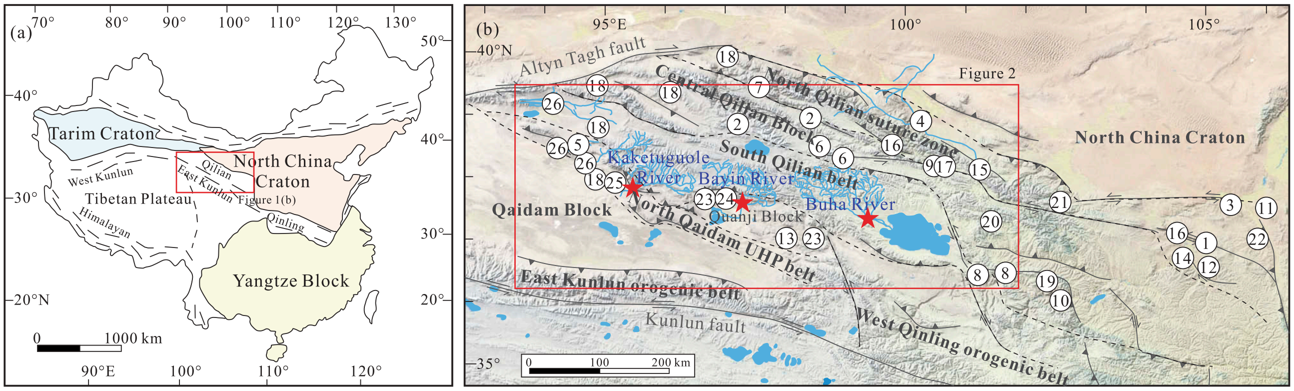

Figure 1. (a) Schematic maps of tectonic units in China (Zhao *et al*. 2001); (b) Tectonic units of the Qilian orogenic belt, sample locations from this study and previous studies. Red stars mean the sample of this study, circled numbers mean the reference numbers shown in Table S1.

North Qilian Ocean, which located between the Central Qilian Block and North China Craton, opened in early-middle Neoproterozoic due to the upwelling of mantle plume (Xu *et al*. 2015, 2016). The Pangea supercontinent started to amalgamate at ~520 Ma; most major crustal fragments had accreted by ~300 Ma and Pangea began to break up by at least ~200 Ma (Olsen 1997; Rogers and Santosh 2002, 2003; Metcalfe 2013; Stampfli *et al*. 2013; Zhao *et al*. 2018). During the amalgamation of Pangea, the North Qilian Ocean lithosphere is thought to have started subducting beneath the Central Qilian Block by ~520 Ma and the North China Craton (or outboard but now accreted island arc terranes) by ~470 Ma (Wu *et al*. 2011). The Central Qilian Block and North China Craton collided in the early Palaeozoic (Song *et al*. 2004, 2012; Lu *et al*. 2006a; Zhang and Meng 2006b; Tung *et al*. 2007a, 2007b; Wu *et al*. 2009; Hu *et al*. 2015; Mu *et al*. 2018). Ophiolites, arc-, and subduction-related plutons, low temperature/high pressure metamorphic rocks, and pre-, syn- and post-collisional granitoids in the Qilian orogenic belt record this accretionary process (Xiao *et al*. 1978; Wu *et al*. 1993; Zhang *et al*. 1998a, 1998b; 2001a, 2001b, 2001c, 2001d, 2009c, 2012a, 2012b; Song *et al*. 2004, 2006, 2007, 2013, 2017, 2019b; Shi *et al*. 2004; Tseng *et al*. 2007; Yang *et al*. 2019). In the Mesozoic and Cenozoic, the Qilian orogenic belt underwent extension and intracontinental orogenesis (Huo and Tan 1995; Vincent and Allen 1999; Yang *et al*. 2001; Zhang *et al*. 2001a, 2001b; Chen *et al*. 2003; Yin *et al*. 2008; Zuza *et al*. 2016, 2018; Allen *et al*. 2017).

Although the framework of tectonic evolution has been widely investigated (Zuza *et al*. 2018 and reference therein), various debates about the tectonic evolution of the Qilian orogenic belt persist. The first issue is the complex Precambrian evolution of the Quanji Block. The Quanji Block (also named as Oulongbuluke Block in some studies) was first proposed by Lu (2002a) based on petrological analysis and zircon U-Pb dating on the Dakendaban Group. Three points about the tectonic recognition of the Quanji Block were proposed, i.e. the Quanji Block has affinity to the North China Craton (Xiao *et al*. 2004; Xing and Lu 2005; Hu *et al*. 2007; Gong *et al*. 2012), to Yangtze Block (Chen *et al*. 2007a, 2007b), and to Tarim Craton (Lu *et al*. 2006b). Differentiating among these tectonic models will be beneficial to better understanding the process of continental amalgamation in east Asia. The second issue is the late Palaeozoic to early Mesozoic tectono-magmatic history of the Qilian orogenic belt. Although orogenesis in the Qilian orogenic belt, which related to the closure of North and South Qilian Ocean, finished at ~360 Ma (Wang *et al*. 2014), a number of magmatic rocks of late Palaeozoic to Triassic have been documented in southern margin of the Qilian orogenic belt (Gehrels *et al*. 2003b; Wu *et al*. 2009; Dong *et al*. 2014, 2015; Chen *et al*. 2015; Cheng *et al*. 2017). The proposed mechanisms of this magmatic activity include: (1) lithospheric subsidence due to intercontinental subduction (Wu *et al*. 2009) and (2) penetrative magmatism led by subducted Paleo-Tethys oceanic plate (Cheng *et al*. 2017).

Zircon is one of the most stable accessory minerals in sedimentary environments. It records the magmatic and metamorphic information of its protolith and is thus useful in understanding the tectonic evolution of continents (Belousova *et al*. 2010; Xu *et al*. 2010a; Gehrels 2014; Zhao *et al*. 2016). Detrital zircon geochronology of river sands can be used to reconstruct continental formation, evolution, and thermal history of crust that is exposed within river catchments (e.g. Lease *et al*. 2007; Yang *et al*. 2009a; Belousova *et al*. 2010; Pepper *et al*. 2016; Gong *et al*. 2017; Liang *et al*. 2018). Modern sand sediments from several rivers across the Qilian orogenic belt were conducted for detrital zircon U-Pb dating in previous studies (Lease *et al*. 2007; Liu *et al*. 2012b; Gong *et al*. 2017; Song *et al*. 2019a, the detailed information of samples is listed in Table S1 (Supporting Information S1)). These target rivers are mainly located in the eastern, northern, and western parts of the orogenic belt. Based on the kernel density estimation (KDE) plots of the published detrital zircon U-Pb data in Figure 2, it can be summarized that (1) all of the samples show an age peak at ~450 Ma, which coincides with the closure of North and South Qilian Ocean, and the collision among the Central Qilian Block, Qiadam Block, and North China Craton; (2) the samples have obviously different detrital zircon age populations especially in the Precambrian ages, indicating the complexity of evolution in Precambrian; (3) a part of samples in study area shows an age peak at ~250 Ma, which indicates a tectono-magmatic event in late Palaeozoic to early Cenozoic.

Previously published studies on river sands detrital zircon U-Pb dating might not cover all of the tectono-magmatic information due to the complexity of the river catchments and the complex structure of the Qilian orogenic belt (Figure 2(a)). Neoarchean–Paleoproterozoic age population, which is important to the early evolution of the orogen, had been usually overlooked in most studies (Lease *et al*. 2007; Liu *et al*. 2012b; Gong *et al*. 2017; Song *et al*. 2019a). In this study, we emphasize two points: (1) complexity of the orogen basement and associated Precambrian evolution and (2) late Palaeozoic to early Mesozoic tectono-magmatic history of the orogen. We collected river sand samples from the regions where river sand detrital zircon U-Pb geochronology has been poorly reported, and compiled all the related zircon U-Pb ages of ancient sedimentary rocks, modern river sands and granitoids in the Qilian orogenic belt to have a better understanding of the tectono-magmatic history of the orogen.

2. Geological setting

2.1. North-Central Qilian belt

The North-Central Qilian belt consists of the North Qilian suture zone and the Central Qilian Block. The North Qilian suture zone is an early Palaeozoic suture zone dominated by Neoproterozoic to Palaeozoic rocks, including ophiolite, intermediate-acid arc-related volcanic and intrusive rocks, and marine gravity flow deposits. This lithostratigraphy is interpreted to indicate subduction of North Qilian Ocean lithosphere and record the subsequent continent-continent collision between the Central Qilian Block and North China Craton in the early Palaeozoic (Zhang *et al*. 1998a; Xia *et al*. 1998; Mao *et al*. 2003; Shi *et al*. 2004; Yang *et al*. 2009b; Yang *et al*. 2016b; Xu *et al*. 2010a, 2010b; Song *et al*. 2006, 2013; Wang *et al*. 2018). The North Qilian suture zone could be divided into northern ophiolite belt, middle arc magmatic belt and southern ophiolite belt. The northern ophiolite belt of the North Qilian suture zone is composed of ultramafic rocks, ultramafic cumulates, N-type mid-ocean ridge basalt (MORB), island arc basalt (IAB), ocean island basalt (OIB) and back-arc basin-related boninites with ages of 449–490 Ma (Zhang *et al*. 1998; Wang *et al*. 2005; Xia and Song 2010; Wu *et al*. 2010; Xia *et al*. 2012; Song *et al*. 2013, 2019b; Chen *et al*. 2014). The middle arc magmatic belt consists of boninite complex, arc-volcanic complex and Caledonian granitic plutons (Song *et al*. 2013; Chen *et al*. 2014). The southern ophiolite belt with the age of 497–550 Ma is composed of mantle peridotite, mafic-ultramafic cumulate pillow basaltic lavas, and radiolarian chert (Shi *et al*. 2004; Tseng *et al*. 2007; Song *et al*. 2009b, 2013; Chen *et al*. 2014).

The upper crust of the Central Qilian Block forms an imbricate thrust belt with Proterozoic metamorphic rocks bound by the North Qilian suture zone to the north, the Quanji Block and South Qilian belt to the south (Wang *et al*. 2018). The Precambrian basement of North-Central Qilian belt is located in the Central Qilian Block. The basement of Central Qilian Block was intruded by plutons with ages of 750–1190 Ma (Gehrels *et al*. 2003a, 2003b; Tseng *et al*. 2006; Tung *et al*. 2013; Wu *et al*. 2017; Zuza *et al*. 2018). Neoproterozoic rocks display similar lithologies and compositions to comparable age rocks of the Yangtze Block and are generally considered to witness the amalgamation of Rodinia (Song *et al*. 2012; Xu *et al*. 2015). Early Palaeozoic orogenesis resulted in I-type (e.g. granodiorite, tonalite) and S-type granites (e.g. two-mica granite) in the Central Qilian Block (Cowgill *et al*. 2003; Tung *et al*. 2013, 2016; Huang *et al*. 2015; Yan *et al*. 2015; Yang *et al*. 2015, 2016a).

2.2. The South Qilian–North Qaidam belt

This belt includes the South Qilian belt, Quanji Block, and North Qaidam UHP belt. The South Qilian belt is an arc accretionary system between the Qaidam Block and Central Qilian Block (Pan *et al*. 2002). The South Qilian belt is composed of Palaeozoic rocks. The Cambrian to early Ordovician ophiolite sequence consists of pillowed picrite, ocean-island tholeiitic alkaline basalt, gabbro, ultramafic rocks, and pelagic chert (Fu *et al*. 2014; Zhang *et al*. 2017b), which recorded the closure of South Qilian Ocean and the collision between the Qaidam and Central Qilian Block in the early Palaeozoic (Yang *et al*. 2019; Song *et al*. 2019b). The ophiolite sequence is covered by middle Ordovician arc volcanic

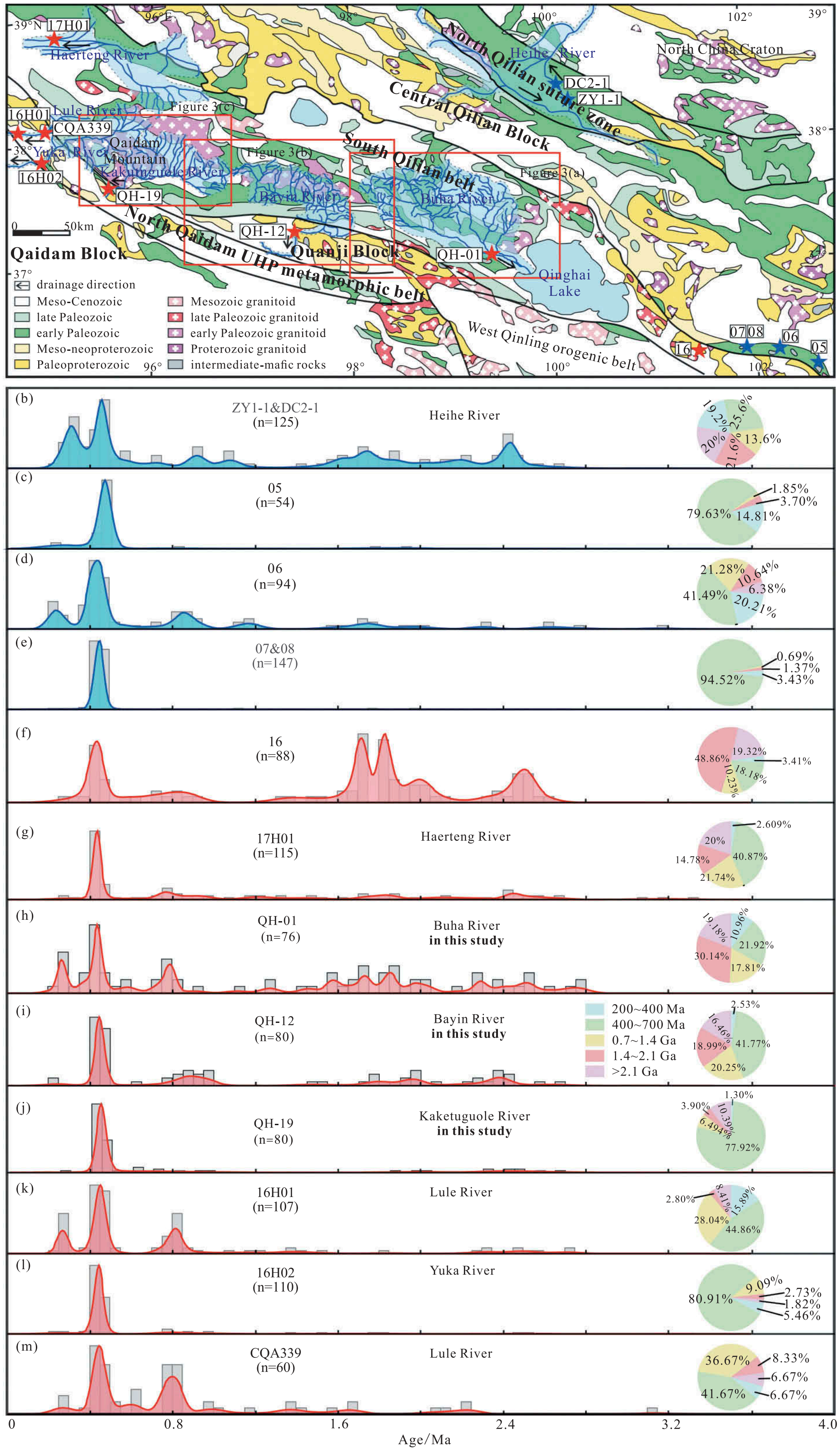

Figure 2. (a) the location of river sand samples for detrital zircon U-Pb dating; (b–m): the detrital zircon age kernel density estimation (KDE) plots of river sand samples in this and previous studies; the sample ZY1-1 and DC2-1were collected from Heihe River (Gong *et al.* 2017); sample 05, 06, 07, 08 and 16 were collected from anonymous rivers (Lease *et al.* 2007); sample 17H01 was collected from Haerteng River (Song *et al.* 2019a); sample 16H01 and CQA339 were collected from Lule River (Liu et al. 2012b; Song *et al.* 2019a); sample 16H02 were collected from Yuka River (Song *et al.* 2019a).The blue stars and KDE plots mean the samples in North-Central Qilian belt, the rea stars and KDE plots mean the samples in North Qilian-South Qaidam belt. Map followed the Geological Map of Tibetan Plateau and Adjacent Area (China Geological Survey, 2004).

rocks, including spilite, pillow basalt, volcaniclastic rocks, and andesitic porphyry, and they are covered by chert and carbonate. The Silurian conglomerate unconformably overlays the Ordovician strata, and is imbricated with the Silurian flysch sediments. The Caledonian granites introduce these strata and volcanic rocks (Lu *et al*. 2002c; Zhao *et al*. 2004b; Xu *et al*. 2006).

The Quanji Block, currently showing as the Precambrian basement of South Qilian–North Qaidam belt, is located among the South Qilian belt, West Qinling orogenic belt, and the NWW-SEE striking North Qaidam UHP belt (Figure 2(a)). The Quanji Block is composed of a crystalline metamorphic basement and a non-metamorphosed sedimentary cover (Hao *et al*. 2004; Wang *et al*. 2006, 2008). The basement consists of the Paleoproterozoic Delingha Complex, Dakendaban Group, and Mesoproterozoic Wandonggou Group, the cover strata consist of Sinian Quanji Group and early Palaeozoic volcano-sedimentary sequences which overlay the basement with a divergent unconformity (Li *et al*. 2007; Chen *et al*. 2007a, 2007b, 2007c; Liu *et al*. 2018b). The Delingha complex and Dakendaban Group underwent the regional metamorphism at the end of Paleoproterozoic, this event was recorded by amphibolite facies and granulite facies rocks (Chen *et al*. 2007a, 2007b). Both mineral Sm-Nd isochron age of granulite (1791 ± 37 Ma) and zircon U-Pb age of rapakivi granite (1776 ± 33 Ma) indicate that the Quanji Block accreted to the Columbia supercontinent in the late Paleoproterozoic (Zhang *et al*. 2001a; Xiao *et al*. 2004). A whole-rock Rb-Sr isochron age (1022 ± 64 Ma) and over grown rims on zircons (~1.0 Ga) from Wandonggou Group metamorphic rocks indicate a regional metamorphic event in the Neoproterozoic (Yu *et al*. 1994; Wang *et al*. 2008).

The North Qaidam UHP belt is ~450 km long with a direction of NWW-SEE. This continental UHP metamorphic belt is located among the Qaidam Block, Quanji Block, and South Qilian belt. There are four well-documented exposures of early Palaeozoic UHP metamorphic rocks in the belt: Dulan; Xitieshan; Shenglikou and Yuka from southeast to northwest (e.g. Yang *et al*. 1998, 2001, 2002, 2005; Song *et al*. 2003a, 2003b, 2004, 2005, 2006, 2007, 2009a, 2009b, 2010b, 2012, 2013, 2014a, 2014b, 2017, 2019b; Mattinson *et al*. 2006a, 2006b; Yin *et al*. 2007; Chen *et al*. 2007c; Zhang *et al*. 2009c; Xiong *et al*. 2012; Fu *et al*. 2015; Zhao *et al*. 2017b). The UHP minerals such as coesites in Yuka eclogite indicate that the peak metamorphism pressure of the North Qaidam UHP belt is 2.8–3.2 GPa and the temperature is 650–700°C (Zhang *et al*. 2009a, 2009b). Rocks in the North Qaidam UHP belt contain ortho- and paragneiss; these rocks intercalated with blocks of eclogite and varying amounts of ultramafic rocks (Song *et al*. 2014b). They are thought to document multi-cycle continental orogenesis from the Neoproterozoic to Palaeozoic. The granitic gneisses with a protolith age of ~0.9–1.0 Ga directly indicates that the magmatism and metamorphism during the formation of Rodinia (Song and Yang 2001; Chen *et al*. 2007c, 2009; Zhang *et al*. 2009a, 2009b; Song *et al*. 2012), and the 850–820 Ma fragment of Large Igneous Province (the protolith of Yuka eclogite) suggested the break-up of Rodinia (Xu *et al*. 2016). The UHP metamorphism occurred in 475–420 Ma due to the continental subduction of Qaidam Block (Song *et al*. 2003a, 2005, 2006; Xu *et al*. 2006; Yang *et al*. 2005, 2019; Yin *et al*. 2007; Zhang *et al*. 2008b, 2009a, 2009b, 2010; Chen *et al*. 2009; Mattinson *et al*. 2006a, 2006b; Meng and Zhang 2009; Yu *et al*. 2011). Furthermore, the Permian-Triassic plutons in the North Qaidam UHP belt are recognized and thought to be related to subduction at the southern margin of Qaidam (Wu *et al*. 2009; Cheng *et al*. 2017).

2.3. Qaidam Block

The supracrustal rocks of the Qaidam Block form an intracontinental basin within the northeast Tibetan Plateau (i.e. the Qaidam Basin). The basin is about 1.2×10^5 km^2 and contains Mesozoic–Cenozoic fluvial-lacustrine sediment that range in thickness between 3 km and 16 km (Sun *et al*. 2005; Jian *et al*. 2013, 2014, 2018, 2019b; Zhang *et al*. 2018). The crystalline basement of the Qaidam Block was influenced by at least three tectonic episodes in the Neoproterozoic, early Palaeozoic, and late Palaeozoic–Mesozoic. The early Palaeozoic and late Palaeozoic–Mesozoic events are recorded by pluton emplacement into the basement rocks. The Cenozoic deformation within Qaidam Block suggests that it is rheologically weaker than the Tarim Craton and North China Craton. Cheng *et al*. (2017) proposed magmatic rejuvenation as the primary reason for this mechanical difference. Far afield stress from the India-Eurasia collision has resulted in differential Cenozoic shortening across the Qaidam Basin with ~300 km in the east and ~100 km in west (Yin *et al*. 2008; Zuza *et al*. 2016).

3. Sampling and analytical methods

3.1. Sample description

Three samples QH-01, QH-12 and QH-19 were collected from three rivers for detrital zircon U-Pb dating. Previous heavy mineral analysis on these sample (Figure S1 in Supporting Information S3) of these rivers shows a high content of hornblende and chlorite, which probably originate from intermediate-acid igneous rocks and metamorphic rocks, respectively. The samples locations are shown in Figure 2(a). Sample QH-01 (37°2′6.28″N, 99°44′ 16.26″E) is a coarse sand sample from the Buha River (Figure 3(a)). The catchment of the Buha River is within the South Qilian belt, and most of the tributaries of the Buha river locate at the northern side of mainstream. The Silurian molasse, Permian sandstone, shale, Triassic terrestrial clastic rocks, dominate the strata in the catchment, with minor Ordovician slate, siltstone, limestone, Neogene mudstone, and marlstone. Early Palaeozoic granitic plutons are exposed at the eastern part of the catchment; and a late Palaeozoic granitic pluton is in the western part of the catchment (Figure 3(a)). Sample QH-12 (37°21′54.59″N, 97°29′37.94″E) is a coarse sand sample from the Bayin River (Figure 3(b)). The mainstream and several tributaries of the Bayin River originate from the early Palaeozoic granitic plutons. The Silurian (besides siltstone, sandstone, slate), Carboniferous (besides limestone, sandstone), Permian strata (besides sandstone, limestone, dolostone) in the South Qilian belt, and the Paleoproterozoic Dakendaban Group schist and granulite in the Quanji Block are located in the Bayin River catchment (Figure 3(b)). Although the Bayin River locates at the South Qilian belt and Quanji Block, the detrital zircon geochronology of this sample could reflect the tectono-magmatic events in the Quanji Block based on the comparison between the detrital zircon age distribution of the sample QH-01 and QH-12. Sample QH-19 (37°40′16.73″N, 95°28′12.11″E) is a fine sand sample from the Kaketuguole River (Figure 3(c)). The Kaketuguole River originates from the western South Qilian belt and erodes the North Qaidam UHP belt. Bedrocks in this catchment are dominated by an early Palaeozoic pluton with an age of 440.8 ± 7.8 Ma (Zhou *et al.* 2013). A few late Palaeozoic plutons are also exposed (Figure 3(c)). The sample QH-19 may indicate the link between the Qaidam Block and the Central Qilian Block because the Kaketuguole River erodes the North Qaidam UHP belt.

3.2. Methods

Zircon grains were separated using heavy liquids and magnetic separation techniques, and then mounted in epoxy grain mounts along with the Zircon Plěovice and Zircon 91,500 reference material to correct for elemental and mass fractionation and NIST610 to determine trace element concentrations (Sláma *et al.* 2008), the weighted mean ages of standards are shown in Figure S2 (Supporting Information S3). The zircon crystals from the samples were then examined with transmitted and reflected light, and then with cathodoluminescence (CL) to identify inclusions that could compromise the analyses. The U/Pb and Pb/Pb ratios were measured using an Agilient 7500a ICP-MS coupled to

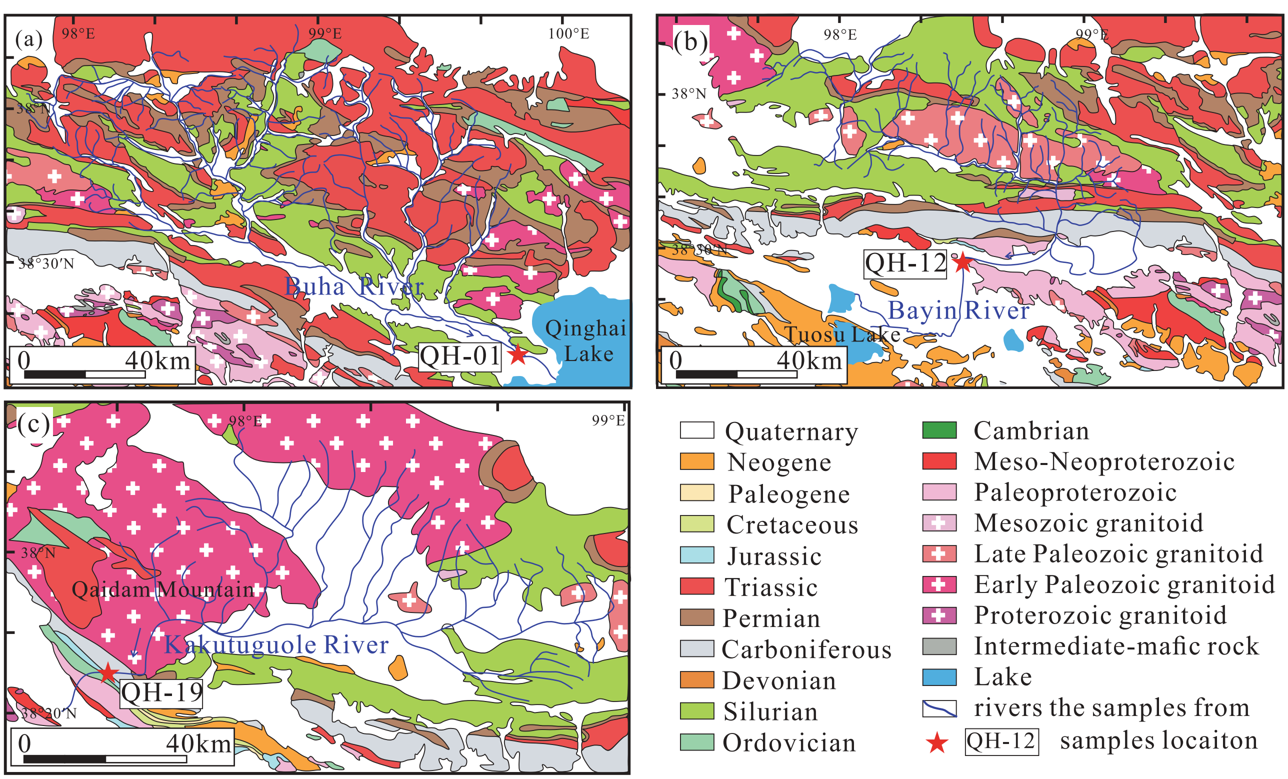

Figure 3. (a) The geological map of the catchment of Buha river; (b) The geological map of the catchment of Bayin river; (c) The geological map of the catchment of Kaketuguole river. Maps followed the Geological Map of Qaidam Basin (China National Petroleum Corporation and China University of petroleum, 1998).

a GeoLas200 M 193 nm ArF-excimer laser-ablation system at the MOE Key Laboratory of Orogenic Belts and Crustal Evolution, Peking University. The analyses were conducted with a 32 μm diameter beam with a fluence of 15 J/cm^2 at 4 Hz. The typical ablation pit depth was 35–50 μm. Isotopic ratios were calculated with the GLITTER software package and were corrected for common-Pb by the approach described by Andersen (2002). Isoplot 3.0 (Ludwig 2012) was used to determine the zircon U-Pb dates and to generate concordia plots. Following the conventional reporting of detrital zircon dates, the dates with poor precision (> ±10%), high discordance (> ±20%) were omitted from the probability density function, the KDE plots, and from interpretation (e.g. Jian *et al*. 2019a). The ^{207}Pb/^{206}Pb ages were adopted for grains older than 1000 Ma, and ^{206}Pb/^{238} U ages for younger than 1000 Ma (Gehrels *et al*. 2006, 2008).

4. Results

Detailed U-Pb isotopic data for the analysed detrital zircon crystals are listed in Supporting Information S2. CL images and U-Pb concordia diagrams are shown in Figure S3–S4 (Supporting Information S3).

Total 240 zircons were dated and 4 crystals were not considered for KDE age plots due to high discordances. The detrital zircon U-Pb age of sample QH-01 ranges from 222.3 ± 4.98 Ma to 2694.9 ± 23.59 Ma (n = 76). The age populations cluster into five major age groups: 200–300 Ma, 400–550 Ma, 700–900 Ma, 1400–2100 Ma and 2200–2500 Ma, with age probability peaks at 258 Ma, 440 Ma,775 Ma and 1842 Ma, respectively (Figure 2(h)). The detrital zircon U-Pb age of sample QH-12 ranges from 237.0 ± 18.04 Ma to 2706.2 ± 21.05 Ma (n = 80). The age populations cluster into four major age groups: 400–500 Ma, 800–1100 Ma, 1700–2000 Ma and 2100–2500 Ma, with a major age peak at 439 Ma, and secondary probability peaks at 833 Ma, 1963 Ma, and 2334 Ma. The two youngest grains have concordant ages of 237.0 ± 18.04 Ma and 248.6 ± 15.59 Ma (Figure 2(i)). The detrital zircon U-Pb age of sample QH-19 ranges from 254.4 ± 5.32 Ma to 2661.3 ± 26.31 Ma (n = 80). Sixty crystals yield a predominant population with an age range of 400–500 Ma, and a 447 Ma age peak is defined for these zircons (Figure 2(j)).

5. Discussion

5.1. The detrital zircon geochronological characteristics of the Qilian orogen river sand

U/Th ratio is widely used to distinguish metamorphic (U/Th >10) and igneous (U/Th <10) zircons (Rubatto 2002; Corfu *et al*. 2003; Wan *et al*. 2011; Kirkland *et al*. 2015). But some zircons don't follow this principle (e.g. Song *et al*. 2006, 2010a, 2019b; Mattinson *et al*. 2006a). Therefore, the interior structure is as important as the element ratio in provenance analysis of detrital zircon. In this study, the results indicate that most zircons with low U/Th ratios (<10) exhibit well-developed crystal faces and magmatic oscillatory zoning, indicating igneous origin. Six detrital zircons exhibit high U/Th (>10), two of them (Sample QH-12-09 and QH-19-02) show well-developed crystal faces and magmatic oscillatory zoning in CL images (Figure S3), which indicate igneous provenance. The others exhibit no obvious crystal characteristics of igneous zircons (Figure S3), we prefer they formed during metamorphism.

All the previously reported river sand detrital zircon U-Pb ages and the new data in this study are shown in Figure 2. The results indicate a fairly high variability of detrital zircon age signatures.

Eight river sand samples collected in the South Qilian–North Qaidam belt show two major age peaks at ~450 Ma and ~800 Ma. The Phanerozoic zircons are generally interpreted to be related to the subduction of the South and North Qilian Ocean and consequent continental collisions (e.g. Zhang *et al*. 2006a; Sun *et al*. 2012; Yan *et al*. 2015; Yang *et al*. 2015, 2016a; Dong *et al*. 2017; Shao *et al*. 2017; Xia *et al*. 2017), and the ~800 Ma age peak may indicate a tectono-magmatic event in Neoproterozoic. Note that some samples (e.g. QH-01 in this study and 16 H-01 and CQA339 in previous studies, Figure 2(h,k,m)) indicate an obvious contribution from Permian–Triassic (220–280 Ma) plutons. Additionally, samples from the east part of the belt (e.g. QH-01 and QH-12 in this study and 16 in previous study, Figure 2(f–i)) also show significant Neoarchean–Paleoproterozoic zircons, which have been always overlooked in previous tectono-magmatic event evaluations. The wide distribution in Precambrian ages reflects the evolution history of the Quanji Block basement (Figure 2).

Four river sand samples collected from the east part of the Central Qilian Block mainly have Phanerozoic detrital zircon ages with a major age peak at ~450 Ma due to the small catchment of the rivers (Lease *et al*. 2007). One sample (06, Figure 2(d)) therein shows more various geochronological information, with three zircon age peaks at ~250 Ma, ~450 Ma, and ~800 Ma, the pre-Neoproterozoic detrital zircon ages are insignificant in these reported river sand samples, but are abundant in the published ancient sedimentary rocks from the Central Qilian Block, which records the evolution of the basement of Central Qilian Block.

Two rivers sand samples (DC2-1 and ZY1-1, from the Heihe River, covering both the Central Qilian Block and the North Qilian suture zone, Figure 2(a)) collected from the North Qilian suture zone, show major detrital zircon age peaks at ~250 Ma and ~450 Ma and secondary age peaks at ~800 Ma, ~1.8 Ga, and ~2.5 Ga. The sedimentary strata covered by the Heihe River catchment are dominated by early Palaeozoic strata, and the Mesoproterozoic Jingtieshan Group (Figure 2(a), Yang *et al*. 2016b). Note that the Central Qilian Block and North China Craton were suggested as major feeders for these early Palaeozoic and Mesoproterozoic sedimentary strata in the North Qilian suture zone (Xu *et al*. 2010a, 2010b; Yang *et al*. 2016b). In this regard, the samples DC2-1 and ZY1-1 may record the tectonic events occurred in the Central Qilian Block and North China Craton, although they were collected in the North Qilian suture zone.

5.2. Precambrian basement and assembly of microcontinents

5.2.1. Basement of the Central Qilian Block

The river detrital zircon geochronology in the North-Central Qilian belt shows a few but wide distribution in Precambrian ages, with age peaks at ~0.8 Ga and ~1.8 Ga (The age peak at~2.5 Ga in Figure 2(b) is considered as the reflect of the detrital zircons from the North China Craton in this study). Therefore, at least two tectono-magmatic events occurred in the Central Qilian Block in the Paleoproterozoic-Mesoproterozoic and Neoproterozoic.

The detrital zircon age probability peak at 1.7 Ga in the Central Qilian Block is slightly younger than the ~1.8 Ga age peaks in the North China Craton, Tarim Craton, and Yangtze Block (Figure 4). This difference in age probability peaks may be an artefact under sampling or the palaeogeographic position of Central Qilian Block crust (or sediment sources) within the Columbia supercontinent (e.g. Rogers and Santosh 2002, 2003; Zhao *et al*. 2002, 2003, 2004a, 2006, 2011; Zhang and Meng 2006b; Zhang *et al*. 2006c, 2011a, 2012b, 2013; Chen *et al*. 2009, 2013; Xiong *et al*. 2009).

The significant detrital zircon age populations in the range of 0.8–1.0 Ga have also been observed within the Tarim Craton and Yangtze Block (Figure 4(b,c)). In addition, the granitic gneissic rocks with the ages 930 ± 8 Ma, 918 ± 14 Ma, and 790 ± 12 Ma in the Central Qilian Block have been correlated to the early and late Grenvillian magmatic activities in the Yangtze Block (Tung *et al*. 2013). The detrital zircon age peak at ~0.9 Ga in the Precambrian basement of the North Qaidam UHP belt (Figures 4(g) and 5) and the magmatic and metamorphic ages of 0.9–1.0 Ga along the North Qaidam UHP belt indicate a Yangtze-Qilian-Qaidam-Tarim Craton link to a part of Rodinia called 'South-West China United Continent' (Song *et al*. 2012). Therefore, we posit that the crust composing the Central Qilian Block accreted to the Rodinia supercontinent between 0.9 and 1.0 Ga. The sample QH-19 was collected in the North Qaidam UHP belt, but it displays an unimodal age peak at ~450 Ma and few age population in 0.9–1.0 Ga. Note that the river system of Kaketuguole River mainly covers the Qaidam Mountain, dominated by a granitic pluton with the age of 437–446 Ma (Zhou *et al*. 2013), although ~850 Ma continental flood basalts are also exposed (Song *et al*. 2010b). We favour that most detrital zircons in sample QH-19 likely came from the Qaidam Mountain.

Fragments of an 820–850 Ma large igneous province, which result from a mantle plume and crustal extension, have been documented in the northern margin of the Qaidam Block (Xu *et al*. 2016). Coeval mafic-ultramafic igneous rocks are also present in the Tarim Craton, Yangtze Block, and southeastern Australia (Powell *et al*. 1994; Preiss 2000; Wang and Li 2003; Xu *et al*. 2005). Such widespread transcontinental rifting events may relate to the mantle plume activity which led to the break-up of Rodinia (Li *et al*. 2008). As a result, the Central Qilian Block rifted from Australia at 600–580 Ma (Xu *et al*. 2015). The relic cores in zircons from ophiolite in North Qilian suture zone indicate the initial opening of the North Qilian Ocean at latest at ~710 Ma (Zhang *et al*. 2007).

In summary, the Central Qilian Block shows affinity to the Tarim Craton and Yangtze Block in the Precambrian evolution history, and they together successively experienced amalgamation of the Columbia and Rodinia supercontinents. The zircon age multi-dimensional scaling (MDS) plot also indicates the similarity of Precambrian basements in the Central Qilian Block, Tarim Craton, and Yangtze Block (Figure 6).

Additionally, detrital zircon U-Pb age distributions of Precambrian basement rocks of the Central Qilian Block and North Qinling terrane yield strikingly similar age distributions (Figure 4(d,e)). The understanding of the Precambrian North Qinling terrane evolution lacks resolution (Dong *et al*. 2011), however, there is compelling evidence to suggest that the North Qinling terrane accreted to Rodinia by ~1.0 Ga before rifting at ~750 Ma (Diwu *et al*. 2010; Yu *et al*. 2015b), and later accreted to the North China Craton at ~640 Ma (Zhu *et al*. 2011b). Additionally, the MDS plot of Precambrian basement detrital zircon age data also shows similarity in this two tectonic units (Figure 6). We suggest that the Central Qilian Block and North Qinling terrane had a similar history from the Mesoproterozoic to the early-middle Neoproterozoic.

5.2.2. Basement of the Quanji Block

The Quanji Block has two significant Precambrian detrital zircon age probability peaks at ~1.8 Ga and ~2.5 Ga,

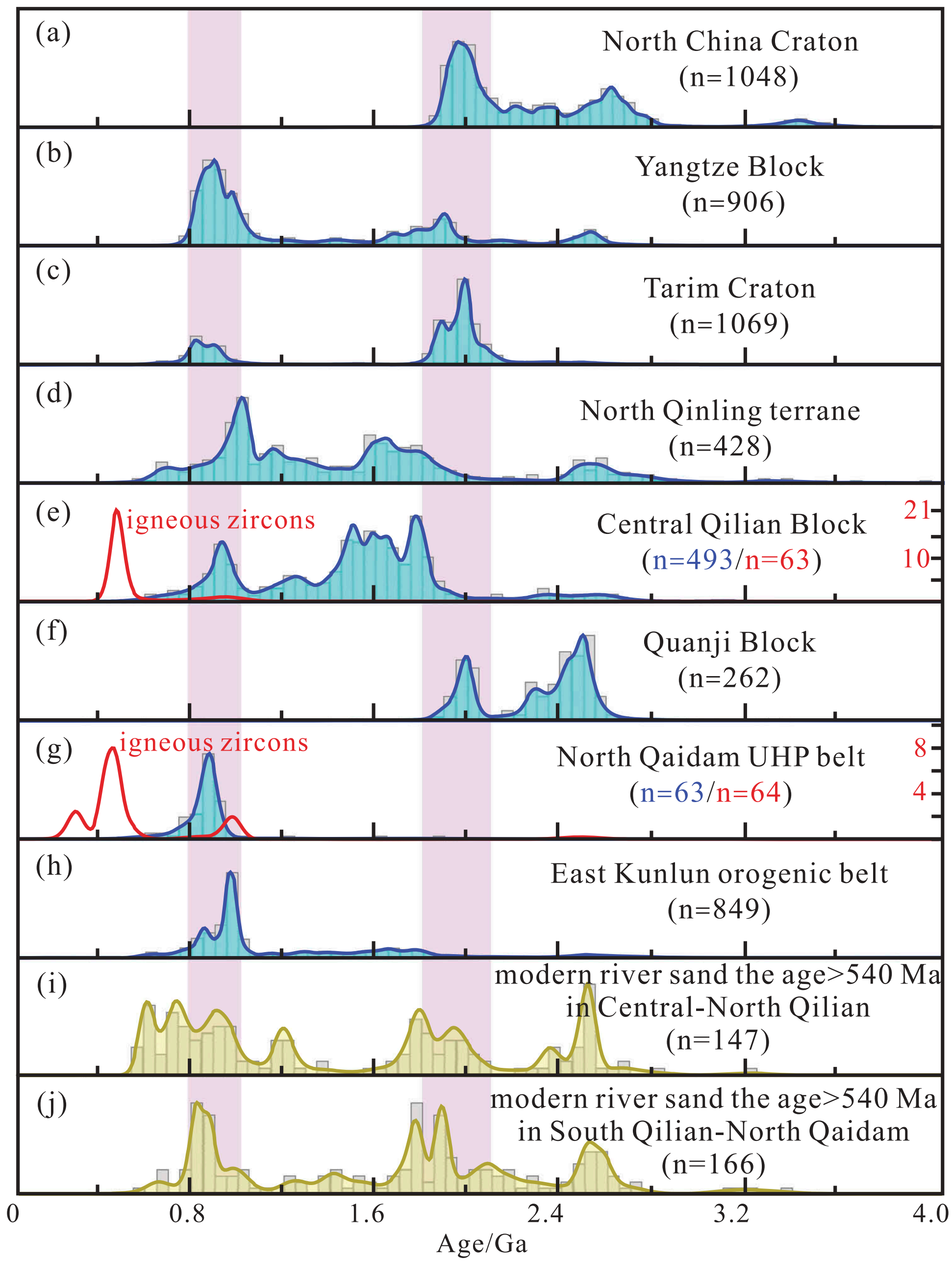

Figure 4. Detrital zircon age KDE plots of Precambrian basement of study- and adjacent areas.

(a) The North China Craton, from the upper Protozoic in Zhuozi Shan (Darby and Gehrels 2006), Wulashan Khondalites (Xia *et al.* 2006a), Jining Colplex (Xia *et al.* 2006b), Songjiashan Group, lower Zhongtiao Group, upper Zhongtiao Group, and Danshanshi Group of Zhongtiao Complex (Liu *et al.* 2012a); (b) the Yangtze Block, from the Mesoproterozoic Kunyang Group, Yanbaian Group and Bikou Group, Sinian Lieguliu Formation, and Guanyinshan Formation (Sun *et al.* 2009), Neoproterozoic Sibao Group and Langjiaxi Group (Wang *et al.* 2007), Meso-Neoproterozoic Fanjingshan Group, Neoproterozoic Xiajiang Group (Wang *et al.* 2010), Neoproterozoic Shuangqiaoshan Group, Xikou Groups, and Nanhua Sequence (Wang *et al.* 2013); (c) the Tarim Craton, from the Upper Neoproterozoic (Gehrels *et al.* 2011; Carroll *et al.* 2013), drilling on Precambrian basement (Xu *et al.* 2013), Mesoproterozoic or Neoproterozoic Aksu blueschist terrane and Sinian sandstone (Zhu *et al.* 2011a); (d) the North Qinling terrane, from the Precambrian Qinling Group (Wan *et al.* 2011) and Neoproterozoic Kuanping Group (Diwu *et al.* 2010; Zhu *et al.* 2011b); (e) the Central Qilian Block, from the Mesoproterozoic to Cambrian (Gehrels *et al.* 2003a, 2011) Precambrian Yemananshan Group, Huangyuan Group, Maxianshan Group (Tung *et al.* 2007b), Neoproterozoic Hualong Group (Xu *et al.* 2007); (f) the Quanji Block, from the Paleoproterozoic Dakendaban Group (Chen *et al.* 2009, 2012); (g) North Qaidam UHP belt, from the Proterozoic (Bektas 2013); (h) the East Kunlun orogenic belt, from the Mesoproterozoic Xiaomiao Formation (Chen *et al.* 2011), Paleoproterozoic Jinshuigou Group, Mesoproterozoic Binggou Group (He *et al.* 2016), Mesoproterozoic Jinshuikou Group (Meng *et al.* 2017), early Palaeozoic Chitai Group (Yan *et al.* 2017), and Jian et al. unpublished data; and (i) River sand ages> 540 Ma in the North-Central Qilian belt (Lease *et al.* 2007; Gong *et al.* 2017); (j) River sand ages >540 Ma in the South Qilian-North Qaidam belt (Lease *et al.* 2007; Liu *et al.* 2012b; Song *et al.* 2019a and this study). The red line in (e) and (g) means the age distributions from granitoid rocks in the North-Central Qilian belt and South Qilian–North Qaidam belt, age data, and location shown in Table S2 and Figure S6 (Wu et al. 2002, 2009, 2014; Cowgwil et al. 2003; Gehrels et al. 2003b; Zhang et al. 2006a, 2017a; Wang et al. 2008, 2014, 2018; Tseng et al. 2009a; Sun et al. 2012; Yu et al. 2012, 2015a; Tung et al. 2013, 2016; Chen et al. 2014; Song et al. 2014a; Fu et al. 2015; Yan et al. 2015; Yang et al. 2015, 2016a; Huang et al. 2016;Cheng *et al.* 2017; Zhao et al. 2017b)

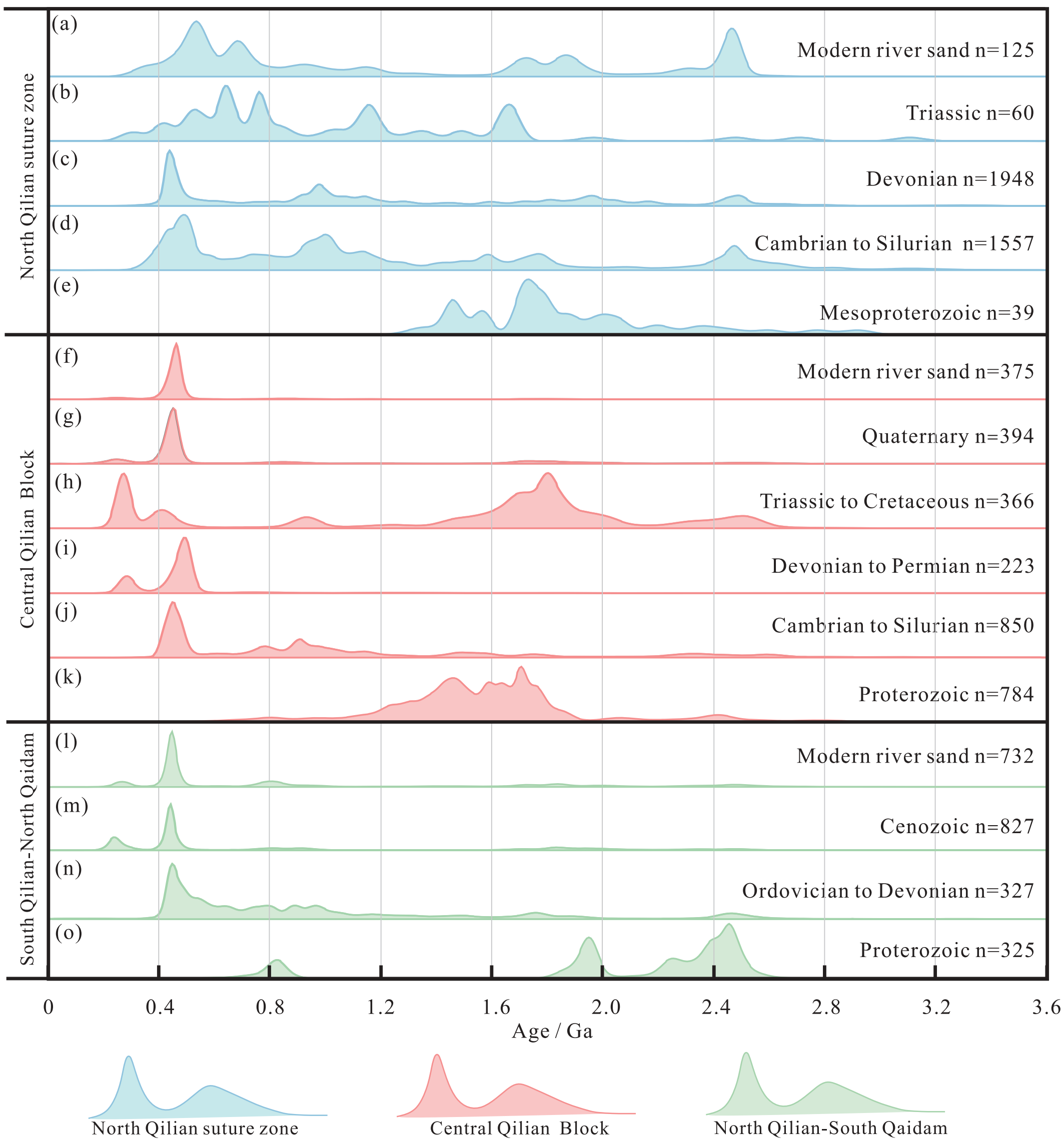

Figure 5. Detrital zircon age KDE plots from previous studies (Gehrels et al. 2003a; Lease et al. 2007; Tung et al. 2007a, 2007b; Xu et al. 2007, 2010a, 2010b; Yan et al. 2007, 2010, 2015; Wang et al. 2008, 2016a; Yang et al. 2009a, 2016b; Chen et al. 2012; Liu et al. 2012b, 2018a; Zhang et al. 2012b; 2015b; Bektas 2013; Yuan and Yang 2015a, 2015b; Zhao et al. 2016, 2017a; Gong et al. 2017; Zuza et al. 2018; Song et al. 2019a, see Table S1 for detailed information).

respectively (Figure 4(f)). Note that the catchment of the Bayin River (the sample QH-12 collected from) covers the South Qilian belt and Quanji block, differing from the sample QH-01 (within the South Qilian belt), the Precambrian age distribution of the sample QH-12 is featured by more concentrative ~1.8 Ga and ~2.5 Ga ages (Figure 2). It is most likely that these ~1.8 Ga and ~2.5 Ga detrital zircons in sample QH-12 were source primarily from the Qunaji Block and specifically the Precambrian strata (Chen *et al*. 2007a, 2007b, 2007c, 2012, 2013; Wang *et al*. 2008, 2015; Gong *et al*. 2012; Zhang *et al*. 2014; see sample QH-12, Figure 2(i)).

The prominence of the 2.5 Ga age probability peak is unique to the Quanji Block and North China Craton in this study (Figure 4(a,f)). This observation along with the 2.43 Ga granitic pegmatite and 2.47 Ga granitic leucosome in Delingha complex, supports the hypothesis of a thermal-magmatic event around 2.5 Ga (Wang *et al*. 2008). The granitic gneissic rocks with a 2.37–2.39 Ga crystallization age in the Quanji Block indicating regional granitic magmatism which is associated with the crustal convergence in ~2.5 Ga (Wang *et al*. 2015). Geochemical results from protolith of the granitic gneiss in Mohe (eastern Quanji Block) are thought to have formed during a continent-continent collision. The granitic gneiss in the Quanji Block shows chemical similarities to the TTG (trondjhemite–tonalite–granodiorite) gneiss in the North China Craton (Gong *et al*. 2012). It has been generally

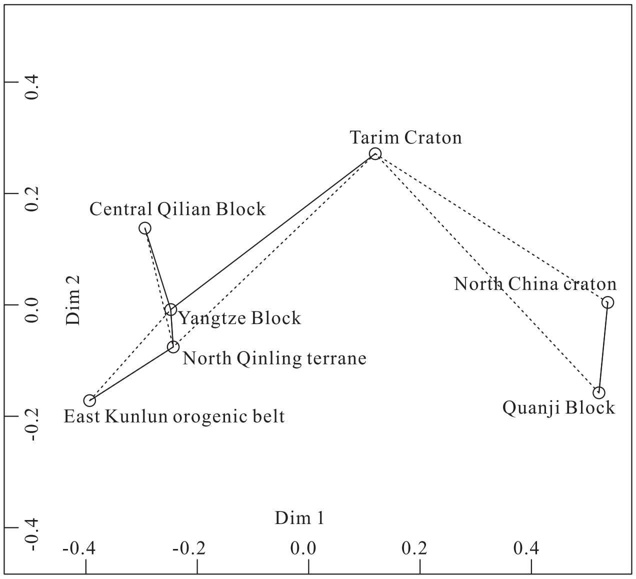

Figure 6. Non-metric multi-dimensional scaling (MDS) plot of Precambrian basement of study- and adjacent areas U–Pb dataset, the reference sees in the caption of Figure 4. Solid lines and dashed lines in MDS plots mean the closest and second closest neighbours, respectively (Vermeesch 2013; Vermeesch *et al.* 2016).

accepted that the reworking of continental crust occurred at ~2.5 Ga in the North China Craton (Zhao *et al.* 2000, 2001, 2002, 2005, 2008a, 2008b; Zhai and Liu 2003; Wilde *et al.* 2004, 2005a; Kröner *et al.* 2005; Wilde and Zhao 2005b; Zhai *et al.* 2005; Geng *et al.* 2006; Santosh *et al.* 2007, 2013; Zhu *et al.* 2012a). Our data supports the argument that the Quanji Block was a part of the North China Craton and experienced the Wutaian Movement at ~2.5 Ga. The Quanji Block, as part of the North China Craton during the Paleoproterozoic, was involved in the Columbia supercontinent (Chen *et al.* 2009, 2012, 2013; Zhang *et al.* 2014; Wang *et al.* 2015). This is supported by the observed ~1.8 Ga age signal in the Quanji Block and the basic granulite with a metamorphic age of 1928 ± 9 Ma in the Quanji Block (Lu *et al.* 2017). The MDS plot (Figure 6) also indicates the affinity between basements of the Quanji Block and North China Craton.

The Rb-Sr isochron age of the Wandonggou Group indicates an metamorphism in 1022 ± 64 Ma (Yu *et al.* 1994), and the Dakendaban Group zircon defined the common lower intercept age of ~0.9 Ga (Wang *et al.* 2008). Note that the same period metamorphism and magmatism widely occurred in the North Qaidam UHP belt (e.g. Zhang *et al.* 2008a, 2008b, 2012a; Lin *et al.* 2006; Chen *et al.* 2007b; Song *et al.* 2012; Yu *et al.* 2013), recognizing as an multiperiod suture. A basaltic andesite from the Quanji Block exhibits a zircon U-Pb age 738 ± 28 Ma (Lu 2002a), which is consistent with the break-up of Rodinia. Therefore, the Quanji Block probably collided with Qaidam Block during the formation of Rodinia and separated with Qaidam Block when the Rodinia was fragmented.

5.3. Phanerozoic accretionary evolution of the Qilian orogenic belt

5.3.1. The early Palaeozoic accretion of microcontinents in Qilian orogenic belt

The detrital zircon age probability distribution of three samples in this study and other river sand samples in previous studies all display distribution at 400–500 Ma with an age peak at ~450 Ma, which indicates the early Palaeozoic orogenesis in the Qilian orogenic belt.

It is generally considered that the subduction and closure of the North Qilian Ocean and subsequent continent-continent collision between the northern Central Qilian Block and North China Craton occurred in the early Palaeozoic (Wu *et al.* 2006, 2011; Yang *et al.* 2006, 2015; Tseng *et al.* 2009a; Tseng 2009b; Song *et al.* 2013; Tung *et al.* 2016; Wang *et al.* 2017; Mu *et al.* 2018).This event is well recorded by ophiolite suite in the North Qilian suture zone (Song *et al.* 2019b and references therein), extensive arc-related intermediate-acid plutons (Figure 4(l,m), Table S2 and Figure S6) and significant ~450 Ma detrital zircon age peak of the Phanerozoic sedimentary rocks (Figure 5) in the North Qilian suture zone and Central Qilian Block. In contrast, subduction of the South Qilian Ocean and collision between the Qaidam Block and Central Qilian Block were likely more complex. The South Qilian Ocean subducted beneath the Quanji Block and Central Qilian Block since 525 Ma and the ocean closed at the 450 Ma (Lai *et al.* 1996; Zhu *et al.* 2015; Wang *et al.* 2016b; Mu *et al.* 2018). As a result, the Central Qilian Block collided with the Quanji Block and Qiadam Block at the southeastern and southwestern margin, respectively. This process was recorded by early Palaeozoic felsic intrusions, MORB, OIB, and south Qilian belt ophiolite suite (Lai *et al.* 1996; Zhang *et al.* 2005a, 2008b, 2009a, 2009b, 2017b; Zhu *et al.* 2012b, 2014, 2015; Yang *et al.* 2015, 2019; Wang et al. 2017; Song *et al.* 2019b). The continental subduction of Qaidam Block occurred at 440–420 Ma pulled by the subducted oceanic crust at a depth 100–200 km. Exhumation occurred at ~400 Ma due to delamination of the subducted oceanic plate and upwelling of the mantle. The continental subduction is indicated by UHP metamorphic rocks and early Palaeozoic continental-melting granites in North Qaidam (e.g. Yang *et al.* 1998, 2001, 2002, 2005, 2019; Zhang *et al.* 2008a, 2009a, 2009b; Song *et al.* 2003a, 2003b, 2004, 2005, 2006, 2007, 2009a, 2009b, 2010b, 2012, 2013, 2014a, 2014b, 2017, 2019b;

Wu *et al*. 2004, 2009, 2014; Mattinson *et al*. 2006a, 2006b; Zha *et al*. 2016). During the subduction and collision, the Quanji Block converged with Qaidam Block and Central Qilian Block at south and north, respectively (Figure 7). This point is supported by the 449–430 Ma metamorphic age of the Dakendaban Group (Wu *et al*. 2007; Li *et al*. 2015; Zha *et al*. 2016).

5.3.2. Penetrative arc magmatism influence by the Paleo-Tethys during the Permian to Triassic

The detrital zircon age probability distribution of sample QH-01 in this study (Figure 2(h)) and some samples in previous studies (Figure 2(b,d)) display an age population of 200–300 Ma. Compared to the Palaeozoic strata, the Mesozoic strata in North Qilian suture zone exhibit less age population of ~1.8 Ga and ~2.5 Ga (Figure 5(b–d)), which reveal minor contributions of the North China Craton and major contributions of the Central Qilian Block. The provenance of the Mesozoic strata in Central Qilian Block can be constrained in the Central Qilian Block and South Qilian-North Qaidam belt, which is indicated by the Precambrian age in Figure 5(h). Therefore, the ~250 Ma age peak represents a magmatic event in Central Qilian Block and South Qilian-North Qaidam belt. As a potential source area, the South Qilian-North Qaidam belt also provided ~250 Ma age zircons for the Cenozoic strata in North Qaidam UHP belt (Figure 6(m)). Additionally, the cotemporaneous plutons present at southern margin of the Qilian Orogenic belt (Figure S6, Gehrels *et al*. 2003b; Zhang *et al*. 2005b; Wu *et al*. 2009; Dong *et al*. 2014, 2015; Chen *et al*. 2015; Cheng *et al*. 2017). Note that tectono-magmatic event which was due to the subduction of

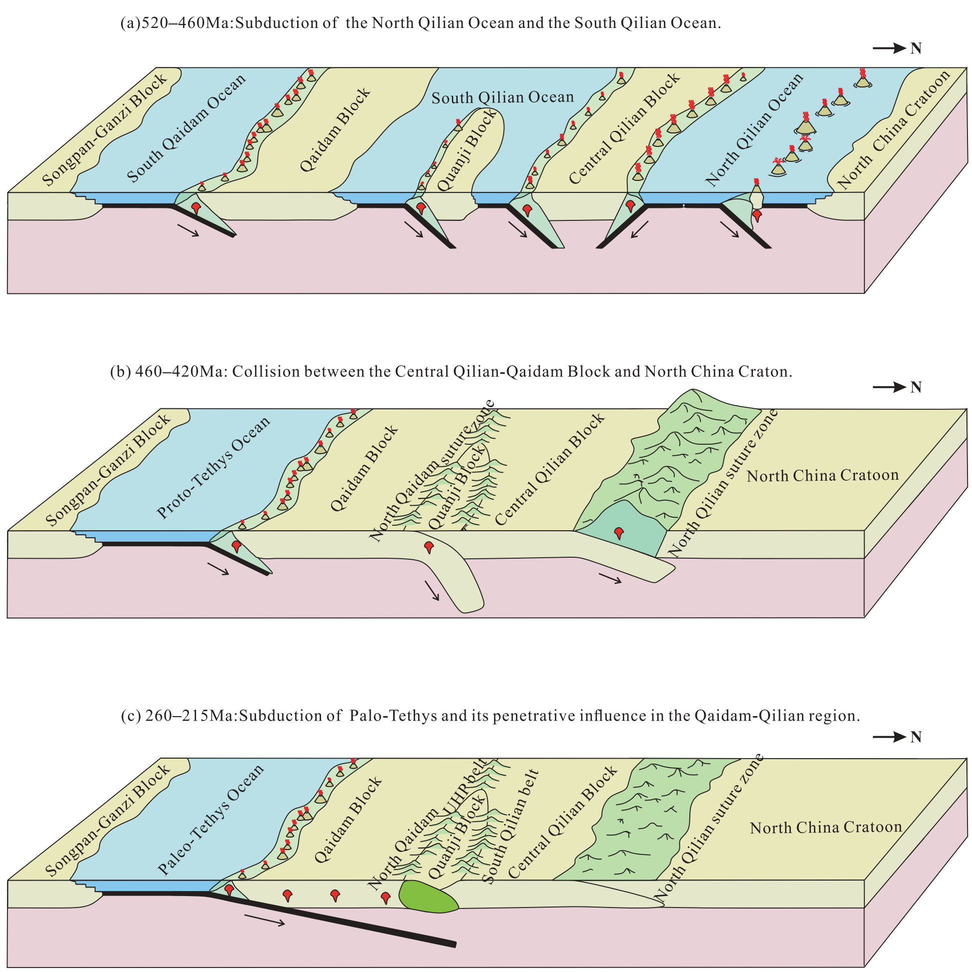

Figure 7. Tectonic evolution of the Qilian region from the Neoproterozoic to early Mesozoic.

(a) The initial subduction polarity of North Qilian Ocean was southwest and then changed to double subduction (Wu *et al*. 2011); The South Qilian Ocean subducted beneath the Quanji Block and Qaidam Block. (b) Continent-continent collision between the Central Qilian Block and island arc, which developed on the northern limb of the North Qilian Ocean, started by 460 Ma and completed by 420 Ma closing the North Qilian Ocean (Xu *et al*. 2010a); The Quanji Block collided with Central Qilian Block at northern margin. The Qaidam Block subducted beneath the Quanji Block and Central Qilian Block after the closure of South Qilian Ocean at 440–420 Ma. (c) The Paleo-Tethys subducted beneath the Qaidam Block from south at a relatively low angle generating 215–260 Ma plutons across the Qaidam-Qilian region.

North and South Qilian Ocean had finished at 360 Ma. The late Palaeozoic to early Mesozoic tectono-magmatic orogenesis that occurred in the East Kunlun orogenic belt, which was likely associated with the subduction of Paleo-Tethys (Liu *et al*. 1984; Guo *et al*. 1998; Luo *et al*. 2002; Mo *et al*. 2007; Yang *et al*. 2009b; Pan *et al*. 2012; Huang *et al*. 2014; Xia *et al*. 2014; Hu *et al*. 2015; Wu *et al*. 2009, 2016, 2017, 2019a, 2019b; Shao *et al*. 2017; Xia *et al*. 2017; Dong *et al*. 2017). Wu *et al*. (2009) suggested that as the subduction of Paleo-Tethys, intercontinental subduction occurred in North Qaidam belt and the lithosphere delamination led to magmatism in the study area. However, plutons lithosphere delamination induced melts would only appears near the paleo-subduction zone, and therefore cannot explain the widespread Permian to Triassic plutons within the Qaidam Block and North Qaidam UHP belt and 200–300 Ma age population of detrital zircon in the Central Qilian Block. We propose an alternative that the spatial and temporal extend of these plutons is relate to magma generated by the subduction of Paleo-Tethys oceanic lithosphere (Gehrels *et al*. 2003b; Cheng *et al*. 2017). Our model suggests that the Paleo-Tethys subducted northward, at a variable but relatively shallow angle, beneath the southern margin of Qaidam Block (e.g. Kunlun orogenic belt). Figure 7(c) explains the wide distribution of Permian to Triassic plutons which were likely caused by low-degree subduction of the Paleo-Tethys.

6. Conclusions

By combing new U-Pb detrital zircon dates from regionally sampling rivers in the Qilian orogenic belt with previous bedrock investigations, we conclude following:

(1) The river sand detrital zircon geochronology shows fairly high variability. The age populations of sample QH-01 cluster into 220–280 Ma, 400–520 Ma, and minor Precambrian age population. The age populations of sample QH-12 show an age peak at 439 Ma, and secondary age peaks at 833 Ma, 1963 Ma, and 2334 Ma. The age populations of sample QH-19 cluster to 400–500 Ma, with few Precambrian age crystals.

(2) The Precambrian zircon age of the sample QH-01 and those reported in the Precambrian basement indicate that the Central Qilian Block showed basement similarity with the Tarim Craton and Yangtze Block. The age peaks at ~1.8 Ga and ~1.0 Ga represent the aggregation of Columbia and Rodinia, respectively.

(3) The ~1.8 Ga and ~2.5 Ga zircon age peaks of the sample QH-12 and those reported in the Precambrian basement indicate possibly similar tectonic history between the Quanji Block and North China Craton prior to the Neoproterozoic. The Neoproterozoic metamorphism in the Quanji Block indicates the assembly to Rodinia.

(4) The zircon age peak at ~450 Ma in the 3 samples indicates the collision among the Quanji Block, Qaidam Block, and Central Qilian Block.

(5) The 220–280 Ma zircon of the sample QH-01 were related to magmatism caused by low-angle subduction of the Paleo-Tethys at the southern margin of Qaidam Block.

Highlights

- The Quanji Block was likely a part of North China Craton during the Pre-Neoproterozoic.
- The Central Qilian Block shows affinity with the Tarim and Yangtze Craton.
- Paleo-Tethys subduction caused magmatism in the southern Qilian belt in 200–300 Ma.

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Disclosure Statement

No potential conflict of interest was reported by the authors.

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