New detrital zircon U–Pb insights on the palaeogeographic origin of the central Sanandaj–Sirjan zone, Iran

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Abstract

New detrital U–Pb zircon ages from the Sanandaj–Sirjan metamorphic zone in the Zagros orogenic belt allow discussion of models of the late Neoproterozoic to early Palaeozoic plate tectonic evolution and position of the Iranian microcontinent within a global framework. A total of 194 valid age values from 362 zircon grains were obtained from three garnet-micaschist samples. The most abundant detrital zircon population included Ediacaran ages, with the main age peak at 0.60 Ga. Other significant age peaks are at c. 0.64–0.78 Ga, 0.80–0.91 Ga, 0.94–1.1 Ga, 1.8–2.0 Ga and 2.1–2.5 Ga. The various Palaeozoic zircon age peaks could be explained by sediment supply from sources within the Iranian microcontinent. However, Precambrian ages were found, implying a non-Iranian provenance or recycling of upper Ediacaran–Palaeozoic elastic rocks. Trace-element geochemical fingerprints show that most detrital zircons were sourced from continental magmatic settings. In this study, the late Grenvillian age population at c. 0.94–1.1 Ga is used to unravel the palaeogeographic origin of the Sanandaj–Sirjan metamorphic zone. This Grenvillian detrital age population relates to the ‘Gondwana superfan’ sediments, as found in many Gondwana-derived terranes within the European Variscides and Turkish terranes, but also to units further east, e.g. in the South China block. Biogeographic evidence proves that the Iranian microcontinent developed on the same North Gondwana margin extending from the South China block via Iran further to the west.

1. Introduction

The Gondwana supercontinent is the result of large-scale amalgamation of continents and microcontinents located within East and West Gondwana. Amalgamation started at the end of the Neoproterozoic period, which led to the formation of the East African orogen (e.g. Stern, 1994; Collins & Pisarevsky, 2005; Stampfli et al. 2013; Meinhold et al. 2013) and consequently records the first stage in the development of the Transgondwanan Supermountain (Squire et al. 2006). From the northern margin of Gondwana, major terranes split off during Palaeozoic time (Şengör, 1990 and references therein), moved to the north and were accreted to the Eurasion margin during Triassic and Cenozoic times (e.g. Agard et al. 2011; Abbo et al. 2015; Hassanzadeh & Wernicke, 2016; Stephan et al. 2019). Understanding the exact origin of these Gondwana-derived terranes along the Gondwana margin has been a major geological challenge in the last decade (e.g. Stampfli et al. 2013; von Raumer et al. 2013; Stephan et al. 2019; Žák et al. 2021; Fig. 1).

Although most of the Neoproterozoic palaeogeographic reconstructions place the Iranian microcontinent along the Prototethyan margin of northern Gondwana, which is close to the East African orogen (e.g. Hassanzadeh et al. 2008; Horton et al. 2008; Fergusson et al. 2016), some new age information and the tectonic setting of the Neoproterozoic rocks indicate that the Iranian microcontinent was originally part of a series of peri-Gondwanan terranes, similar to the Avalonian (640–540 Ma) and Cadomian (616–540 Ma) arc terranes (e.g. Murphy et al. 2004; Moghadam et al. 2020; Fig. 1).

The age and nature of the continental crust in Iran have been documented during previous research, including zircon U–Pb ages published over the last two decades that demonstrate the dominance of Pan-African continental crustal material in the Iranian microcontinent, recording widespread late Neoproterozoic subduction-related magmatism (e.g. Ramezani & Tucker, 2003; Hassanzadeh et al. 2008; Rahmati-Illkchi et al. 2011; Jamshidi Badr et al. 2013; Nutman et al.
Recent research on amphibolites in the central Sanandaj–Sirjan metamorphic zone (SSMZ) identified Neoarchaean xenocrystic zircons that revealed the presence of hidden Neoarchaean crustal components in Iran (Shakerardakani et al. 2019).

In addition, detrital zircon data from Neoproterozoic, Palaeozoic and Triassic clastic sediments have recently become available from many different portions of the Iranian microcontinent, such as from the central Alborz, Zagros, northwestern Central Iranian terrane and NE Iran (e.g. Horton et al. 2008; Etemad-Saeed et al. 2015; Honarmand et al. 2016; Zhang et al. 2017; Moghadam et al. 2017; Meinhold et al. 2020; Zoleikhaei et al. 2020).

Previous detrital zircon studies indicated that the dominant age population in the upper Neoproterozoic–Cambrian sandstones from the Kahar, Bayandor, Barut, Lalun and Mila formations of the Alborz and Zagros mountains is Neoproterozoic, with a main age peak at 0.6 Ga as well as minor peaks at 1.0 Ga, 1.8 Ga and 2.5 Ga (Horton et al. 2008). In the central Alborz Mountains, alongside the youngest, prominent (0.55–0.56 Ga) detrital zircon population, 0.9–1.0 Ga, 2.0–2.2 Ga, 2.5–2.7 Ga and 2.9–3.2 Ga age populations appear in the Neoproterozoic sandstones from the Kahar Formation (Etemad-Saeed et al. 2015). In addition, Cambrian sandstones of the Lalun Formation reveal similar reoccurring age clusters as observed in the Kahar Formation, dominated by Cryogenian–Ediacaran ages, with pre-Neoproterozoic and Cambrian zircon grains a minor component (Zoleikhaei et al. 2020). Some Neoproterozoic sandstones from the Kahar and Bayandor formations in Central Iran are dominated by 0.62–0.64 Ga zircon ages, with minor age populations at 0.82 Ga, 0.92–0.94 Ga, 1.9–2.3 Ga and 2.5–3.0 Ga (Honarmand et al. 2016). The dominant age population from Cambrian sandstones of the Zaigin Formation is Cryogenian to Tonian (Grenvillian) (0.7–0.9 Ga), with subordinate Palaeoproterozoic to Neoarchaean (2.4–2.6 Ga) populations. However, the Triassic Nakhlahk Group sandstones of Central Iran show a pronounced age population at c. 240–280 Ma, with subordinate pre-Permian Palaeozoic peaks at c. 320 Ma and 480 Ma. Meinhold et al. (2020) suggested sediment supply from the Permian–Triassic magmatic rocks of the Silk Road Arc further north. The Neoproterozoic and Palaeoproterozoic zircons have predominantly rounded shapes suggesting recycling of older sedimentary rocks (Meinhold et al. 2020). In NE Iran, the Ordovician to Lower Devonian sandstones are characterized by distinct age groups at 2.5 Ga, 0.6–0.8 Ga, 0.5 Ga and 0.4–0.5 Ga, as well as a minor age peak at 1.0 Ga (Moghadam et al. 2017).

In this paper, we carry out, for the first time, a coupled U–Pb age and trace-element analysis of detrital zircons from three garnet-micaschist samples (primarily Neoproterozoic–early Palaeozoic in age) distributed along a ~100 km long central segment of the SSMZ in the Zagros orogenic belt (Fig. 1). For the interpretation of our results, we integrate our new data with the previously published detrital zircon U–Pb data from other Precambrian–Palaeozoic clastic sediments throughout the Alborz, Central Iran and NE Iran. We juxtapose the new detrital U–Pb zircon data with biogeographic evidence to constrain the position of the Iranian microcontinent on the northern Gondwana margin and its relation to the global framework as was recently also postulated by Yang et al. (2020) and Meredith et al. (2021). We show that the SSMZ as part of the Iranian microcontinent bears similar detrital zircon age spectra to those known from the Arabian–Nubian shield, in peri-Gondwanan terranes to the west of Iran as well as to those of the South China block in the east.

2. Geological background

Iran is regarded as a fragment of Gondwana and comprises several blocks or domains, e.g. the Alborz and Zagros mountain belts, the Central Iranian plateau and the Kopet Dagh Mountains, that are separated by deep-seated faults or suture zones (e.g. Stocklin, 1968; Berberian & King, 1981; Fig. 1). Major areas of exposed crystalline basement rocks with variable dimensions occur within all of the continental tectonic zones in Iran barring the Kopet Dagh Mountains to the northeast.

The NW–SE-trending Zagros orogen of western Iran is part of the Alpine–Himalayan orogenic belt and developed as the result of the continental collision between the African–Arabian continent
and the Iranian microcontinent (e.g. Berberian & King, 1981; Alavi, 1994; Mohajel et al. 2003; Agard et al. 2011; Moutherereau et al. 2012). The Zagros Mountains are subdivided into four parallel tectonostratigraphic zones, namely (from NE to SW) the Urumieh–Dokhtar magmatic arc (UDMA), the SSMZ, the Imbricate zone or High Zagros, and the Zagros fold–thrust belt (Stöcklin, 1968; Falcon, 1974; Alavi, 1994; Fig. 2a).

The SSMZ forms the innermost crystalline part of the Zagros orogen, where the continental and oceanic units were tectonically juxtaposed against the Arabian plate along the Main Zagros thrust (e.g. Agard et al. 2011; Hassanzadeh & Wernicke, 2016). The SSMZ is primarily composed of Precambrian–Palaeozoic metamorphic and sedimentary sequences, which are unconformably overlain by Permian–Triassic marbles, Jurassic phyllites and Aptian–Albian limestones (Stöcklin, 1968; Berberian & King, 1981). In addition, this zone represents the largest exposure and well-preserved record of key events during late Palaeozoic to middle Cenozoic times, which represent the formation and destruction of the Neotethys Ocean (e.g. Mohajel et al. 2003; Hassanzadeh & Wernicke, 2016). The SSMZ, Central Iran and (southern and central) Alborz are considered part of the Iranian microcontinent, bearing a similar late Ediacaran–Palaeozoic and Mesozoic stratigraphy (e.g. Hassanzadeh & Wernicke, 2016; Moghadam et al. 2017 and references therein).

3. Geological setting and sampling

3.a. Dorud–Azna area

The Dorud–Azna region is located in the central part of the SSMZ close to the Main Zagros thrust, which is known to comprise a polychronous metamorphic succession (Mohajel et al. 2003; Nutman et al. 2014; Shakerardakani et al. 2015, 2021; Fig. 2b). Structural studies and our previous U–Pb zircon dating work on this area demonstrated three metamorphic units, which are from footwall to hangingwall (Fig. 2b): (1) the Triassic June Complex, metamorphosed within greenschist-facies conditions; overlain by (2) the amphibolite-grade metamorphic Pan-African Galeh-Doz orthogneiss, which is intruded by some mafic dykes, and (3) the Amphibolite–Metagabbro unit, which includes Carboniferous metagabbro bodies (Shakerardakani et al. 2015; Ferguson et al. 2016), Carboniferous granitic orthogneiss (Shabanian et al. 2020) and undated amphibolites. These units have almost invariably undergone a complex history of repeated shearing, folding and transposition of ductile fabrics, which are associated with polyphase Jurassic and Cretaceous greenschist- to amphibolite-facies metamorphism. In the eastern part, the overlying low-grade metamorphic Triassic sequence is intruded by the Upper Jurassic Darijune gabbro (Shakerardakani et al. 2015).

The metamorphic rocks studied in this work occur in several small outcrops within the Amphibolite–Metagabbro unit in contact with metagabbro over more than 1 km around Dare-Hedavand village (Fig. 2b). The studied micaschist is brown, exhibits a weak schistosity and consists of garnet, plagioclase, quartz, K-feldspar, biotite and chlorite (Fig. 3a, b).

3.b. Muteh–Golpaygan metamorphic complex

The Muteh–Golpaygan metamorphic complex is located close to the northeastern boundary of the central SSMZ, close to the UDMA within the hinterland of the Zagros orogen (Fig. 2c). The Muteh–Golpaygan metamorphic complex is generally bounded by NE–SW- to E–W-trending high-angle normal faults that dip outward from the centre of the complex and juxtapose it against unmetamorphosed rocks in the hangingwall (Moosavi et al. 2014; Shakerardakani et al. 2019, 2020). Besides rare remnants of Neoarchaean rocks, the Muteh–Golpaygan metamorphic complex comprises mainly Neoproterozoic basement material dominated by granitic orthogneisses and metapelites locally interlayered with marbles along with minor quartzite (e.g. Thiele, 1966; Rachidnejad-Orman et al. 2002; Moritz et al. 2006; Moosavi et al. 2014; Hassanzadeh & Wernicke, 2016). All these lithologies are cross-cut by abundant leucogranitic rocks and dykes in the western part of the complex (Shakerardakani et al. 2020). The Neoarchaean basement of the Muteh–Golpaygan metamorphic complex has recently been constrained by 207Pb–206Pb ages of c. 2.7 and 2.5 Ga from xenocrystic zircons within amphibolite (Shakerardakani et al. 2019). Unmetamorphic to very low-grade metamorphic Mesozoic and Cenozoic shale, sandstone, siltstone, slate, dolomite and conglomerate units overlie the basement rocks in the study area and are in turn mostly covered by Quaternary rocks.

The depositional age of the metapelitic rocks from the Muteh–Golpaygan metamorphic complex is unknown. The metapelites are dominantly characterized by amphibolite-facies mineral assemblages, including garnet, staurolite and kyanite (Moritz et al. 2006). K–Ar amphibole ages of c. 156 Ma (Rachidnejad-Orman et al. 2002) suggest that metamorphism was predominantly of Late Jurassic age (Moosavi et al. 2014; Hassanzadeh & Wernicke, 2016). Samples GQ-12 and GQ-21 are strongly foliated garnet-micaschists from the Muteh–Golpaygan metamorphic complex (Fig. 3c, d) and consist of biotite, porphyroblastic garnet (up to 1 mm in size), white mica, plagioclase, chlorite and opaque phases.

4. Analytical methods

In this study, we analysed the detrital zircon populations of three garnet-micaschist samples from the SSMZ to gain insight into the provenance of these strata and how it changes through time and along the SSMZ. Two samples, GQ-12 and GQ-21, were collected to the north of the Muteh–Golpaygan metamorphic complex, while the third sample, LJ-140, was collected northeast of the Dorud area (Fig. 2b; online Supplementary Material Table S1). All three samples contain abundant zircon grains.

Zircons were extracted from a garnet-micaschist (sample LJ-140) of the Dorud–Azna region at Salzburg University. About 3 kg of each sample was crushed in a steel disc mill to obtain the ~50–250 μm sieve fraction. Zircons were concentrated by a standard plastic pan and warm water, Frantz isodynamic magnetic separator and methylene iodide heavy liquid separation procedures, and handpicking under a binocular microscope. A total of 130 zircon grains were dated in situ on an excimer (193 nm wavelength) laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) at the State Key Laboratory of Continental Dynamics, Northwest University, Xi’an, China. Trace elements were measured simultaneously. The analytical details follow Liu et al. (2008) and are described in Appendix 1.

U–Pb and trace-element analysis of a total of 228 detrital zircon grains obtained from two garnet-micaschist samples (GQ-12 and GQ-21) within the Muteh–Golpaygan metamorphic complex was performed at the China University of Geosciences, Beijing by LA-ICP-MS, using the methodology of Song et al. (2010). Detrital zircon grains (~50–200 μm) were separated from crushed rocks using a standard plastic pan and warm water and subsequent magnetic
Fig. 2. (Colour online) (a) Main zones under consideration in Iran. (b) Simplified geological map of the Dorud–Azna region and sample location of garnet-micaschist. Ages are given in Ma; sources of data: 1 – Shakerardakani et al. (2015); 2 – Fergusson et al. (2016). (c) Geological map of the Muteh–Golpaygan area and location of investigated samples (modified after Shakerardakani et al. 2020 and references therein). Sources of data: 1 – Shakerardakani et al. (2020); 2 – unpublished data; 3 – Hassanzadeh et al. (2008).
separation and heavy liquid separation followed by handpicking. The analytical details are given in Appendix 2.

For interpretation of the age data, we used the recent version (http://www.stratigraphy.org) of the time-scale calibration proposed by Cohen et al. (2013).

5. Analytical results

Together, we carried out a coupled U–Pb age and trace-element analysis of 362 detrital zircons from three garnet-micaschist samples (primarily Palaeozoic–early Mesozoic in age, see Sections 5.a and 5.b) distributed along a ~100 km long section of the central SSMZ, and they can be taken as representative of the central part of the SSMZ.

5.a. Detrital zircon ages: Dorud–Azna area

Zircons from sample LJ-140 have crystal lengths of ~70 to 200 μm. Except those with an early Proterozoic age or with an age at the middle/late Proterozoic boundary, most grains are euhedral or subhedral, implying relatively short transport. As shown in representative cathodoluminescence (CL) images (Fig. 4), the majority of the investigated zircon grains exhibit clear inner structures with a broad zoning, an internal oscillatory zoning and very rarely thin bright rims under CL, interpreted as metamorphic overgrowths. Zircons have Th and U contents ranging from 2.06 to 1357 ppm and 34.21 to 2618 ppm, respectively. The Th/U ratios range from 0.10 to 1.78 with a mean value of 0.53, except four spots (Th/U < 0.1), indicating that the majority of the zircons are of magmatic origin (Corfu et al. 2003; Corfu, 2004).

In total, 134 analyses were obtained for 130 zircon grains from the garnet-micaschist sample; 30 analyses are not considered because of a discordance of >10 %, and 104 grains are subconcordant between 90 and 110 % concordancy (Fig. 5; online Supplementary Material Table S1). The majority of the zircon populations (96 %) contain grouping of 565–700 Ma, 737–805 Ma, 820–915 Ma, 0.93–1.1 Ga, 1.81–2.07 Ga and one younger, Cambrian age (~507 Ma). Owing to low Th/U ratios and missing oscillatory zoning, four zircons (507 ± 9 Ma, 586 ± 8 Ma, 692 ± 9 Ma and 702 ± 11 Ma) are interpreted as metamorphic zircons. Only four Archaean ages (<4 %) were discovered (~2.62, 2.68, 2.73 and 3.24 Ga).

5.b. Detrital zircon ages: Muteh–Golpaygan metamorphic complex

A total of 90 valid age values out of 228 zircon grains were obtained based on whether their U–Pb analyses were concordant or not. Most zircon grains from the sample GQ-21 are euhedral to subhedral prisms (50 to 150 μm in length) with a clear oscillatory (e.g. spot 50) and/or sector zoning (e.g. spots 41, 87) in CL images and Th/U ratios ranging from 0.11 to 3.13, suggesting that they have a magmatic origin (Figs 4, 6). However, nine zircon grains appear homogeneous in CL images and were recorded to possess low Th/U ratios of 0.03 to 0.07; these characteristics typically imply a metamorphic origin (e.g. Rubatto, 2002).

Zircon U–Pb analyses yielded diverse age groups, indicating different sources for the zircons (Fig. 5). Six major age populations dominate the GQ-21 detrital zircon grains, with populations at 547–611 Ma, 642–788 Ma, 868–931 Ma, 0.97–1.17 Ga, 1.79–2.07 Ga and 2.36–2.5 Ga. From a total of 40 dated subconcordant zircons, one gave an Ordovician age (~467 Ma), two gave Cambrian ages (~505 Ma, 532 Ma) and one gave a Neoarchaean age (~2.58 Ga; online Supplementary Material Table S1). Six Proterozoic zircons (1787 ± 35 Ma, 1030 ± 52 Ma, 642 ± 4 Ma, 611 ± 5 Ma, 602 ± 5 Ma, 552 ± 4 Ma) are considered to have a metamorphic origin.
With the exception of few sub-rounded zircon grains in sample GQ-12, the vast majority of the zircons are nearly euhedral or sub-hedral and prismatic (~50 to 100 μm in length). Many zircons show a clear oscillatory or sector zoning in CL images, and some of them exhibit thin overgrowth rims of weak or no zoning (Fig. 4).

The Th/U ratios of the zircons range from 0.10 to 2.03, except four spots (<0.1). The U and Th concentrations range from 75.5 to 2759 ppm and from 18.21 to 2218 ppm, respectively.

The zircon age populations from sample GQ-12 span characteristic intervals of time, namely 200–323 Ma, 383–423 Ma, 559–

![Cathodoluminescence images of dated zircons from garnet-micaschists of the Dorud–Azna and Muteh–Golpaygan regions. $^{206}$Pb–$^{238}$U age (Ma) is shown for ages <1000 Ma, the $^{207}$Pb–$^{206}$Pb age when older than 1000 Ma. Circles represent analysis spot positions with spot numbers and their ages in Ma.](https://doi.org/10.1017/S0016756821000728)
626 Ma, 808–963 Ma and 1.81–2.5 Ga, displaying a multi-peaked age distribution pattern (Fig. 5). Five out of 50 subconcordant zircons analysed have Jurassic (~149–200 Ma) ages. This sample yields a small portion (~<4%) of metamorphic zircons (1916 ± 24 Ma, 1808 ± 21 Ma).

5.c. Trace-element chemistry of the zircons

Trace-element compositions of zircon grains can identify the most likely source rock types within which the detrital zircon grains crystallized (e.g. Belousova et al. 2002; Hoskin & Schaltegger, 2003; Grimes et al. 2007, 2015; Portner et al. 2011; Ranjan et al. 2020). Chondrite-normalized rare earth element (REE) patterns (online Supplementary Material Table S2; Fig. 7) for most of the laser spots of sample LJ-140 indicate features typical for a wide variety of crustal rocks (Hoskin & Schaltegger, 2003), with heavy rare earth element (HREE) abundance between 100× and 10 000× chondrite. Spider plots show prominent positive and negative Ce and Eu anomalies, respectively (Fig. 7). The REE patterns, zircon internal textures and high Th/U ratios (Th/U = 0.1–1.78) suggest that a majority of the zircons are typical of magmatic protoliths with mild effects of late-magmatic/metamorphic recrystallization, as indicated by the flat HREE patterns for a few zircons (Fig. 7).

The chondrite-normalized zircon REE patterns for all age populations of sample GQ-21 show a similar pattern of depleted light rare earth elements (LREEs), progressively increasing HREEs, a prominent positive Ce anomaly and a negative Eu anomaly. These observations are consistent with the textural features indicating zircon growth from melts as a dominant process for the growth of all zircon populations (Rubatto & Hermann, 2007).

Discrimination diagrams using U/Yb or Th/Yb ratios provide a robust method for distinguishing modern zircons crystallized within continental or oceanic crust (Grimes et al. 2007, 2015). Generally, the U/Yb ratio is controlled by the difference in element solubility. Incompatible elements, such as U, are readily soluble in fluids and thus subsequently enriched in continental crust relative to oceanic crust and upper mantle (Grimes et al. 2007). Consequently, continental crust is less enriched in incompatible elements, such as Y and Yb, relative to oceanic crust (e.g. Belousova et al. 2002; Grimes et al. 2007). On the U/Yb versus Hf (and U versus Yb) diagrams, the detrital zircons in both samples plot predominantly in the field of continental zircons; based on available data they are clearly distinct from the field of oceanic crustal zircons (Fig. 8a, b). Furthermore, Grimes et al. (2015) have shown that the Nb/Th and Nb/U ratios of zircons reflect the ratios of their host rocks and that zircons from continental arcs have lower Nb/Th and Nb/U ratios compared to zircons in rocks from non-arc settings. Plotting the detrital zircons shows that nearly all
of the detrital zircon populations (92–95 %) are enriched in U/Yb ratios and plot in the continental field (Fig. 8a–c). This result cannot be attributed to a homogeneous source region or derivation of detritus from a single source but was considered by Hoskin & Ireland (2000) to confirm the apparent monotony of REE patterns and abundances in zircons derived from a range of common crustal rock types (Hoskin & Schaltegger, 2003).

6. Discussion
6.a. Depositional ages
In order to determine the most reliable maximum depositional age for each sample, we utilize four alternate measures of the maximum depositional ages as outlined by Dickinson & Gehrels (2009). These include: (1) the age of the youngest single grain within a sample with a 1σ error less than 10 Ma (e.g. Stevens Goddard et al. 2018); (2) the youngest graphical peak detrital zircon age controlled by more than one grain age; (3) the calculated weighted mean age of the youngest age peak from an at least three-grain cluster with overlapping ages within the 2σ error and a mean square weighted deviation (MSWD) ≤1; and (4) the weighted average age of the youngest two or more grains that overlap in age at 1σ error.

The oldest sample in this study (sample LJ-140) was collected from the north of the Dorud–Azna region in the central SSMZ (Fig. 2b). The sample displays a prominent peak at 577 ± 9 Ma, which is only ~10 Ma younger than the Cadomian orthogneiss basement and which is in close contact with the sample (608 ± 18 Ma and 588 ± 41 Ma; Shakerardakani et al. 2015) implying a tectonic contact between these two lithologies. This 577 Ma age provides the maximum depositional age for this unit. A grain with an age of 507.1 ± 9.41 Ma possesses a low Th/U ratio of <0.1 indicating metamorphic growth, which could be post-depositional.

East of the oldest sample from the central SSMZ, close to the UDMA, two samples (GQ-21 and GQ-12) were collected from the Muteh–Golpaygan metamorphic complex. The first sample

Fig. 7. Chondrite-normalized REE patterns for zircons from sample LJ-140. Chondrite data are from McDonough & Sun (1995).
(sample GQ-21) is distinguished by its prominent peak near 561 Ma, but it also contains one Middle Ordovician (467 ± 8 Ma) and two Cambrian (505 ± 4 Ma, 532 ± 4 Ma) detrital zircon grains. The weighted mean age for four grains at the prominent peak mentioned above is 552 ± 4 Ma (MSDW = 0.69). The ~552 Ma age peak for sample GQ-21 is close to the 577 Ma peak of sample LJ-140 from the Dorud–Azna region. The youngest single grain yielding an age of 467 ± 8 Ma (1σ), however, may indicate a younger depositional age.

The second sample from the northwestern part of the Muteh–Golpaygan complex (GQ-12) displays a marked change in provenance to Mesozoic–Palaeozoic sources with main peaks at...
230 Ma, 404 Ma, 609 Ma and 1867 Ma (Fig. 5). The youngest peak in this sample is at the Late Triassic–Early Jurassic boundary (205 ± 5 Ma; MSDW = 1.9), and only three zircons are distinctly younger (149 ± 2 Ma, 158 ± 3 Ma and 168 ± 3 Ma) than the rest (>190 Ma). We assume therefore a maximum depositional age of earliest Jurassic for this sample, which is reasonable as metamorphosed Jurassic sediments are widespread within the central SSMZ and represent the metamorphosed cover on the Cadomian basement (e.g. Rachidnejad-Omran et al. 2002; Sheikholeslami et al. 2003; Fazlnia et al. 2007; Davoudian et al. 2016). As geochronology constrains the age of metamorphism to the Late Jurassic period (156 Ma; Rachidnejad-Omran et al. 2002), the depositional age is within the short period between 205 and 156 Ma.

6.b. Provenance

6.b.1. Magmatic history of the SSMZ

Previous studies have provided a wealth of isotopic age constraints for many of the regional and long-lived magmatic events in the SSMZ (Hassanzadeh & Wernicke, 2016). Although Palaeozoic magmatic rocks are rare in Iran, compared to abundant Mesozoic and Cenozoic magmatism, they record multiphase magmatism during Ordovician–Silurian, Devonian–Carboniferous and Permian times (e.g. Berberian & King, 1981; Hassanzadeh & Wernicke, 2016; Moghadam et al. 2020). This precludes the possibility that the Late Triassic zircons are of xenocrystic origin through crustal contamination during the ascent of basaltic magmas through the continental crust of the SSMZ. As suggested by Shakerardakani et al. (2018), this basaltic magmatism may have originated from hotspot magmas intruding into the crustal base of the thinned Sanandaj–Sirjan passive margin basement and rising up into shallow levels. The latest Triassic/earliest Jurassic maximum depositional age of sample GQ-12 corresponds in age with the Middle–Upper Triassic to Jurassic sedimentary rocks, which were deposited on the passive continental margin of the Neotethys Ocean (Hassanzadeh & Wernicke, 2016; Shakerardakani et al. 2018). On the other hand, an origin of Triassic zircons from Late Triassic granites of Central Iran cannot be excluded (e.g. Ramezani & Tucker, 2003). Abundant similar Early Triassic to Permian ages were recently reported by Meinhold et al. (2020) from Triassic sandstones of Central Iran.

Furthermore, two Carboniferous–early Permian age peaks were recorded for zircons of sample GQ-12, matching the modal age of extensive Carboniferous and earliest Permian granite-gabbro intrusive suites appearing both in the SSMZ and Central Iran, as well as in the Alborz Mountains and NE Iran (e.g. Bagheri & Stampfl, 2008; Zanchi et al. 2009a,b; Zanchetta et al. 2013, 2019; Bea et al. 2011; Buchs et al. 2013; Saccani et al. 2013;
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Kargarabafghi et al. 2015; Moghadam et al. 2015; Shakerardakani et al. 2017; Honarmand et al. 2017; Shabanian et al. 2020). Late Palaeozoic rifting of the future Neotethys Ocean formed ribbon continental fragments in Iran that broke away from the northern margin of Gondwana (e.g. Berberian & King, 1981; Şengör, 1990; Agard et al. 2011; Richards, 2015). Subsequently, after a long period of epeirogeny and significant breaks in the sedimentary record during Ordovician–Carboniferous times, the late Carboniferous to early Permian was a period of marine transgression associated with a major extensional phase that affected most parts of Iran (Berberian & King, 1981; Alavi-Naini, 2009).

The available source for the early Permian zircons (sample GQ-12) is dominated by the isolated early Permian anorogenic Hasanoht pluton (294–288 Ma), which is located south of the Muteh–Golpaygan metamorphic complex and intruded into upper Carboniferous – lower Permian strata (Alirezaei & Hassanzadeh, 2012; Honarmand et al. 2017). The Carboniferous ages of detrital zircons can be explained by subordinate granitic orthogneisses and metagabbros of the region (Shakerardakani et al. 2015; Ferguson et al. 2016; Shabanian et al. 2020).

Vestiges of volcanic activity during Devonian time, mostly restricted to sill-like intrusions, dykes and lava flows interlayered within sedimentary formations, are particularly known in Alborz, Central Iran, the SSMZ, and NE and NW Iran (e.g. Assereto, 1963; Alavi & Bolourchi, 1973; Lammerer et al. 1984; Houshmazdadeh et al. 1990; Wendt et al. 2002, 2005; Derakhshi & Ghasemi, 2015; Ghasemi & Dayhimi, 2015). Early Devonian detrital zircons can be traced from intra-oceanic Palaeoethys subduction and continental-type magmatism (e.g. Ghazi et al. 2001; Zanchetta et al. 2013; Moghadam et al. 2017). The Early Devonian age population of the Golpaygan detrital zircons is scattered around 404 Ma, but it is unlikely that such zircons could be transported from NE and NW Iran across the Palaeoethys to be deposited in the future SSMZ (Moghadam et al. 2017). Paidar-Saravi (1989) described a range of different metavolcanic rocks, including rhyolitic, dacitic and andesitic lava, which are interlayered with schists in the Muteh–Golpaygan metamorphic complex. Rachidnejad-Omran et al. (2002) also mentioned the presence of metarhyolite and metavoacanic tuff. They suggested that metamorphites together with amphibolites represent a bimodal volcanic suite and, together with the host schist and gneiss, an early Palaeoethys volcano-sedimentary complex. Our field observations show that the undated rhyolitic rocks are interlayered within a Devonian–Carboniferous unit including marble, slate and metasandstone and are located in close contact with schists, orthogneisses and amphibolites in the central part of the Muteh–Golpaygan metamorphic complex. Therefore, we conclude that Early Devonian detrital zircons have mostly local sources.

The same is true for the ages around 600 Ma, which are well known in Palaeozoic and Mesozoic sediments and Precambrian magmatic basement rocks in the SSMZ and Central Iran (e.g. Ramezani & Tucker, 2003; Hassanzadeh et al. 2008; Nutman et al. 2014; Shakerardakani et al. 2015; Moghadam et al. 2018, 2020; Meinhold et al. 2020).

Consequently, age populations older than c. 600 Ma are distinctive for the derivation of the SSMZ.

6.6.2. Palaeogeographic relationships of the SSMZ

Detrital zircon geochronology has been widely used as a robust method with which to identify the source of sedimentary rocks (Gehrels, 2014). It also represents a powerful means of resolving the displacement history of potentially displaced terranes (Gehrels, 2014). The palaeogeographic relationships of the SSMZ are usually considered to relate to the Arabian–Nubian shield with its Neoproterozoic magmatic arcs and back-arc complexes. Particularly interesting are the age groups of 740–760 Ma and around 826 Ma. Based on our new U–Pb zircon ages, we discuss here two potential relationships: (1) the Arabian–Nubian shield connection and (2), as an alternative, which is also supported by biogeographic relationships, the South China block connection. For comparison, age spectra of these regions are shown in Figure 9.

6.6.2.1. Correlation of Gondwanan detrital zircon age spectra.

The age population clusters at 0.55–0.63 Ga, 0.64–0.78 Ga, 0.80–0.91 Ga, 0.94–1.1 Ga, 1.8–2.0 Ga and 2.1–2.5 Ga are present in nearly all samples (Fig. 5). The percentage of >540 Ma zircons in each sample generally decreases with younger stratigraphic ages, ranging from ~96 % in the oldest sample to <25 % in the youngest samples. A comparison of the Neoproterozoic and early Palaeozoic detrital zircon age spectra has important implications for the palaeotectonic reorganization at the Gondwana margin. Our data show a significant concentration of detrital zircons at 0.55–0.63 Ga, consistent with ages of widespread Pan-African subduction-related granitic basement in Iran (e.g. Ramezani & Tucker, 2003; Hassanzadeh et al. 2008; Nutman et al. 2014; Shakerardakani et al. 2015; Moghadam et al. 2018).

The age groups of c. 0.6–0.9 Ga compose ~35 % of all analysed zircons of samples LJ-140 and GQ-21. Based on ion-microprobe U–Pb analyses of detrital zircon grains from various Neoproterozoic to Cambrian sandstones of the Alborz and Zagros mountains and from the basement of the Central Iranian plateau, Horton et al. (2008) proposed that a basal clastic succession representing the earliest sedimentary record in Iran displays a provenance age signature dominated by Pan-African (0.9–0.6 Ga) rocks, which are similar to detrital zircon age spectra for age-equivalent units of the west and south in Israel, Jordan, Egypt and Saudi Arabia in northern Gondwana (e.g. Aivigad et al. 2003, 2015, 2017; Kolodner et al. 2006; Meinhold et al. 2021). Because of the lack of significant pre-600 Ma detrital zircon ages, these authors have therefore concluded that the main sources were likely located in Pan-African basement provinces of Arabia and Africa, particularly in the Arabian–Nubian shield, although the Iranian basement may have contributed some sediment. In addition, Moghadam et al. (2017) suggested that the 0.6–0.5 Ga old detrital zircons belong to the local Cadomian magmatism in Iran and surroundings or, alternatively, to the Arabian–Nubian shield and other reworked continental crust of Gondwana.

Pre-Neoproterozoic zircons, grouped at c. 0.9–1.1 Ga (Grenvillian), c. 1.8–2.0 Ga (early Proterozoic A) and c. 2.1–2.5 Ga (early Proterozoic B) make up nearly 35 % of the total zircon ages. For the Palaeoproterozoic zircons, there is a plausible origin from the Arabian–Nubian shield and Africa with a juvenile mantle source (Honarmand et al. 2016; Moghadam et al. 2017). Variable amounts of ~980 Ma ages also occur in Palaeozoic sedimentary rocks of Saudi Arabia (Meinhold et al. 2021), and the Grenvillian population of our samples might have their source there. The Grenvillian detrital zircons first appear in the Alborz and Zagros succession in the upper Neoproterozoic to Cambrian formations (Horton et al. 2008). Zoleikhaei et al. (2020) recently found a minor population peak at ~980–1015 Ma in the Cambrian sandstones of the central Alborz. Nutman et al. (2014) reported a similar age group of 0.9–1.0 Ga with juvenile initial εHf values in inherited zircon cores of some
Pan-African granitoids in a nearby region of Dorud within the central SSMZ. The provenance of the Grenvillian-age zircons in Central Iran was interpreted as being involved in crustal evolution in an island arc setting, continuing in an active continental margin (Honarmand et al. 2016). In NE Iran, it was suggested that detrital zircons belonging to the Grenvillian-age cluster at c. 1020 Ma might be derived from a basement like that found in a sliver of Sinai basement rocks or lower Palaeozoic sandstones from Libya and Jordan (Be’eri-Shlevin et al. 2012; Moghadam et al. 2017).

The distribution of c. 1.0 Ga detritus (Meinhold et al. 2013) was used for the palaeogeographic reconstruction of fragments rifted from Gondwana during Palaeozoic and Mesozoic times. This led to the division of the North African margin of Gondwana, on the basis of zircon age data from Cambrian sandstones, into two separate domains comprising an eastern domain containing 1.0 Ga detrital zircons and a western domain practically devoid of c. 1.0 Ga detrital zircons (Meinhold et al. 2013). The age population of 1.0 Ga, which is rare in western North Africa (Algeria, Morocco), is more common in the east (Libya, Israel, Jordan), where it was supplied with detritus from the Transgondwanan Supermountain via the Gondwana superfan system (Squire et al. 2006; Meinhold et al. 2013; Neubauer, 2014).

In summary, it can be concluded that the Neoproterozoic detrital zircons from the studied schist samples of the SSMZ could have their origin in the Arabian–Nubian shield. In the further
discussion, we examine potential relationships to blocks further east, particularly to the South China block.

The South China block was formed by amalgamation of the Yangtzhe and Cathaysia blocks at c. 0.85 Ga, followed by anorogenic, rift-related magmatism at c. 820–740 Ma, centring around 850, 820, 800, 780 and 750 Ma, that are coeval with the break-up of the Rodinia supercontinent (e.g. Li et al. 2008; Li et al. 2009, 2014; Yao et al. 2014; Shu et al. 2021). As suggested by Yao et al. (2014; Fig. 9) and discussed in detail by Li et al. (2014), the South China block was most likely an integral part of Gondwanaland during early Palaeozoic time, which matches the palaeomagnetic analysis (Zhang, 2004) and recent plate tectonic reconstructions (Merdith et al. 2021). Available geological data shows that the South China block has a great affinity with India or Australia. However, the exact position of the South China block in Gondwana has not been well constrained. For instance, detrital zircon age patterns indicate that the South China block was either adjacent to northern India (Li et al. 2014; Yao et al. 2014) or between India and Australia (Yu et al. 2008; Wang et al. 2010; Duan et al. 2011; Cawood et al. 2013). Furthermore, the presence of the c. 533 Ma metamorphic event documented in the horblendeit in Cathaysia indicates that the South China block preserves the record of a major Pan-African orogeny, supporting the South China block being an integral part of the Gondwanan assembly (Li et al. 2017). More significantly, it can help to constrain the location of the South China block in Gondwana, suggesting that the South China block (together with Indochina) was most likely connected to northern India by a ‘Pan-African’ collisional orogeny (Li et al. 2014). Recently, Yang et al. (2020) found pronounced Neooproterozoic and Cambrian detrital zircon age populations from Ediacaran to Cambrian sandstones of the South China block and interpreted these as evidence for amalgamation and collision of the South China block with Gondwana. These authors also noted the similarity of the South block patterns to those of Iran (Fig. 9).

Taken together, the Arabian–Nubian shield is often referred to as the greatest potential source for the major Precambrian–Palaeozoic detrital zircons in the Indian microcontinent (e.g. Moghadam et al. 2017; Zoleikhai et al. 2020). However, we note that the Iranian microcontinent and South China block may have been geographically close, sharing a similar palaeoenvironment on the northern Gondwana margin.

6.b.2.b. Palaeobiogeographic arguments. The late Neooproterozoic to early Palaeozoic palaeobiogeographic patterns provide further important constraints on the relative position of the Iranian microcontinent on the northern Gondwana margin. As mentioned before, the SSMZ, Central Iran and (southern and central) Alborz are considered to have been part of the Iranian microcontinent with the Palaeoethys Ocean in the north and the Neotethys Ocean in the south during late Palaeozoic to Mesozoic times. They bear similar upper Ediacaran to Cambrian siphonotretide genera, e.g. on both sides of the lapetus belt in South China, India, Pakistan, Kazakhstan and Mongolia.

The new late Cambrian species of Siphonotretida recognized in the Alborz is the only known Cambrian representative of the group with distinct characteristics (Popov et al. 2009a), different from other siphonotretide genera, e.g. on both sides of the lapetus Ocean in Laurentia and Gondwana (Armorica), and in west Antarctica (Shergold et al. 1976; Popov et al. 2002; González-Cómez, 2005). The unique features of the late Cambrian Siphonotretidae of Iran are also characteristics of most of the Ordovician siphonotretide genera, which likely were rooted originally in high to temperate latitudes of peri-Gondwana (Fig. 10; Havišček, 1982; Mergl, 2002; Popov et al. 2008). Popov et al.
(2013) suggested that it can be typified by those described from the Middle Ordovician of Baltica (Gorjansky, 1969; Holmer, 1989) and South China (Zhang, 1995).

Dong et al. (2004) discussed 13 middle Cambrian through lowermost Ordovician conodont zones in Hunan, South China and their similarities with Iran (Müller, 1973) and correlated these with North China, western USA, western Newfoundland and Canada. In addition, the Early–Middle Ordovician palaeobiogeographic patterns of the brachiopod faunas from the Upper Yangtze Platform, South China were documented (Zhan & Jin, 2014), indicating a close faunal relationship between South China and Iran (Popov et al. 2009b).

The Lower Ordovician (Tremadocian) trilobite assemblage, as well as Darriwilian brachiopods in the Alborz, exhibit a close similarity to contemporaneous trilobite faunas of South China (e.g. Gobadi Pour, 2006; Gobadi Pour et al. 2007, 2011; Álvaro et al. 2013; Kebrī-ee Zadeh et al. 2015). Gobadi Pour et al. (2007) noted the species *Tathungshania miqueli* (Bergeron, 1894), the third diagnosable species, which has been recorded from South China, Turkey and Southern France, indicating North Gondwanan faunal affinities. In the eastern Alborz (Gerd-Kuh section), the lower Tremadocian *Asaphellus inflatus–Ductylocephalus* and *Psilocephalina lubrica* zones are characterized by medium diversity trilobite associations with strong links to contemporaneous faunas of South China (Gobadi Pour et al. 2013b). In addition, abundant and diverse brachiopods are present throughout the Gerd-Kuh section, and, as Popov & Cocks (2017) pointed out, Alborz is one of the few places globally which has a strophomenoid-dominated benthic assemblage in the Middle Ordovician brachiopod fauna, providing the opportunity to investigate the palaeogeographic and climatic control on their initial divergence. These authors suggested that the Australasian (Sibumasu) sector of Gondwana was the primary location of the origin and initial dispersion of the Strophomenoida, as well as the adjacent terranes and satellite plates of peri-Gondwana, including Alborz, North China and South China (Popov & Cocks, 2017).

The first occurrence of Late Ordovician trilobites from the High Zagros, has been reported in the middle member of the Seyahou Formation (Gobadi Pour et al. 2015a). This formation hosts a trilobite assemblage including *Dalmanitina (Dalmanitina) dargazensis*, which shows strong affinities with high-to-mid-latitude peri-Gondwanan faunas, and displays close similarities with taxa from the Mediterranean margin of Gondwana (mainly Sardinia and Bohemia/Perunica) and, to a lesser extent, with the Turkish Taurides (Gobadi Pour et al. 2015a).

Ameri (2015) reported a peri-Gondwanan trilobite assemblage from the Kuhbanan Formation at Dahu, north Kerman, which is the most complete fossiliferous upper lower Cambrian – middle Cambrian sequence in Central Iran. The distribution of the Kuhbanan Formation trilobite species (*Redlichia Biozone*) shows close faunal connections to the Hormoz Formation from South and SW Iran, the Salt Range (Pakistan), the Himalayan region, southern Siberia, Australia and South China (Ameri, 2015).

Popov et al. (2014) reported an important record of biotic recovery of benthic faunas in the Late Ordovician deposits of Iran after the terminal Ordovician mass extinction in temperate and high latitude Gondwana, which is still poorly known in the Mediterranean, North African and Arabian segments of Gondwana. A significant number of taxa from the shallow shelf biofacies indicates clear links to contemporaneous low-latitude faunas, for instance to Laurentia.
Baltica and South China (Popov et al. 2014). The authors proposed the close proximity of the peri-Gondwanan terranes of Central Iran, Kopet Dagh and Afghanistan, owing to the bearing of shallow water faunas during the Aeronian of the Silurian period.

In summary, late Neoproterozoic to the early Silurian faunas, restricted to the same type of palaeoenvironment, are shared by the Iranian microcontinent and South China block and represent key elements to determine their palaeogeographic similarities along the Gondwanan margin (Figs 10, 11). Li et al. (2014) and Yang et al. (2020) proposed that the South China block was accreted to East Gondwana during late Neoproterozoic–Cambrian times. Consequently, the Iranian microcontinent including the SSMZ can be considered as being part of the same Cambrian–early Silurian Gondwanan margin. Comparison of detrital zircons show similar age patterns in terranes originating from north of the Arabian–Nubian shield via the Iranian microcontinent to far in the east, along the northern Gondwana margin (Fig. 11).

7. Conclusions

New detrital U–Pb zircon ages from the SSMZ provide new insights into the palaeogeographic reconstruction of the Iranian microcontinent. Our conclusions are summarized as follows:

1. The youngest peak and weighted mean ages in the probability diagrams provide geochronological maximum depositional ages for hitherto undated metamorphic units. In particular, detrital zircon ages from the younger garnet-micaschist sample (GQ-12) represent a maximum depositional age of the sediments not older than latest Triassic, consistent with the metamorphosed Jurassic sediments widespread within the central SSMZ.

2. The reproducibility is remarkable of the age population peak at c. 0.6 Ga, which represents a distinct signal related to the late Neoproterozoic crystalline basement in Iran as well as to the Arabian–Nubian shield and other Pan-African domains in northern Gondwana. The other significant Neoproterozoic age populations in all three samples likely derived from magmatic rocks and/or recycled sedimentary sources, possibly from the eastern Arabian–Nubian shield.

3. New zircon age data from garnet-micaschists demonstrates the presence of a late Grenvillian age population at c. 0.94 to 1.1 Ga within the SSMZ, which led to deducing the proximity of the Sanandaj–Sirjan zone to distal parts of the ‘Gondwana superfan’ at the northern margins of Gondwana. The Grenvillian detrital age population suggests that the ‘Gondwana superfan’ even spread detrital material far east along the northern Gondwana margin and reached the South China block, where this age group occurs but remains subordinate (e.g. Yang et al. 2020).

4. It is worth noting that further research should focus on more detrital zircon ages from metamorphic clastic rocks and Cambrian–Ordovician sandstones as well as obtaining the biogeographic distribution of Cambrian–Ordovician shallow marine organisms that would also provide better insights into the palaeogeographic reconstruction of the northern Gondwana margin during early Palaeozoic time.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/500116756821000728
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Zircons were separated from the one sample from the Dorud area (LJ-140) in the laboratory of the Geophysics and Geology Department of Salzburg University, Austria. The selected zircon grains were dated in situ on an excimer (193 nm wavelength) laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) at the State Key Laboratory of Continental Dynamics, Northwest University. The ICP-MS was used an Agilent 7500a (with shield torch). The unique shield torch increases analytical sensitivity by a factor of >10 (for example, 4500 cps/ppm 238U at a spot size of 40 μm and laser frequency of 10 Hz), which is important for LA-ICP-MS. The GeoLas 200M laser ablation system (MicroLas, Göttingen, Germany) was used for the laser ablation experiments. Helium was used as the carrier gas. The used spot size and laser frequency were set at 40 μm and 10 Hz, respectively. The data acquisition mode was peak jumping (20 ms per isotope each cycle). Raw count rates were measured for 26Si, 204Pb, 206Pb, 207Pb, 208Pb, 232Th and 238U. U, Th and Pb concentrations were calibrated by using 26Si as an internal standard and NIST SRM 610 as the reference standard. Each analysis consisted of 30 s gas blank and 40 s signal acquisition. High-purity argon was used together with a custom helium filtration column, which resulted in 204Pb and 208Hg being less than 100 cps in the gas blank. Therefore, the contribution of 208Hg to 204Pb as revealed by detrital zircon studies was negligible and no correction was made. 206Pb/238U, 207Pb/206Pb, 206Pb/207Pb, 232Th/238U, U/Hf, Th/Hf and Pb/Hf ratios, calculated using GLITTER 4.0 (Macquarie University), were corrected for both instrumental mass bias and depth-dependent elemental and isotopic fractionation using Harvard zircon 91500 as an external standard. The ages were calculated using Isoplot 3 (Ludwig, 2003). Our measurement of TEMORA 1 as an unknown yielded a weighted 206Pb/238U age of 415 ± 4 Ma (MSWD = 0.112, n = 24) (Yuan et al., 2004), which is in good agreement with the recommended ID-TIMS age of 416.75 ± 0.24 Ma (Black et al., 2003). Analytical details for age and trace and rare earth element determinations of zircons and tracers are reported in Yuan et al. (2004). Common Pb corrections were made following the method of Andersen (2002). Because measured 204Pb usually accounts for <0.3 % of the total Pb, the correction is insignificant in most cases.

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ICP-MS) coupled with a New Wave SS UP193 laser sampler at the Elemental Geochemistry Lab of the Institute of Earth Sciences, China University of Geosciences, Beijing. For the present work, the laser spot size was set to ~36 μm for one sample (GQ-21) and to 25 μm for sample GQ-12 with a small size of zircons; the laser energy density was set at 8.5 J cm⁻² and repetition rate at 10 Hz. The procedure of laser sampling includes 5-s pre-ablation, 20-s sample-chamber flushing and 40-s sampling ablation. The ablated material is carried into the ICP-MS by the high-purity helium gas stream with a flux of 0.8 L min⁻¹. The whole laser path was fluxed with N₂ (15 L min⁻¹) and Ar (1.15 L min⁻¹) in order to increase energy stability. The counting time for U, Th, ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb and ²⁰⁴Pb is 20 ms, and is 15 ms for other elements. Calibrations for the zircon analyses were carried out using NIST 610 glass as an external standard and Si as an internal standard. U–Pb isotope fractionation effects were corrected using zircon 91500 (Wiedenbeck et al. 1995) as an external standard. The zircon TEMORA (417 Ma, Black et al. 2003) and Qinghu (159.5 ± 0.2 Ma; Li et al. 2013) were used as the secondary standards to supervise the deviation of age measurement/calculation. Data reduction was carried out on the software GLITTER (version 4.4, Macquarie University). The common lead correction was made following Andersen (2002), and Isoplot 3 (Ludwig, 2003) was used for age calculations and plots of concordia diagrams.