

Detrital zircon U

–

Pb geochronology, trace-element and Hf isotope

geochemistry of the metasedimentary rocks in the Eastern Himalayan

Gondwana Research 41 (2017) 20

[7](http://dx.doi.org/10.1016/j.gr.2015.07.013)

[–](http://dx.doi.org/10.1016/j.gr.2015.07.013)

22

[1](http://dx.doi.org/10.1016/j.gr.2015.07.013)



Contents lists available at

ScienceDirec

[t](http://www.sciencedirect.com/science/journal/1342937X)

GondwanaResearch

journal homepage:

www.elsevier.com/locate/g

[r](http://www.elsevier.com/locate/gr)

syntaxis: Tectonic and paleogeographic implications

Liang Guo a,⁎, Hong-Fei Zhang a, Nigel Harris b, Wang-Chun Xu a, Fa-Bin Pan a

a State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China b Department of Environmental, Earth and Ecosystems, The Open University, Milton Keynes MK7 6AA, UK

# a r t i c l e i n f o

Article history:

Received 29 April 2015

Received in revised form 19 July 2015

Accepted 22 July 2015 Available online 8 September 2015

Keywords:

Detrital zircon

Eastern Himalayan syntaxis

Greater Himalayan Sequence

South Lhasa terrane

Paleogeography

# a b s t r a c t

The origin of the Greater Himalayan Sequence in the Himalaya and the paleogeographic position of the Lhasa terrane within Gondwanaland remain controversial. In the Eastern Himalayan syntaxis, the basement complexes of the northeastern Indian plate (Namche Barwa Complex) and the South Lhasa terrane (Nyingchi Complex) can be studied to explore these issues. Detrital zircons from the metasedimentary rocks in the Namche Barwa Complex and Nyingchi Complex yield similar U–Pb age spectra, with major age populations of 1.00–1.20 Ga, 1.30–1.45 Ga, 1.50–1.65 Ga and 1.70–1.80 Ga. The maximum depositional ages for their sedimentary protoliths are ~1.0 Ga based on the mean ages of the youngest three detrital zircons. Their minimum depositional ages are ~477 Ma for the Namche Barwa Complex and ~499 Ma for the Nyingchi Complex. Detrital zircons from the Namche Barwa Complex and Nyingchi Complex also display similar trace-element signatures and Hf isotopic composition, indicating that they were derived from common provenance. The trace-element signatures of 1.30–1.45 Ga detrital zircons indicate that the 1.3–1.5 Ga alkalic and mafic rocks belt in the southeastern India is a potential provenance. Most 1.50–1.65 Ga zircons have positive εHf(t) values (+1.2 to +9.0), and most 1.70–1.80 Ga zircons have negative εHf(t) values (−7.1 to −1.9), which are compatible with those of the Paleo- to Mesoproterozoic orthogneisses in the Namche Barwa Complex. Provenance analysis indicates that the southern Indian Shield, South Lhasa terrane and probably Eastern Antarctica were the potential detrital sources. Combined with previous studies, our results suggest that: (1) the Namche Barwa Complex is the northeastern extension of the Greater Himalaya Sequence; (2) the metasedimentary rocks in the Namche Barwa Complex represent distal deposits of the northern Indian margin relative to the Lesser Himalaya; (3) the South Lhasa terrane was tectonically linked to northern India before the Cambrian.

© 2015 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.

## 1. Introduction

The Himalaya-Tibetan orogen was built upon a complex tectonic collage resulting from several continental collision events since the Early Paleozoic (Allègre et al., 1984; Yin and Harrison, 2000; Zhu et al., 2013). From north to south, it consists of the Kunlun–Qaidam, Songpan–Ganzi, Qiangtang, Lhasa terranes and Himalaya (Fig. 1a), which are separated by the Anyimaqen–Muztagh suture, Jinshajiang suture, Bangong–Nujiang suture, and Indus–Tsangpo suture, respectively. Reconstruction of the Neoproterozoic–Paleozoic paleogeography for different terranes, such as the Himalaya, Lhasa and Qiangtang terranes, is therefore of critical importance to our understanding of the formation and evolution of the Himalaya-Tibetan orogen (Allègre et al., 1984; DeCelles et al., 2000; Yin and Harrison, 2000; Myrow et al., 2003;

|  |
| --- |
| ⁎ Corresponding author. Tel.: +86 27 67883003; fax: +86 27 67883002. E-mail address: lguo@cug.edu.cn (L. Guo). <http://dx.doi.org/10.1016/j.gr.2015.07.013> |

Gehrels et al., 2011; Zhu et al., 2011a, 2013; Zhang et al., 2012a, 2014; McQuarrie et al., 2013).

The paleogeographic position of Lhasa terrane within Gondwanaland remains a matter of dispute. Traditionally, the Lhasa terrane was sandwiched between the Indian plate and Qiangtang terrane (Metcalfe, 1996; Yin and Harrison, 2000; Dong et al., 2010; Gehrels et al., 2011; Burrett et al., 2014). However, recent studies argued that the Lhasa terrane was located adjacent to Northwest Australia (Ferrari et al., 2008; Zhu et al., 2011a; Ran et al., 2012). The Lhasa terrane can be divided into the South and North Lhasa terranes by the Permian North Gangdese suture (Fig. 1b) (Yang et al., 2009; Zhang et al., 2014). Zhang et al. (2012a, 2014) proposed that the North Lhasa terrane might have been derived from the northern segment of the East African Orogen, and the South Lhasa terrane might be related to Northwest Australia or northern India. The evidence supporting the Australian affinity is that detrital zircon age spectra of Carboniferous– Permian sedimentary rocks in the North Lhasa terrane are similar to those of Northwest Australia, but different from those of Tethyan

1342-937X/© 2015 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.

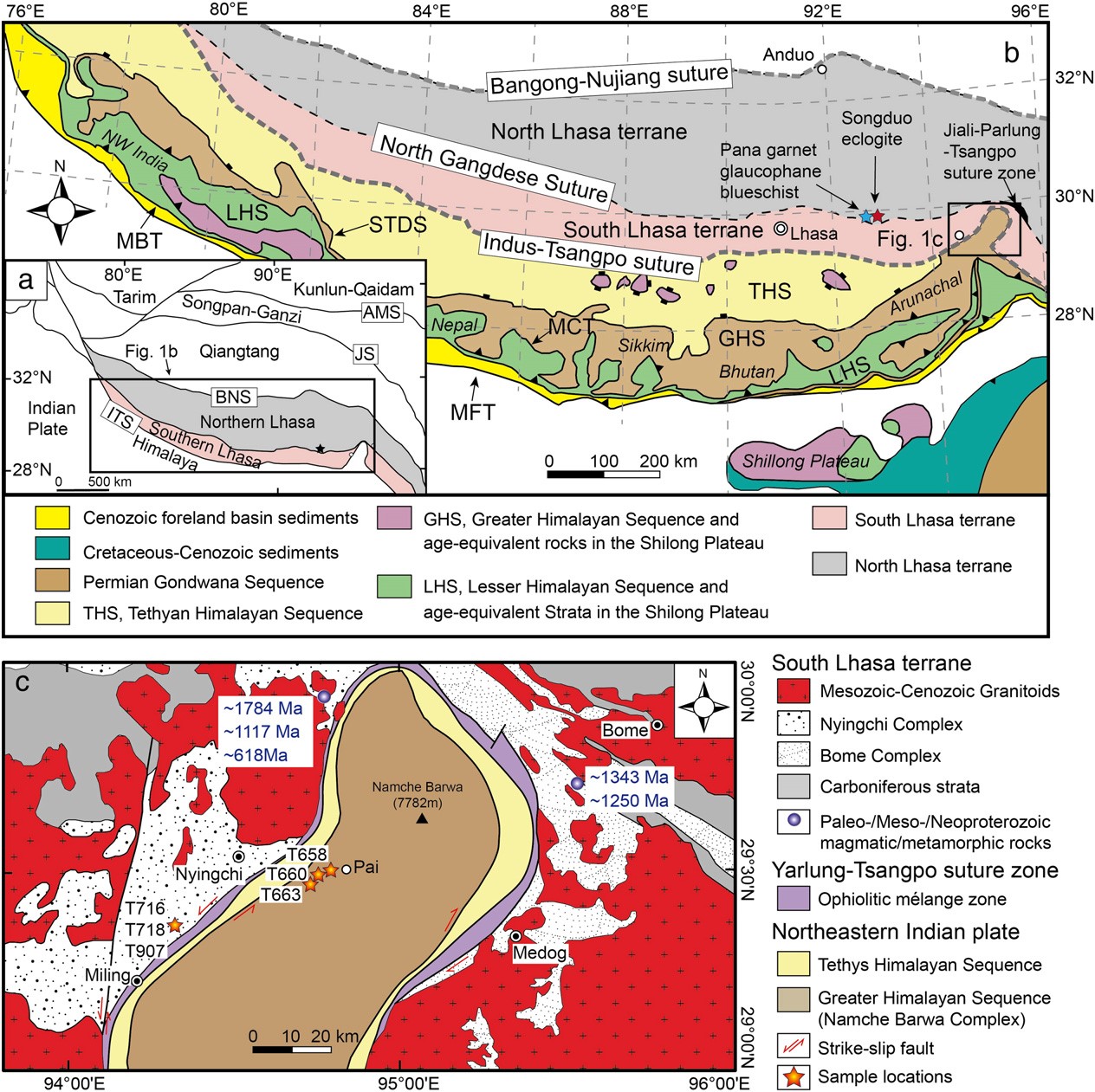


Fig. 1. (a) Tectonic outline of the Himalayan–Tibetan Plateau. AMS = Anyimaqen–Muztagh suture; BNS = Bangong–Nujiang suture; JS = Jinshajiang suture; ITS = Indus–Tsangpo suture. (b) Tectonic framework of the Himalayan orogen and Lhasa terrane (modified from Yin et al. (2010a); Zhu et al. (2011b) and Yang et al. (2009)), showing the location of this study area in the Eastern Himalayan syntaxis. The locations of Songduo eclogite belt (Yang et al., 2009), Pana garnet glaucophane blueschist (Liu et al., 2009) and Jiali–Parlung–Tsangpo suture zone (Geng et al., 2006) are also displayed. Abbreviations: STDS = South Tibet detachment system; MCT = Main Central thrust; MBT = Main Boundary thrust; MFT = Main Frontal thrust. (c) Simplified geological map of the Eastern Himalayan syntaxis (modified from Xu et al. (2012) and Zhang et al. (2015)), showing the locations of the studied samples and Paleoproterozoic–Neoproterozoic magmatic/metamorphic rocks (Lin et al., 2013; Xu et al., 2013b).

Himalaya (Zhu et al., 2011a, 2013). The South Lhasa terrane is the key connection between the Indian plate and the North Lhasa terrane (Fig. 1b), thus constraining its paleogeographic position is essential for reconstructing the paleogeography of the northern East Gondwana. In the Eastern Himalayan syntaxis, the metamorphic basement complexes of the northern Indian plate (Namche Barwa Complex) and the South Lhasa terrane (Nyingchi Complex) can be studied to explore this issue.

In this study, our new data show that the Namche Barwa Complex is likely the northeastern extension of the Greater Himalayan Sequence. The metasedimentary rocks in the Namche Barwa Complex represent the distal deposits of northern Indian margin. The similar detrital zircon U–Pb age spectra, trace-element signatures and Hf isotopic compositions between the Namche Barwa Complex and Nyingchi Complex indicate that their sedimentary protoliths were derived from common provenance, and that the South Lhasa terrane was linked to the northern Indian plate before the Cambrian.

## 2. Geological background and sample descriptions

2.1. Geological background

The Himalayan orogenic belt is separated from the Lhasa terrane by Indus–Tsangpo suture (Fig. 1b). It has been divided into four tectonostratigraphic units from south to north: Sub-Himalayan, Lesser Himalayan Sequence (LHS), Greater Himalayan Sequence (GHS), and Tethyan Himalayan Sequence (THS), separated by the Main Front thrust, Main Boundary thrust, Main Central thrust, and South Tibetan detachment series, respectively (Fig. 1b) (Yin, 2006, and references therein). The LHS can be further subdivided into lower LHS and upper LHS by an unconformity between Mesoproterozoic and Neoproterozoic (McQuarrie et al., 2008, 2013; Kohn et al., 2010; Long et al., 2011). The lower LHS consists of Late Paleoproterozoic to the earliest Mesoproterozoic metasedimentary strata with small volume of igneous rocks, and the upper LHS consists of Late Mesoproterozoic–Early Neoproterozoic to Cambrian strata (DeCelles et al., 2000; Yin, 2006; McQuarrie et al., 2008, 2013; Kohn et al., 2010; Myrow et al., 2010; Long et al., 2011; McKenzie et al., 2011). The GHS is mainly composed of Neoproterozoic–Paleozoic strata, which were intruded by Cambrian–Ordovician granitoids and Miocene leucogranites (DeCelles et al., 2000; Myrow et al., 2010; Yin, 2006, and references therein). The THS consists of Proterozoic to Eocene siliciclastic and carbonate sedimentary rocks interbedded with Paleozoic and Mesozoic volcanic rocks (Brookfield, 1993; Myrow et al., 2003; Yin, 2006, and references therein).

The Lhasa terrane is separated from the Qiangtang terrane to the north by the Bangong–Nujiang suture zone and from the Tethyan Himalaya to the south by the Indus–Tsangpo suture zone (Fig. 1b). The Lhasa terrane can be divided into the South and North Lhasa terranes (Fig. 1b) by the Permian–Triassic North Gangdese suture zone (Yang et al., 2009). The North Lhasa terrane is underlain by a Proterozoic–Archean crystalline basement (Zhu et al., 2011b, 2013) that experienced multiple episodes of metamorphic overprinting and magmatism from Neoproterozoic to Cenozoic times (Xu et al., 1985; Hu et al., 2005; Kapp et al., 2005; Dong et al., 2011; Zhu et al., 2012a; Zhang et al., 2012a, 2014). This crystalline basement is covered by Permo-Carboniferous and Upper Jurassic–Lower Cretaceous strata and volcanic rocks, and minor Cambrian–Devonian and Triassic strata (Zhu et al., 2012a). The South Lhasa terrane is dominated by the Jurassic– Neogene Gangdese batholith and Linzizong volcanic succession (Coulon et al., 1986; Chu et al., 2006; Wen et al., 2008; Ji et al., 2009; Guo et al., 2011; Zhu et al., 2011b; Pan et al., 2014). Its metamorphic basement is exposed in the eastern part of the South Lhasa terrane (Zhang et al., 2008; Dong et al., 2010; Guo et al., 2011; Lin et al., 2013; Xu et al., 2013b).

In the Eastern Himalayan syntaxis, the South Lhasa terrane is separated from the northeastern Indian plate by the Yarlung–Tsangpo suture zone (Fig. 1c) (Burg et al., 1997; Geng et al., 2006; Guo et al., 2011; Zhang et al., 2012b). The South Lhasa terrane consists of the high-grade Nyingchi Complex and Bome Complex, Paleozoic–Mesozoic strata and Mesozoic–Cenozoic granitoids (Booth et al., 2009; Burg et al., 1997; Geng et al., 2006; Guo et al., 2011, 2012, 2013; Xu et al., 2013a,b; Zhang et al., 2008, 2010a). The Nyingchi Complex is composed of orthogneiss, paragneiss, amphibolite, marble, schist, quartzite, migmatite, and minor granulites (Geng et al., 2006; Booth et al., 2009; Wang et al., 2009; Dong et al., 2010; Zhang et al., 2010b, 2013, 2014; Guo et al., 2011, 2012, 2013). The Bome Complex has similar lithological assemblage to that of the Nyingchi Complex except for the lack of granulites (Xu et al., 2013a,b). Both the Nyingchi and Bome Complexes were previously considered to be the Precambrian metamorphic basement of the Lhasa terrane based on their middle- and high-grade metamorphism (Geng et al., 2006). However, recent studies show that they experienced multiple episodes of metamorphism from Late Mesoproterozoic, Late Neoproterozoic, Late Cretaceous to Miocene (Booth et al., 2009; Wang et al., 2009; Dong et al., 2010; Zhang et al., 2010b, 2013, 2014; Guo et al., 2012, 2013; Lin et al., 2013; Xu et al., 2013a). Detrital zircon geochronological studies revealed that the metasedimentary rocks have various depositional ages ranging from Paleozoic to Cenozoic (Zhang et al., 2008; Dong et al., 2010; Guo et al., 2012, 2013; Zhang and Wu, 2012; Xu et al., 2013a). In this study, we report that the Nyingchi Complex contains N499 Ma sedimentary rock. The orthogneisses have protolith crystallization ages ranging from Paleoproterozoic (~1782 Ma), Cambrian (~496 Ma), Late Devonian–Carboniferous (367–345 Ma), Jurassic (~165 Ma), and Cretaceous to Eocene (Dong et al., 2010, 2014; Guo et al., 2011, 2012, 2013; Ji et al., 2012; Lin et al., 2013; Zhang et al., 2013, 2014).

The northeastern Indian plate consists of THS and GHS (Fig. 1c) (Zhang et al., 2012b). The THS consists of Paleozoic and Mesozoic sedimentary strata which experienced greenschist- to amphibolite-facies metamorphism (Booth et al., 2009; Zhang et al., 2012b). The GHS, referred to as the Namche Barwa Complex, consists of orthogneiss, paragneiss, marble, schist, quartzite, granulite, and migmatite (Ding et al., 2001; Geng et al., 2006; Liu et al., 2007, 2011; Guo et al., 2008; Xu et al., 2010, 2012; Zhang et al., 2010b, 2012b, 2015). Detrital zircon from the paragneisses yielded U–Pb age populations of ~0.5 Ga, 0.8– 1.2 Ga, 1.5–1.8 Ga, and ~2.5 Ga (Xu et al., 2010; Zhang et al., 2012b). The granitic gneisses intruding the paragneisses have crystallization ages of 490–500 Ma (Xu et al., 2010; Zhang et al., 2012b). Zircon U–Pb dating results show that some orthogneisses formed during 1594– 1759 Ma (Guo et al., 2008; Zhang et al., 2012b). The Namche Barwa Complex underwent high-pressure and high-temperature granulitefacies metamorphism and crustal anatexis (Ding et al., 2001; Geng et al., 2006; Liu et al., 2007; Xu et al., 2010, 2012; Zhang et al., 2012b, 2015). Zhang et al. (2015) proposed that the near-peak and peakmetamorphism of the high-pressure granulites occurred at ~40– 30 Ma, and the high-pressure granulites underwent a long-lived hightemperature granulite-facies metamorphic process from ~40 Ma to ~8 Ma.

2.2. Sample descriptions

Four metasedimentary rock samples were collected from the basement complexes in the Eastern Himalayan Syntaxis: samples T716 and T718 from the Nyingchi Complex, and samples T660 and T663 from the Namche Barwa Complex (Fig. 1c). In addition, an augen granitic gneiss (T907) intruding the metasedimentary rocks in the Nyingchi Complex and a granitic gneiss (T658) intruding the metasedimentary rocks in the Namche Barwa Complex were collected to constrain the minimum depositional ages for the sedimentary protoliths.

Three samples were collected from a section of the Nyingchi Complex in the eastern South Lhasa terrane (Fig. 2a). In this section, the quartz mica schist is interbedded with the biotite quartzite (Fig. 2b). These metasedimentary rocks are intruded by augen granitic gneiss (Fig. 2a and c). Both the metasedimentary rocks and granitic gneiss are strongly foliated (Fig. 2b and c). Sample T716 is a lepidogranoblastic quartz mica schist (Fig. 3a) mainly composed of biotite, quartz, and muscovite. Sample T718 is a fine grained biotite quartzite (Fig. 3b) consisting of quartz, biotite, and muscovite. Sample T907 is a foliated porphyritic granitic gneiss (Fig. 2c). The phenocrysts consist of Kfeldspar, quartz and minor plagioclase (Figs. 2c and 3c). A few euhedral garnets which experienced chemical erosion are included in the plagioclase (Fig. 3c). The matrix is composed of quartz, plagioclase, K-feldspar and biotite (Fig. 3c).

Two quartzite samples and a granitic gneiss sample were collected from the Namche Barwa Complex (Fig. 2d–f). The fine grained biotite quartzite (sample T660) is mainly composed of quartz and biotite (Fig. 3d). The quartzite (sample T663) consists of quartz and muscovite (Fig. 3e). The granitic gneiss (sample T658) is mainly composed of quartz, plagioclase, K-feldspar, and biotite (Fig. 3f). 3. Analytical methods

3.1. Zircon U–Pb dating and trace elements

|  |
| --- |
| Fig. 2. Field photographs of the Nyingchi Complex and Namche Barwa Complex in the Eastern Himalayan syntaxis. (a) NW-dipping metasedimentary rocks of the Nyingchi Complex intruded by augen granitic gneiss, showing locationsof Fig. 2b and 2c; (b) the quartz mica schist (sample T716) interbed with biotite quartzite (sample T718); (c) well foliated augen granitic gneiss (sample T907) – the inset shows the phenocrysts of K-feldspar and quartz; (d) the fine-grained biotite quartzite sample T660 and (e) the quartzite sample T663 from the Namche Barwa Complex; (f) the granitic gneiss (Sample T658) intruding the metasedimentary rocks in the Namche Barwa Complex. |

Zircon grains were separated from the metasedimentary rock samples using conventional heavy liquid and magnetic separation techniques. Zircon grains were mounted in epoxy resin and polished to approximately half thickness. Cathodoluminescence (CL) images, taken at Northwest University (China), were used to check the internal structures of individual zircon grains and to guide U–Pb dating and Hf isotope analysis. U–Pb dating and trace-element analyses of zircon were conducted synchronously by laser-ablation, inductively coupled plasma mass spectrometer (LA-ICP-MS) at the State Key Laboratory of Geological Processes and Mineral Resources (SKLGPMR), China University of Geosciences (CUG), Wuhan. Detailed operating conditions for the laser ablation system and the ICP-MS instrument and data reduction are the same as description by Liu et al. (2010). Off-line selection and integration of background and analyte signals, and time-drift correction and quantitative calibration for trace-element analyses and U–Pb dating were performed by ICPMSDataCal (Liu et al., 2010). The U–Pb Concordia plots were processed using the ISOPLOT program of Ludwig (Ludwig, 2003). As recommended by Vermeesch (2012), the distributions of detrital zircon ages are visualized using the program of DensityPlotter version 4.3 based on Kernel density estimation. Statistical comparison of age distributions during provenance analysis is carried out through multiple two-sample Kolmogorov–Smirnov (K–S) tests. K–S tests were performed using an Excel-based macro developed by the Arizona LaserChron Center in the Department of Geosciences at the University of Arizona (Guynn and Gehrels, 2010). The K–S test is a nonparametric statistical method that returns a probability value (P value) for two samples being drawn from the same population. P values N0.05 indicate that the null hypothesis that two distributions are the same or came from the same parent population cannot be rejected based on the sampled distributions (Guynn and Gehrels, 2010).

3.2. Zircon Lu–Hf isotopes

|  |
| --- |
| Fig. 3. Photomicrographs for the metasedimentary and orthogneiss samples collected from the Eastern Himalayans syntaixs area. The quartz-mica schist sample T716 (a), biotite quartzite sample T718 (b), and augen granitic gneiss sample T907 (c) from the Nyingchi Complex. The quartzite samples T660 (d), T663 (e), and granitic gneiss sample T658 (f) from the Namche Barwa Complex. Mineral abbreviations: Bt = biotite; Grt = garnet; Ms = muscovite; Pl = plagioclase; Qtz = quartz. |

Zircon Hf isotope measurements were performed on the dated zircons using a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Germany) in combination with a Geolas 2005 excimer ArF laser ablation system (Lambda Physik, Göttingen, Germany), at the SKLGPMR, CUG, Wuhan. The analyses were undertaken using a spot size of 44 μm.

Detailed operating conditions for the laser ablation system and the MCICP-MS instrument and analytical method are the same as the description by Hu et al. (2012). Off-line selection and integration of analyte signals, and mass bias calibrations were performed using ICPMSDataCal (Liu et al., 2010). The decay constant for 176Lu and the chondritic ratios of 176 177 176 177 −11

Hf/ Hf and Lu/ Hf used in calculations are 1.865 × 10 /year (Scherer et al., 2001), and 0.282772 and 0.0332 (Blichert-Toft and Albarede, 1997), respectively. The single-stage model age (TDM1) was calculated relative to the depleted mantle with a present-day 176Hf/177Hf ratio of 0.28325 and 176Lu/177Hf ratio of 0.0384 (Griffin et al., 2000), and two-stage model ages (TDM2) were calculated by assuming a mean 176Lu/177Hf value of 0.015 for the average continental crust (Vervoort and Blichert-Toft, 1999). Initial 176Hf/177Hf ratios and εHf(t) values are calculated by the zircon crystallization ages.

## 4. Results

Representative zircon cathodoluminescence (CL) images for the studied samples are shown in Fig. 4. Detrital zircon U–Pb age, traceelement and Hf isotope data are given in the electronic supplements as Table A1, A2, and A3, respectively. For statistical purposes, zircon grains with discordance b10% were considered as usable. The zircon U–Pb concordia diagrams are shown in Fig. 5. The classifications of an individual zircon grain in terms of its host magma as described by Belousova et al. (2002) are reported as a modeled rock type in the Table A2. The degree of similarity between two detrital zircon age spectra can be assessed quantitatively by using the two-sample Kolmogorov–Smirnov (K–S) statistic test (Guynn and Gehrels, 2010). The probability (P value) results of K–S test are shown in Table 1.

4.1. Zircon U–Pb ages

4.1.1. Metasedimentary rocks

Detrital zircon grains in the metasedimentary rocks from the Nyingchi Complex (T716 and T718) and Namche Barwa Complex (T660 and T663) are rounded or subrounded, dark to slightly transparent brown, and range from 50 to 300 μm in size. Most zircon grains exhibit oscillatory zoning in the CL images (Fig. 4a–d), indicating that they are magmatic in origin (Corfu et al., 2003). Several grains are homogeneous or structureless (Fig. 4a–d), probably indicating a metamorphic origin (Corfu et al., 2003). Most zircons have narrow (b10 μm) luminescent and irregular rims (Fig. 4a–d), suggesting that they underwent late metamorphism.

Detrital zircon grains in the quartz mica schist T716 and quartzite T718 from the Nyingchi Complex yield U–Pb ages of 1017–1848 Ma and 1006–3020 Ma (Table A1, Fig. 5a and b), respectively. The P value of K–S statistic test between T716 and T718 is 0.256, indicating that their age distributions are indistinguishable at the 95% confidence level (Table 1). They yielded four major age populations of 1.00– 1.20 Ga, 1.35–1.45 Ga, 1.50–1.65, and 1.70–1.80 Ga (Fig. 6a). The mean ages of the youngest three zircons that overlap in age at 2σ from samples T716 and T718 are 1021 ± 19 Ma and 1009 ± 30 Ma, respectively.

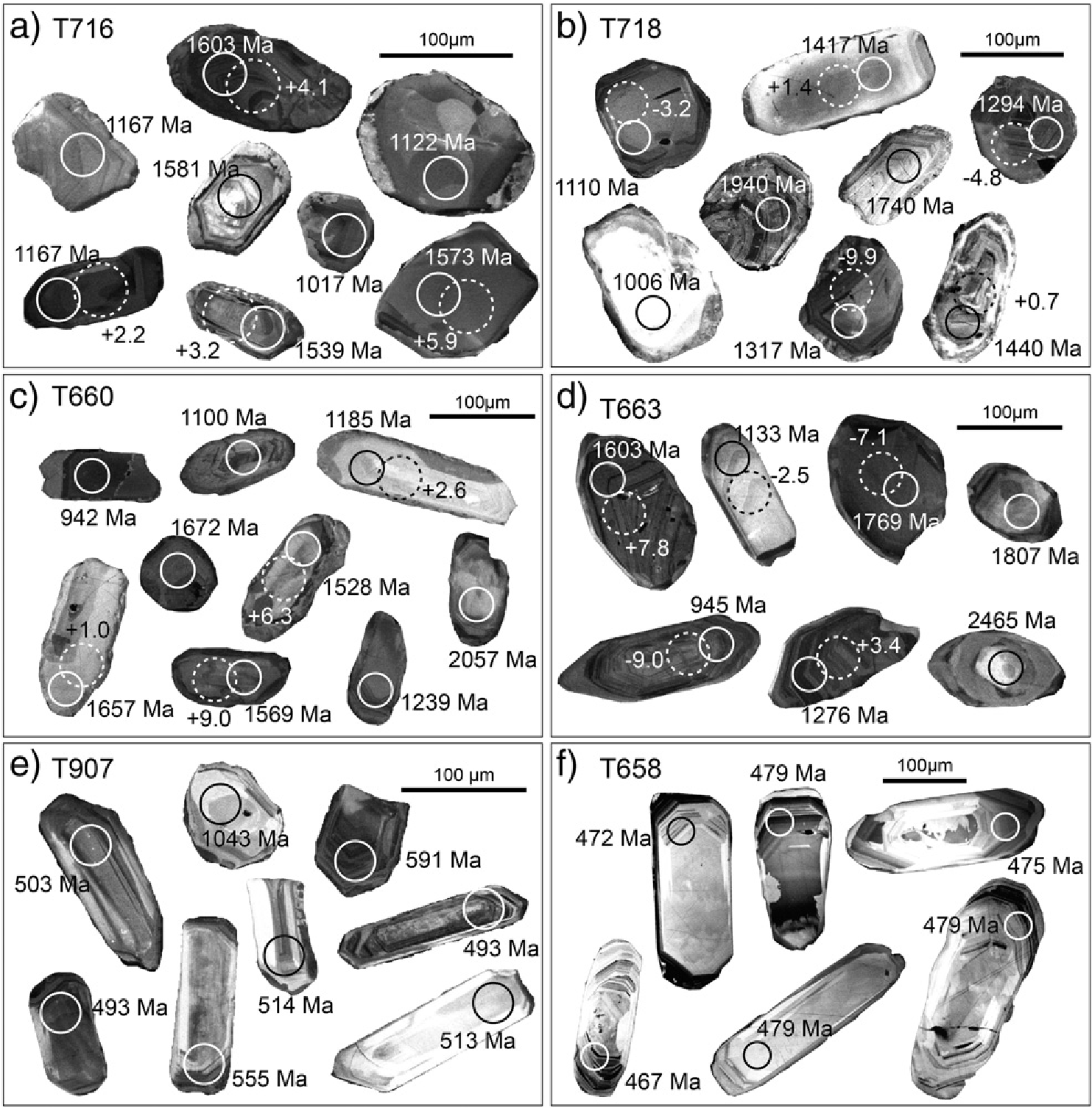


Fig. 4. Typical zircon Cathodoluminescence (CL) images for the studied samples. The smaller circles show LA-ICP-MS dating spots and corresponding U–Pb ages (in Ma); the dashed circles show locations of Hf isotope analysis and corresponding εHf(t) values.

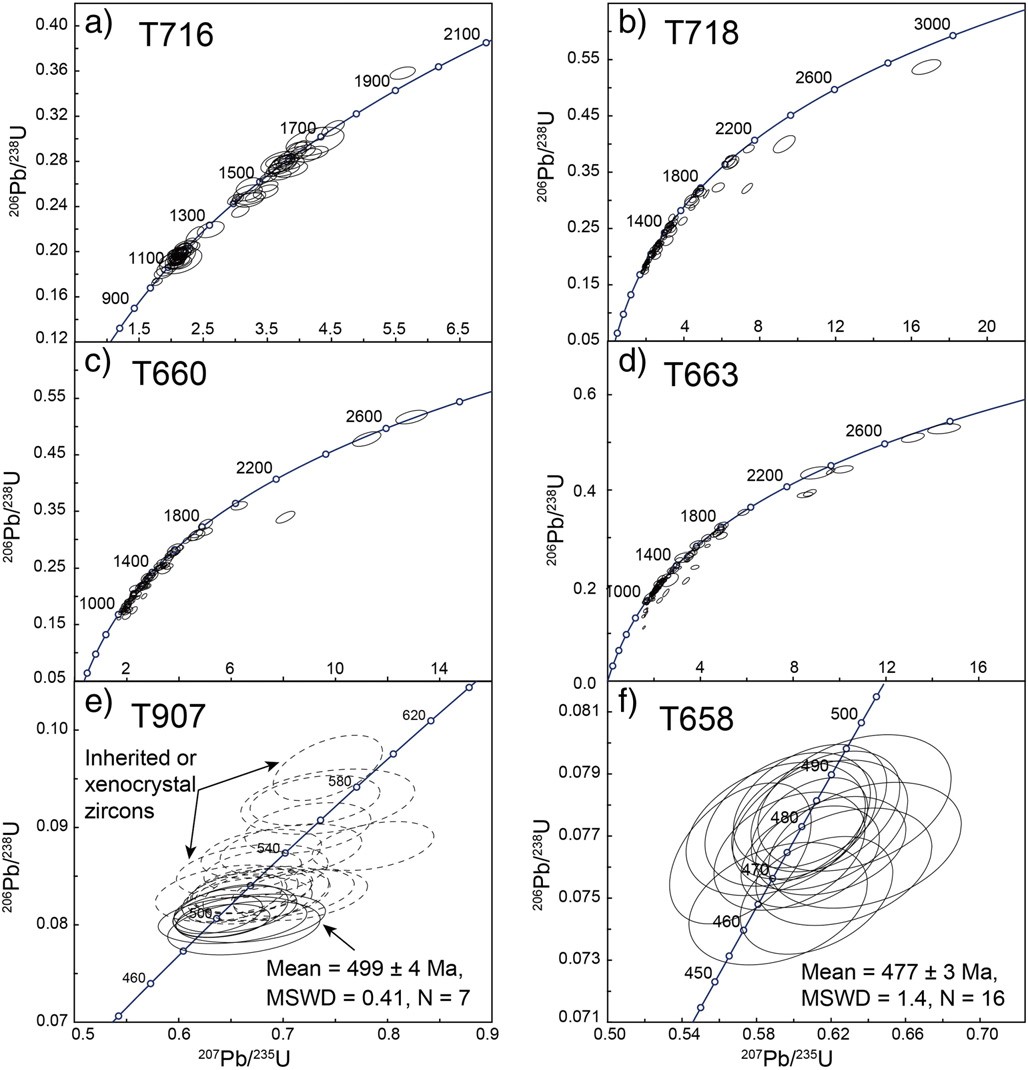


Fig. 5. U–Pb concordia diagrams for zircons from the metasedimentary rocks (a–d) and metaigneous rocks (e–f) in the Eastern Himalayan syntaxis.

Detrital zircon grains from the quartzite samples T660 and T663 in the Namche Barwa Complex yield similar age populations (Table A1, Fig. 5c and d), and they are indistinguishable at the 95% confidence based on the high P value (0.554) of K–S test (Table 1). They yielded

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 1  Kolmogorov–Smirnov (K–S) statistic applied to probability density function of U–Pb detrital zircon results.   |  |  |  |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Samples | Nyingchi complex | | Namche Barwa Complex | | GHS (Arunachal Himalaya)a | | | Upper LHS (Arunachal Himalaya)b | | Shilong Group (NE India)c | | | T716  (n = 90) | T718  (n = 89) | T660  (n = 82) | T663  (n = 92) | AY–02–13–06–7  (n = 99) | AY–02–13–06–9B  (n = 105) | AY–02–13–06–8  (n = 111) | AY9160314A  (n = 81) | AY9170315  (n = 84) | AY24612  (n = 31) | AY204418  (n = 91) | | T716 |  | 0.256 | 0.372 | 0.289 | 0.072 | 0.002 | 0.000 | 0.002 | 0.103 | 0.056 | 0.000 | | T718 | 0.256 |  | 0.821 | 0.702 | 0.144 | 0.005 | 0.000 | 0.061 | 0.309 | 0.018 | 0.000 | | T660 | 0.372 | 0.821 |  | 0.554 | 0.111 | 0.004 | 0.000 | 0.013 | 0.086 | 0.012 | 0.000 | | T663 | 0.289 | 0.702 | 0.554 |  | 0.304 | 0.022 | 0.000 | 0.003 | 0.322 | 0.022 | 0.000 | | AY–02–13–06–7 | 0.072 | 0.144 | 0.111 | 0.304 |  | 0.065 | 0.000 | 0.126 | 0.807 | 0.071 | 0.000 | | AY–02–13–06–9B | 0.002 | 0.005 | 0.004 | 0.022 | 0.065 |  | 0.000 | 0.000 | 0.012 | 0.001 | 0.000 | | AY–02–13–06–8 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |  | 0.000 | 0.000 | 0.000 | 0.000 | | AY9160314A | 0.002 | 0.061 | 0.013 | 0.003 | 0.126 | 0.000 | 0.000 |  | 0.251 | 0.285 | 0.157 | | AY9170315 | 0.103 | 0.309 | 0.086 | 0.322 | 0.807 | 0.012 | 0.000 | 0.251 |  | 0.244 | 0.011 | | AY24612 | 0.056 | 0.018 | 0.012 | 0.022 | 0.071 | 0.001 | 0.000 | 0.285 | 0.244 |  | 0.037 | | AY204418 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.157 | 0.011 | 0.037 |  |   Published data: a. Webb et al., 2013; b. Yin et al., 2006; c. Yin et al., 2010b. |

U–Pb ages of 942–2807 Ma, with four major age populations of 1.00– 1.20 Ga, 1.30–1.45 Ga, 1.50–1.65, and 1.75–1.85 Ga (Fig. 6b). The mean ages of the youngest three zircons that overlap in age at 2σ from samples T660 and T663 are 996 ± 13 Ma and 971 ± 4 Ma,

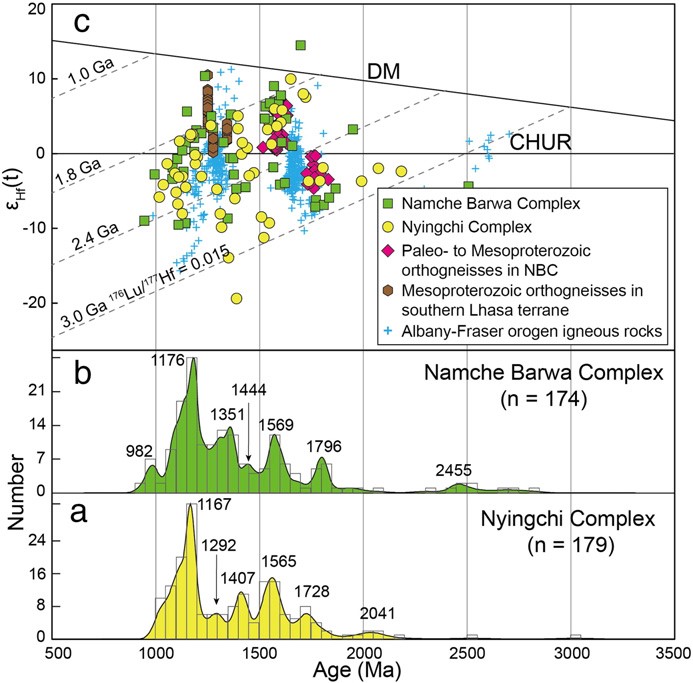


Fig. 6. The kernel density estimation (KDE) plots and histograms for detrital zircon from metasedimentary rocks in the Nyingchi Complex (a) and Namche Barwa Complex (b). (c) Plots of εHf(t) versus U–Pb ages for the studied samples. For comparison, the Paleoproterozoic–Mesoproterozoic orthogneisses from the Bome Complex and the

Namche Barwa Complex (NBC) in the Eastern Himalayan syntaxis (this study; Xu et al., 2013b), and 1.1–2.8 Ga igneous rocks from Albany–Fraser orogen in southwest Australia (Smits et al., 2014, and references therein) are also plotted.

respectively. The high P values (0.289–0.821) of the K–S test for the samples from the Nyingchi Complex and Namche Barwa Complex suggest that they cannot be distinguished at the 95% confidence level (Table 1).

4.1.2. Metaigneous rocks

Most zircons in the augen granitic gneiss sample T907 from the Nyingchi Complex are subhedral or euhedral, with grain length of 100–200 μm. Few grains are subrounded, suggesting that they are inherited or xenocrystic zircons. They show clear magmatic oscillatory zoning in the CL images (Fig. 4e). Twenty-seven analyses on twentyseven zircon grains were carried and yield ages of 493–1043 Ma (Table A1). Seven youngest analyses which overlap within analytical errors yield a weighted mean age of 499 ± 4 Ma (MSWD = 0.41, Fig. 5e), representing the crystallization age of the protolith of the augen granitic gneiss (Fig. 5e). The other twenty analyses have older ages of 501– 1043 Ma (Table A1, Fig. 5e), indicating that they are inherited from their source rocks or captured from their wall rocks.

The zircons in the granitic gneiss sample T658 from the Namche Barwa Complex are euhedral, and range in length from 150 to 300 μm. They exhibit magmatic oscillatory zoning in the CL images (Fig. 4f). Several zircons show resorption phenomena (Fig. 4f), indicating possible resorption and new growth. Sixteen analyses yield 206Pb/238U ages of 465–485 Ma (Fig. 5f), with a weighted mean age of 477 ± 3 Ma

(MSWD = 1.4), representing the crystallization age for the protolith of granitic gneiss.

4.2. Zircon trace elements

4.2.1. Metasedimentary rocks

Most of detrital zircons from our metasedimentary samples have high Th/U ratios (N0.10), and exhibit fractionated REE patterns with positive Ce anomalies and marked negative Eu anomalies (Fig. 7a–d), indicating that they are of magmatic origin (Hoskin and Schaltegger, 2003). Seven grains from the Nyingchi Complex and two grains from the Namche Barwa Complex have low Th/U ratios (b0.10) and LREE contents (Table A1 and A2; Fig. 7a, b, and d), indicating a metamorphic origin (Hoskin and Schaltegger, 2003). Their ages range from ~997 Ma to ~2061 Ma (Table A1). Analyses spot T663-11 (1129 ± 32 Ma) exhibits flat HREE pattern (Fig. 7d), suggesting coexistence with garnet (Rubatto, 2002).

The trace-element compositions of the magmatic zircons can be used to recognize broad categories of magmatic rocks from which zircon crystallized (Belousova et al., 2002). The probability of correct classification for zircons from kimberlites, mafic rocks (dolerites and basalts), carbonatites, syenitic rocks (syenites, larvikites) and Nesyenites is N80% (Belousova et al., 2002; Griffin et al., 2004). On the basis of the classification and regression trees analysis (Belousova et al., 2002), the modeled rock types of detrital zircons from Nyingchi Complex and Namche Barwa Complex include granitoids (b65% and 70–75% SiO2), dolerite, and minor basalt, carbonatite, N75% SiO2 granitoid, syenite/monzonite and metamorphic rocks (Table A2). Thirty-three (18.3%) zircons from Nyingchi Complex and thirty-six (19.3%) zircons from the Namche Barwa Complex are classified as mafic rocks. The “mafic” zircons from the Nyingchi Complex and Namche Barwa Complex yield similar age distribution with age populations of 1.00– 1.20 Ga, 1.30–1.45 Ga and 1.50–1.65 Ga (not shown). The traceelement composition of zircons crystallized from mafic magma can be used to distinguish the tectonic setting in which the mafic rocks formed (Schulz et al., 2006). On the basis of the trace-elements discrimination diagrams (Schulz et al., 2006), the “mafic” zircons plot into or closed to the volcanic-arc-basalt (VAB) and within-plate-basalt (WPB) fields (Fig. 8). It is noteworthy that most 1.00–1.20 Ga zircons plot into the VAB field, and most 1.30–1.45 Ga zircons plot into the WPB field (Fig. 8).

4.2.2. Metaigneous rocks

Zircons in the augen granitic gneiss from the Nyingchi Complex and granitic gneiss from the Namche Barwa Complex have high Th/U ratios of 0.11–1.17 and 0.50–0.96, respectively (Table A1). Both the inherited/ xenocrystic and magmatic zircons are characterized by enrichments in HREE, positive Ce anomalies and marked negative Eu anomalies (Fig. 7e and f), which are typical characteristics of magmatic zircon (Hoskin and Schaltegger, 2003).

4.3. Zircon Hf isotope

4.3.1. Metasedimentary rocks from the Nyingchi Complex and Namche Barwa Complex

A total of 100 Hf isotopic analyses were carried out on the dated detrital zircons (Table A3): fifty from the Nyingchi Complex and fifty from the Namche Barwa Complex. Detrital zircons from the Nyingchi Complex have εHf(t) values ranging from −19.4 to +10.0 (Table A3, Fig. 6c), which are similar to those (εHf(t) = −9.5–+14.5) of detrital zircons from the Namche Barwa Complex (Table A3, Fig. 6c). The εHf(t) values of 1.00–1.20 Ga zircons from the Nyingchi Complex (−8.1 to +2.6) and Namche Barwa Complex (−9.5 to +5.6) overlap within the analytical errors (Fig. 6c). Except for two analyses T718-02 and T718-16, the 1.30–1.45 Ga zircons from the Nyingchi Complex also have similar εHf(t) values (−9.9 to +5.0) to those of 1.30– 1.45 Ga zircons (−8.7 to +5.2) from the Namche Barwa Complex (Fig. 6c). Most 1.50–1.65 Ga zircons have positive εHf(t) values (+1.2 to +9.0), and most 1.75–1.85 Ga zircons have negative εHf(t) values (−7.1 to −1.9) (Fig. 6c).

4.3.2. Mesoproterozoic orthogneiss from the Namche Barwa Complex

Three orthogneiss samples T614, T610, and T616 from the Namche Barwa Complex have protolith crystallization ages of 1759 ± 10 Ma, 1594 ± 13 Ma, and 1583 ± 6 Ma (Guo et al., 2008), respectively. Sample T614 has εHf(t) values of −4.6 to −0.3 and TDM2 of 2.45–2.71 Ga. Sample T610 has εHf(t) values of +1.4–+7.3 and TDM2 of 1.85–2.24 Ga.

|  |
| --- |
| Fig. 7. The chondrite-normalized rare earth elements (REE) patterns of the zircons from the studied samples. Chondrite normalization values from Sun and McDonough (1989). |

Sample T614 has εHf(t) values of +0.5–+5.4 and TDM2 of 1.96–2.26 Ga (Table A3, Fig. 6c).

## 5. Discussion

5.1. The ages of the sedimentary protoliths

5.1.1. Nyingchi Complex in the South Lhasa terrane

In a sedimentary basin with active magmatic activity the youngest detrital zircon grains may approximate the time of sediment accumulation (Dickinson and Gehrels, 2009; Cawood et al., 2012). In contrast, in a basin situated in rift or passive margin generally lack abundant young detrital zircons, and hence the youngest detrital zircon grains will provide a maximum depositional age (Cawood et al., 2012; McKenzie et al., 2014). The minimum depositional ages can be constrained by cross-cutting intrusive rocks. The weighted mean ages of the youngest three zircons, which overlap in age at 2σ, yielded maximum depositional age of ~1.0 Ga for the metasedimentary rocks from the Nyingchi Complex in this study. The intruding augen granitic gneiss yielded a crystallization age of 499 ± 4 Ma (Fig. 5e), providing a minimum depositional age bound for their sedimentary protoliths. Previous detrital zircon U–Pb geochronological studies revealed that the metasedimentary rocks from the Nyingchi Complex had maximum depositional ages ranging from Cambrian, through Carboniferous, to Paleogene (Zhang et al., 2008; Dong et al., 2010; Guo et al., 2012; Zhang and Wu, 2012). Compared with the Paleozoic strata from the Lhasa terrane (Zhang et al., 2008; Dong et al., 2010; Gehrels et al., 2011; Zhu et al., 2011b; Guo et al., 2012; Zhang and Wu, 2012), the absence of ~0.5–0.9 Ga detrital zircons indicates that the studied metasedimentary rocks from the Nyingchi Complex probably have protolith ages of Late Mesoproterozoic–Early Neoproterozoic.

5.1.2. Namche Barwa Complex in the Eastern Himalayan Syntaxis

The maximum depositional age for the metasedimentary rocks in the Namche Barwa Complex is ~1.0 Ga, which is constrained by the mean ages of the youngest three zircons that overlap in age at 2σ. The granitic gneiss intruding these metasedimentary rocks have crystallization age of 477 ± 3 Ma (Fig. 5f), providing an upper age bound for their deposition. Previous studies show that some metasedimentary rocks from Namche Barwa Complex yielded detrital zircon age populations of ~0.5 Ga, 0.8–1.0 Ga, 1.1–1.2 Ga, 1.3–1.5 Ga and 1.6–1.7 Ga (Xu et al., 2010; Zhang et al., 2012b). In addition, the ~0.5–0.9 Ga detrital zircons are abundant in Cryogenian and younger strata throughout the Himalaya (Gehrels et al., 2011; Hofmann et al., 2011; McKenzie et al., 2011). By contrast, detrital zircon age populations of ~0.5–0.9 Ga are absent in our metasedimentary rock samples (Fig. 6b), indicating that their protoliths probably represent an older stratigraphic unit. We propose that their sedimentary protoliths likely have Early Neoproterozoic depositional age. The Nyingchi Complex and the Namche Barwa Complex show consistent age spectra and the high P values (0.289–0.821) of K–S test (Table 1) suggest that they probably have similar depositional ages.

|  |
| --- |
| Fig. 8. The trace-element discrimination diagrams for zircons crystallized from mafic magma (dolerite and basalt) (Schulz et al., 2006). NBC = Namche Barwa Complex; NC = Nyingchi |

Complex.

5.2. The affinity of the Namche Barwa Complex

In the Eastern Himalayan Syntaxis, the Namche Barwa Complex is generally interpreted as the northeastern extremity of the exposed GHS (Ding et al., 2001; Geng et al., 2006; Xu et al., 2010). However, Zhang et al. (2012b) considered that the Namche Barwa Complex was originally part of the eastern segment of the Central Indian Tectonic Zone (CITZ) based on the discrepancies of detrital zircon age spectra between the Namche Barwa Complex and GHS in central Himalaya. In this study, the quartzites (samples T660 and T663) from the Namche Barwa Complex share similar age spectra with the GHS paragneisses (samples AY-02-13-06-7 and AY-02-13-06-9B) from the Arunachal Himalaya (Webb et al., 2013) (Fig. 9a). The high P values (up to 0.304) of K–S tests also confirm that they are not statistically different from one another (Table 1). In contrast to our results, the metasedimentary rocks reported by Xu et al. (2010) and Zhang et al. (2012b) contain abundant ~0.5 Ga and 0.8–1.0 Ga zircon grains (Fig. 9a), indicating that they represent younger stratigraphic units. It is interesting that their age pattern is similar to that of the GHS paragneiss sample AY02-13-06-8 from Arunachal Himalaya (Webb et al., 2013) except for the age population of ~0.5 Ga (Fig. 9a). We remove the b600 Ma grains arbitrarily from these metasedimentary rocks, and reran the K–S tests (P value up to 0.371), which revealed that these metasedimentary rock samples could not be distinguished from the sample AY02-13-06-8. The ~0.5 Ga zircon grains were most likely derived from the ~0.5 Ga granitoids that are widespread in the Eastern Himalayan syntaxis (Burg et al., 1997; Liu et al., 2007; Xu et al., 2010; Zhang et al., 2012b) and GHS along the Himalaya (Le Fort and Rai, 1999; DeCelles et al., 2000; Gehrels et al., 2003). The discrepancy of age spectra is likely due to differences in depositional age. On the basis of the above discussion, we propose that the Namche Barwa Complex is the northeastern extension of the GHS. This speculation is supported by that the Namche Barwa Complex and GHS have similar Paleoproterozoic crystallization basement that extend from South Tibet, Bhutan, to Eastern Himalayan Syntaxis (also see next section) (Guo et al., 2008; Liao et al., 2008; Chakungal et al., 2010; Kohn et al., 2010; Zhang et al., 2012b).

5.3. Correlation between the GHS, LHS and Indian craton in the Eastern Himalayan Syntaxis

Previous studies suggested that the GHS and THS can be distinguished from the LHS by Sr–Nd–Hf isotopic and detrital zircon geochronological differences, with the GHS and THS yielding less negative εNd values and containing abundant Neoproterozoic–Paleozoic (~1.0 Ga and ~0.5 Ga) detrital zircon, whereas the LHS yielding more negative εNd values and containing no detrital zircon younger than 1.6 Ga (Parrish and Hodges, 1996; Ahmad et al., 2000; DeCelles et al., 2000; Argles et al., 2003; Richards et al., 2005, 2006; Mottram et al., 2014). On the basis of these isotopic differences, the GHS was interpreted as an accreted terrane tectonically consolidated with the Greater India during early Paleozoic time (DeCelles et al., 2000; Gehrels et al., 2003) or as distal and proximal basins on the Indian margin (Myrow et al., 2003, 2010; McQuarrie et al., 2008, 2013; Yin et al., 2010a; Long et al., 2011; McKenzie et al., 2011; Webb et al., 2013; Mottram et al., 2014).

In the Eastern Himalayan Syntaxis, detrital zircon age spectra of the quartzites from the Namche Barwa Complex are remarkably similar to those of the coeval rocks in the upper LHS in Arunachal (Yin et al., 2006) and cratonic successions (Alwar Group, Ganga Group, the upper Vindhyan Group, and Shillong Group) in northern India (Malone et al., 2008; McKenzie et al., 2011, 2013; Turner et al., 2014) (Fig. 9b). The K–S tests between the samples from the Namche Barwa Complex, upper LHS (samples AY9160314A, AY24612) in Arunachal (Yin et al., 2006) and Shillong Group (sample AY24612) in northeastern Indian craton (Yin et al., 2010b) yield high P values (up to 0.807, Table 1). The similar age distributions and high P values suggest that these areas were depositionally linked (Webb et al., 2013; Yin et al., 2010b; and this study). In addition, the orthogneisses from the Namche Barwa Complex have protolith crystallization ages of 1759–1583 Ma

|  |
| --- |
| Fig. 9. The kernel density estimation (KDE) plots of detrital zircons from the metasedimentary rocks in this study and previous works. (a) Comparison of detrital zircon age signature of samples from the Namche Barwa Complex (Xu et al., 2010; Zhang et al., 2012b; this study), Greater Himalayan Sequence in Arunachal (Webb et al., 2013), upper Lesser Himalayan Sequence in Arunachal (Yin et al., 2006), Indian cratonic successions (Malone et al., 2008; McKenzie et al., 2011, 2013; Turner et al., 2014; Yin et al., 2010b) and Lhasa terrane (Zhu et al., 2011a; this study). (b) Further comparison of detrital zircon age signature of samples from the Indian cratonic successions (upper Vindhyan Group, Alwar Group, Ganga Group, and Shil- |

long Group) and South Lhasa terrane. The yellow band highlights the ~1.2 Ga age peak.

(Guo et al., 2008; Zhang et al., 2012b), which are comparable with the Paleo- to Mesoproterozoic orthogneisses from the GHS and LHS in Arunachal and NE Indian craton (Ameen et al., 2007; Yin et al., 2010a, b), suggesting that these areas share the same crystalline basement that belongs to the Indian craton. Therefore, we propose that the Paleo- to Mesoproterozoic orthogneisses in the Namche Barwa Complex represents the crystalline basement of the Indian craton, and the metasedimentary rocks represent the distal deposits along the continuous north Indian margin during Neoproterozoic–Cambrian.

5.4. Provenance of the metasedimentary rocks

In this study, detrital zircons from the Namche Barwa Complex and Nyingchi Complex show similar age spectra, with major age populations of 1.00–1.20 Ga, 1.30–1.45 Ga, 1.50–1.65 Ga and 1.70–1.85 Ga (Fig. 6a and b). The high P values (up to 0.821) of K–S tests between the Namche Barwa Complex and Nyingchi Complex indicate that they cannot be statistically distinguished at 95% confidence level (Table 1). The zircon trace-element compositions indicate that they were derived from granitoids, dolerite, and minor metamorphic rocks, basalt, carbonatite, and syenite/monzonite (Table A2, Fig. 8). In addition, they have similar zircon Hf isotopic composition (Fig. 6c). The consistent detrital zircon U– Pb age spectra, trace-element signatures and Hf isotopic compositions strongly suggest that their sedimentary protoliths were derived from common sources, and therefore suggest paleogeographic proximity.

The 1.00–1.20 Ga age population is prominent in the Namche Barwa Complex and Nyingchi Complex (Fig. 6a and b). Previous studies considered that the 1.00–1.20 Ga zircon grains in the Neoproterozoic–Paleozoic strata from Himalayan units and Lhasa terrane (Fig. 9a) were most likely derived from the Wilkes–Albany–Fraser Orogen (WAFO) (Fig. 10) (Yoshida and Upreti, 2006; Zhu et al., 2011a). The WAFO recorded two-stages (1.14–1.22 Ga and 1.26–1.35 Ga) of metamorphism and magmatism response to the continent–continent collision between the combined North and West Australian Cratons and the combined

|  |
| --- |
| Fig. 10. Paleogeographic reconstruction of the Lhasa terrane prior to the assemblage of Gondwana (modified from Bhowmik et al. (2012); Boger (2011); McKenzie et al. (2013); McQuarrie et al. (2013); Myrow et al. (2010); Turner et al. (2014); Upadhyay (2008)). The inferred paleocurrent directions are modified from McQuarrie et al. (2013). Abbreviations: ADMB = Aravalli-Delhi Mobile Belt; CITZ = Central Indian Tectonic Zone; CLB = Coats Land Block; DC = Dharwar craton; GC = Gawler Craton; GI = Great India; H = Himalaya; KC = Kalahari Craton; MC = Mawson Craton; MNB = Maud-Natal Blet; NL = North Lhasa terrane; PO = Pinjarra Orogen; REGO = Rayner-Eastern Ghats Orogen; RV = Rajasthan Vindhyan; SB = Sibumasu; SL = South Lhasa terrane; SV = Son Valley Vindhyan; WAFO = Wilkes–Albany–Fraser Orogen. |

East Antarctic and South Australian Cratons (Clark et al., 2000; Cawood and Korsch, 2008; Kirkland et al., 2011; Smits et al., 2014). Both the

Namche Barwa Complex and the Nyingchi Complex contain 1.30– 1.45 Ga detrital zircons (Fig. 6a and b). The age distributions apparently indicate that the 1.00–1.2 Ga and 1.30–1.45 Ga grains in our samples were derived from the WAFO. However, the following two aspects do not support this speculation. Firstly, the zircon trace-element compositions indicate that most magmatic host rocks of the 1.30–1.45 Ga

“mafic” zircons formed in within plate setting (Fig. 8). By contrast, the 1.2–1.7 Ga magmatism in WAFO represents a continuous activemargin magmatic activity (Smits et al., 2014). Secondly, the 1.30– 1.45 Ga detrital zircon define a broad band of εHf(t) (−19.4 to +5.2), and most of them have more negative εHf(t) values (Fig. 6c) than those of the contemporaneous igneous rocks in WAFO (Smits et al., 2014). The most likely source of the 1.30–1.45 Ga grains is the contact between the Eastern Ghats orogen (EGO) and the cratons (Bhandara, Singhbhum and Dharwar cratons) in southeastern India (Fig. 10), where abundant Mesoproterozoic (1.3–1.5 Ga) alkalic and mafic magmatism formed in a rift tectonic setting (Upadhyay and Raith, 2006a, 2006b; Upadhyay et al., 2006a, 2006b; Vijaya Kumar et al., 2007; Upadhyay, 2008; Vijaya Kumar and Rathna, 2008; Ratre et al., 2010). In addition, Xu et al. (2013b) reported ~1343 Ma and ~1276 Ma A-type granites from the Bome Complex in the South Lhasa terrane that formed in a continental rift setting (Fig. 1c). The Mesoproterozoic (1.3–1.5 Ga) rift could be related to separation of India from east Antarctica corresponding to the breakup of Columbia supercontinent (Upadhyay, 2008, and references therein). Therefore, the 1.30–1.45 Ga detrital zircons most likely were derived from the southeastern India and South Lhasa terrane itself. The modeled rock type of a 1448 ± 48 Ma detrital zircon from Namche Barwa Complex is syenite (Table A2, Fig. 8), which is compatible with the ~1480 Ma nepheline syenite from the Khariar alkaline complex in the southeastern India (Upadhyay et al., 2006a), further supporting our speculation.

The 1.00–1.20 Ga zircon grains are not only the dominant population in our samples but also the important component in the Purana Basins (Alwar Group, Ganga Group, the upper Vindhyan Group, and Shillong Group) in the northern India (Fig. 9, Fig. 10) (Malone et al., 2008; Yin et al., 2010b; McKenzie et al., 2011, 2013; Turner et al., 2014). The 1.00–1.20 Ga magmatic rocks have been documented in the CITZ, EGO, and northeastern Indian craton (Fig. 10) (Aftalion et al., 1988;

Patranabis-Deb et al., 2007; Roy and Chakraborti, 2008; Yin et al., 2010a; Rekha et al., 2011; Mukherjee et al., 2012; Pradhan et al., 2012). Turner et al. (2014) suggested that the 1.0–1.2 Ga grains in the upper Vindhyan Group were derived from the CITZ. Yin et al. (2010b) suggested that the ~1.1 Ga grains in the Shillong Group and upper LHS most likely stemmed from the EGO and northeastern Indian craton. The 1076–1092 Ma metamorphic zircon in the Nyingchi Complex (Table A2) are consistent with the 0.9–1.1 Ga metamorphic events resulted from broadly coeval collisional events at along the AravalliDelhi Mobile Belt (ADMB), CITZ, Shillong Plateau Gneissic Complex and EGO resulted in the final amalgamation of the North Indian Block, the South Indian Block and Marwar Block (Bhowmik et al., 2012, and references therein). A metamorphic zircon of 1129 ± 32 Ma (spot T663-11) from the Namche Barwa Complex has a flat HREE pattern (Fig. 7d), which is compatible to the REE patterns of 1117 ± 29 Ma metamorphic zircon in the two-mica plagioclase gneiss from the South Lhasa terrane in the Eastern Himalayan Syntaxis (Fig. 1c) (Lin et al., 2013), suggesting that South Lhasa terrane represents a potential source. In addition, the Rayner, Rauer, and Maud Provinces of Eastern Antarctica contain abundant Mesoproterozoic basement rocks (Myrow et al., 2010, and references therein), and thus could also be possible sources for the 1.00–1.20 Ga grains in our samples. Therefore, we considered that the 1.00–1.20 Ga grains were most likely derived from the Late Mesoproterozoic orogens (e.g., ADMB, CITZ and EGO) in southern Indian Shield, South Lhasa terrane, and probably Eastern Antarctica (Fig. 10).

The age populations of 1.50–1.65 Ga and 1.70–1.85 Ga are consistent with the crystallization ages of the Paleo- to Mesoproterozoic orthogneisses in the Eastern Himalayan Syntaxis, Bhutan and Arunachal Himalaya, NE India craton, and the CITZ (Ameen et al., 2007; Guo et al., 2008; Yin et al., 2010a; Bhowmik et al., 2011, 2012; Zhang et al., 2012b; Bora et al., 2013). The Hf isotopic compositions of the 1.50–1.65 Ga and 1.70–1.85 Ga detrital zircons also are comparable to those of the 1759– 1583 Ma orthogneisses in the Namche Barwa Complex (Fig. 6c). The coherent ages and Hf isotopic composition support the local sources for the 1.50–1.65 Ga and 1.70–1.85 Ga detrital zircons. The minor Mesoarchean to Paleoproterozoic (3.0–2.0 Ga) zircon grains in our samples are consistent with the ages of magmatic rocks in the Dharwar craton (Fig. 10) (Dey, 2013).

5.5. Paleogeographic implications

As discussed above, our data support the link between the northern India and the South Lhasa terrane. This speculation is supported by that the eastern South Lhasa terrane has similar tectono-thermal evolution history to that of northeastern India. Lin et al. (2013) reported two Paleoproterozoic (~1784 Ma and ~1782 Ma) orthogneisses from the Nyingchi Complex, which experienced granulite-facies metamorphism at ~1117 Ma and amphibolite-facies metamorphism at 618–604 Ma. These orthogneisses are comparable with the Paleo- to Mesoproterozoic (1.6–1.85 Ga) magmatic rocks in the Namche Barwa Complex, GHS, LHS, and northeastern Indian Craton (e.g., Ameen et al., 2007; Guo et al., 2008; Chakungal et al., 2010; Kohn et al., 2010; Yin et al., 2010a; Kaur et al., 2011; Zhang et al., 2012b), suggesting that the South Lhasa terrane has a similar Paleoproterozoic basement to that of the northeastern India. Both the South Lhasa terrane and the eastern proto-Indian margin experienced Mesoproterozoic (~1.3–1.5 Ga) continental rifting (Upadhyay, 2008, and references therein; Xu et al., 2013b). The ~1117 Ma granulite-facies metamorphism is consistent with the 1.0– 1.2 Ga granulite-facies metamorphism in the EGO (Yin et al., 2010a; Lin et al., 2013). The 618–604 Ma metamorphism and ~500 Ma magmatism correspond to the protracted Prydz orogenesis between the eastern India, northwest Australia, and northeast of East Antarctica during Late Neoproterozoic–Cambrian (600–500 Ma) (Fig. 10) (Dong et al., 2010; Lin et al., 2013; Xu et al., 2013b; Yin et al., 2010a; this study). Therefore, we suggest that the South Lhasa terrane and northern India were tectonically linked before Cambrian (Fig. 10).

Zhu et al. (2011a) found that detrital zircons from Carboniferous– Permian metasedimentary rocks in the Lhasa terrane define a distinctive age population of ~1170 Ma (Fig. 9a), whereas those from THS define an age population of ~950 Ma. They considered that the ~1170 Ma detrital zircons were derived from the AFO in southwest Australia, and thus suggested that the Lhasa terrane was located adjacent to the Northwest Australia during the Late Precambrian–Early Paleozoic. According to this paleogeographic scenario (Zhu et al., 2011a), the Carboniferous–Permian sedimentary rocks in Lhasa terrane should contain abundant Archean zircon grains because the river systems draining from AFO would pass through the Archean Yilgarn craton. However, the Archean zircon population is insignificant in these sedimentary rocks (Fig. 9a), indicating the AFO source is unlikely. Burrett et al. (2014) carried out K–S tests for the samples from the Lhasa terrane and Northwest Australia. The low P values also do not support the affinity between the Lhasa terrane and the Northwest Australia (Burrett et al., 2014). In addition, Zhu et al. (2010, 2012b, 2013) and Guo et al. (in press) proposed that the Lhasa terrane was an isolated microcontinent within the Paleo-Tethys ocean basin during Carboniferous–Permian. If this is the case, Carboniferous–Permian sediments in North Lhasa terrane were mainly derived from the basement and pre-Carboniferous cover rocks in the Lhasa terrane instead of AFO.

We suggest that the combined South and North Lhasa terranes were located in the northern Indian margin before Early Cambrian (Fig. 10). The sedimentary basins (Purana Basins, upper LHS, GHS and combined Lhasa terrane) in the northern Indian margin received sediment input from the Late Mesoproterozoic orogens in the Indian Shield before the Early Cambrian (Myrow et al., 2010; Yin et al., 2010b; McKenzie et al., 2011, 2013; McQuarrie et al., 2013), and thus contain abundant 1.0– 1.2 Ga detritus (Fig. 9). During the Late Cambrian–Ordovician, the northern Indian margin switched from the open ocean environment to a north-facing active margin (Fig. 10) (Garzanti et al., 1986; Cawood et al., 2007; Gehrels et al., 2011; Zhu et al., 2012b; McQuarrie et al., 2013; Ding et al., 2015). After that, the northern Indian margin became a passive margin from Ordovician to the Eocene. During this interval all of the cratonic rocks, including the Vindhyan, Alwar, Ganga, and Shillong Groups (Fig. 9b), would have been at the surface being eroded and contributing detritus to the northern margin until the Lhasa terrane was rifted. During the Late Devonian–Early Carboniferous, the combined Lhasa terrane probably had rifted from the northern Indian margin and formed a microcontinent within the Paleo-Tethys ocean basin (Zhu et al., 2010, 2012b, 2013; Guo et al., in press). The 1.0–1.2 Ga detrital zircons in the Carboniferous–Permian strata from the Lhasa terrane were mainly recycled from the basement and pre-Carboniferous cover rocks in the Lhasa terrane.

## 6. Conclusions

In the Eastern Himalayan syntaxis, some metasedimentary rocks from the Nyingchi Complex in the South Lhasa terrane and the Namche Barwa Complex in the northeastern India have maximum depositional ages of ~1.0 Ga. The Namche Barwa Complex is the northeastern extension of the Greater Himalayan Sequence, and represents the distal deposits of northern Indian margin. Detrital zircons from these metasedimentary rocks have similar U–Pb age spectra, trace-element signatures and Hf isotopic compositions, indicating that they were derived from common sources. This further indicates that the South Lhasa terrane was tectonically linked to northern India before Cambrian.

Supplementary data to this article can be found online at [http://dx.](http://dx.doi.org/10.1016/j.gr.2015.07.013)

[doi.org/10.1016/j.gr.2015.07.013](http://dx.doi.org/10.1016/j.gr.2015.07.013).

## Acknowledgments

We thank Alex Webb and Ryan McKenzie for their thorough and insightful reviews that helped to improve the manuscript. We are also grateful to the experts who read the earlier manuscript and made so many useful comments and suggestions. Prof. Ze-Ming Zhang is thanked for his editorial handling. This research is supported by the Natural Science Foundation of China (grants: 41073046 and 41303023), SinoProb 04-02 (2101105) and the Fundamental Research Funds for the Central Universities, China University of Geosciences (Wuhan).

## References

Aftalion, M., Bowes, D.R., Dash, B., Dempster, T.J., 1988. [Late Proterozoic Charnockites in Orissa, India](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0005) [—](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0005) [a](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0005) [U–Pb and Rb–Sr isotopic study. Journal of Geology 96, 663–676](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0005).

Ahmad, T., Harris, N., Bickle, M., Chapman, H., Bunbury, J., Prince, C., 2000. [Isotopic constraints on the structural relationships between the Lesser Himalayan Series and the High Himalayan Crystalline Series, Garhwal Himalaya. Geological Society of America Bulletin 112, 467–477](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0010).

Allègre, C.J., Courtillot, V., Tapponnier, P., Hirn, A., Mattauer, M., Coulon, C., Jaeger, J.J.,

Achache, J., Scharer, U., Marcoux, J., Burg, J.P., Girardeau, J., Armijo, R., Gariepy, C., Gopel, C., Li, T.D., Xiao, X.C., Chang, C.F., Li, G.Q., Lin, B.Y., Teng, J.W., Wang, N.W., Chen, G.M., Han, T.L., Wang, X.B., Den, W.M., Sheng, H.B., Cao, Y.G., Zhou, J., Qiu, H.R., Bao, P.S., Wang, S.C., Wang, B.X., Zhou, Y.X., Ronghua, X., 1984. [Structure and evolution of the Himalaya–Tibet Orogenic Belt. Nature 307, 17–22](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0015).

Ameen, S.M.M., Wilde, S.A., Kabir, M.Z., Akon, E., Chowdhury, K.R., Khan, M.S.H., 2007. [Paleoproterozoic granitoids in the basement of Bangladesh: a piece of the Indian shield or an exotic fragment of the Gondwana jigsaw? Gondwana Research 12, 380–387](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0020).

Argles, T., Foster, G., Whittington, A., Harris, N., George, M., 2003. [Isotope studies reveal](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0025) [a complete Himalayan section in the Nanga Parbat syntaxis. Geology 31, 1109–1112](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0025).

Belousova, E.A., Griffin, W.L., O'Reilly, S.Y., Fisher, N.I., 2002. [Igneous zircon: trace element composition as an indicator of source rock type. Contributions to Mineralogy and Petrology 143, 602–622](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0030).

Bhowmik, S.K., Wilde, S.A., Bhandari, A., 2011. [Zircon](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0035) [U–Pb/Lu–Hf and monazite chemical dating of the Tirodi biotite gneiss: implication for latest Palaeoproterozoic to Early Mesoproterozoic orogenesis in the Central Indian Tectonic Zone. Geological Journal 46,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0035) [574–596](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0035).

Bhowmik, S.K., Wilde, S.A., Bhandari, A., Pal, T., Pant, N.C., 2012. [Growth of the Greater Indian Landmass and its assembly in Rodinia: geochronological evidence from the Central Indian Tectonic Zone. Gondwana Research 22, 54–72](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0040).

Blichert-Toft, J., Albarede, F., 1997. [The Lu–Hf isotope geochemistry of chondrites and the evolution of the mantle–crust system. Earth and Planetary Science Letters 148, 243–258](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0045).

Boger, S.D., 2011. [Antarctica](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0050) [—](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0050) [before and after Gondwana. Gondwana Research 19, 335–371](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0050).

Booth, A.L., Chamberlain, C.P., Kidd, W.S.F., Zeitler, P.K., 2009. [Constraints on the metamorphic evolution of the eastern Himalayan syntaxis from geochronologic and petrologic studies of Namche Barwa. Geological Society of America Bulletin 121, 385–407](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0055).

Bora, S., Kumar, S., Yi, K., Kim, N., Lee, T.H., 2013. [Geochemistry and](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0060) [U–Pb SHRIMP zircon chronology of granitoids and microgranular enclaves from Jhirgadandi Pluton of Mahakoshal Belt, Central India Tectonic Zone, India. Journal of Asian Earth Sciences 70–71,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0060) [99–114](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0060).

Brookfield, M.E., 1993. [The Himalayan passive margin from Precambrian to Cretaceous times. Sedimentary Geology 84,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0065) [1–35](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0065).

Burg, J.P., Davy, P., Nievergelt, P., Oberli, F., Seward, D., Diao, Z.Z., Meier, M., 1997. [Exhumation during crustal folding in the Namche-Barwa syntaxis. Terra Nova 9, 53–56](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0070).

Burrett, C., Khin, Z., Meffre, S., Lai, C.K., Khositanont, S., Chaodumrong, P., Udchachon, M., Ekins, S., Halpin, J., 2014. [The configuration of Greater Gondwana—evidence from LA ICPMS,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0075) [U–Pb geochronology of detrital zircons from the Palaeozoic and Mesozoic of Southeast Asia and China. Gondwana Research 26, 31–51](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0075).

Cawood, P.A., Korsch, R.J., 2008. [Assembling Australia: Proterozoic building of a continent. Precambrian Research 166,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0090) [1–38](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0090).

Cawood, P.A., Johnson, M.R.W., Nemchin, A.A., 2007. [Early palaeozoic orogenesis along the Indian margin of Gondwana: Tectonic response to Gondwana assembly. Earth and Planetary Science Letters 255, 70–84](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0085).

Cawood, P.A., Hawkesworth, C.J., Dhuime, B., 2012. [Detrital zircon record and tectonic setting. Geology 40, 875–878](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0080).

Chakungal, J., Dostal, J., Grujic, D., Duchene, S., Ghalley, K.S., 2010. [Provenance of the Greater Himalayan sequence: evidence from mafic granulites and amphibolites in NW Bhutan. Tectonophysics 480, 198–212](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0095).

Chu, M.F., Chung, S.L., Song, B.A., Liu, D.Y., O'Reilly, S.Y., Pearson, N.J., Ji, J.Q., Wen, D.J., 2006. [Zircon](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0100) [U–Pb and Hf isotope constraints on the Mesozoic tectonics and crustal evolution of southern Tibet. Geology 34, 745–748](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0100).

Clark, D.J., Hensen, B.J., Kinny, P.D., 2000. [Geochronological constraints for a two-stage history of the Albany–Fraser Orogen, Western Australia. Precambrian Research 102, 155–183.](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0105)

Corfu, F., Hanchar, J.M., Hoskin, P.W.O., Kinny, P., 2003. [Atlas of zircon textures. Reviews in Mineralogy and Geochemistry 53, 469–500](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0110).

Coulon, C., Maluski, H., Bollinger, C., Wang, S., 1986. [Mesozoic and Cenozoic volcanic rocks from Central and Southern Tibet:](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0115) [39Ar–40Ar dating, petrological characteristics and geodynamical significance. Earth and Planetary Science Letters 79, 281–302](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0115).

DeCelles, P.G., Gehrels, G.E., Quade, J., LaReau, B., Spurlin, M., 2000. [Tectonic implications of](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0120) [U–Pb zircon ages of the Himalayan orogenic belt in Nepal. Science 288, 497–499](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0120).

Dey, S., 2013. [Evolution of Archaean crust in the Dharwar craton: the Nd isotope record. Precambrian Research 227, 227–246.](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0125)

Dickinson, W.R., Gehrels, G.E., 2009. [Use of](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0130) [U–Pb ages of detrital zircons to infer maximum depositional ages of strata: a test against a Colorado Plateau Mesozoic database. Earth and Planetary Science Letters 288, 115–125](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0130).

Ding, L., Zhong, D.L., Yin, A., Kapp, P., Harrison, T.M., 2001. [Cenozoic structural and metamorphic evolution of the eastern Himalayan syntaxis (Namche Barwa). Earth and Planetary Science Letters 192, 423–438](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0140).

Ding, H., Zhang, Z., Dong, X., Yan, R., Lin, Y., Jiang, H., 2015. [Cambrian ultrapotassic rhyolites from the Lhasa terrane, south Tibet: evidence for Andean-type magmatism along the northern active margin of Gondwana. Gondwana Research 27, 1616–1629](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0135).

Dong, X., Zhang, Z., Santosh, M., 2010. [Zircon](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0150) [U–Pb chronology of the Nyingtri Group, Southern Lhasa Terrane, Tibetan Plateau: implications for Grenvillian and PanAfrican Provenance and Mesozoic–Cenozoic metamorphism. The Journal of Geology 118, 677–690](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0150).

Dong, X., Zhang, Z., Santosh, M., Wang, W., Yu, F., Liu, F., 2011. [Late Neoproterozoic thermal events in the northern Lhasa terrane, south Tibet: Zircon chronology and tectonic implications. Journal of Geodynamics 52, 389–405](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0155).

Dong, X., Zhang, Z., Liu, F., He, Z., Lin, Y., 2014. [Late Paleozoic intrusive rocks from the southeastern Lhasa terrane, Tibetan Plateau, and their Late Mesozoic metamorphism and tectonic implications. Lithos 198–199, 249–262](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0145).

Ferrari, O.M., Hochard, C., Stampfli, G.M., 2008. [An alternative plate tectonic model for the Palaeozoic–Early Mesozoic Palaeotethyan evolution of Southeast Asia (Northern Thailand–Burma). Tectonophysics 451, 346–365](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0160).

Garzanti, E., Casnedi, R., Jadoul, F., 1986. [Sedimentary evidence of a Cambro-Ordovician orogenic event in the northwestern Himalaya. Sedimentary Geology 48, 237–265](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0165).

Gehrels, G.E., DeCelles, P.G., Martin, A., Ojha, T.P., Pinhassi, G., Upreti, B.N., 2003. [Initiation of the Himalayan Orogen as an early Paleozoic thin-skinned thrust belt. GSA Today 13,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0175) [4–9](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0175).

Gehrels, G., Kapp, P., DeCelles, P., Pullen, A., Blakey, R., Weislogel, A., Ding, L., Guynn, J., Martin, A., McQuarrie, N., Yin, A., 2011. [Detrital zircon geochronology of preTertiary strata in the Tibetan–Himalayan orogen. Tectonics 30, TC5016](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0170).

Geng, Q.R., Pan, G.T., Zheng, L.L., Chen, Z.L., Fisher, R.D., Sun, Z.M., Ou, C.S., Dong, H., Wang, X.W., Li, S., Lou, X.Y., Fu, H., 2006. [The Eastern Himalayan syntaxis: major tectonic domains, ophiolitic melanges and geologic evolution. Journal of Asian Earth Sciences 27, 265–285](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0180).

Griffin, W.L., Pearson, N.J., Belousova, E., Jackson, S.E., van Achterbergh, E., O'Reilly, S.Y., Shee, S.R., 2000. [The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. Geochimica Et Cosmochimica Acta 64, 133–147.](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0190)

Griffin, W.L., Belousova, E.A., Shee, S.R., Pearson, N.J., O'Reilly, S.Y., 2004. [Archean crustal evolution in the northern Yilgarn Craton:](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0185) [U–Pb and Hf-isotope evidence from detrital zircons. Precambrian Research 131, 231–282](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0185).

Guo, L., Zhang, H.F., Xu, W.C., 2008. [U–Pb zircon ages of migmatite and granitic gneiss from Duoxiongla in eastern Himalayan syntaxis and their geological implications. Acta Petrologica Sinica 24, 421–429](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0210).

Guo, L., Zhang, H.F., Harris, N., Pan, F.B., Xu, W.C., 2011. [Origin and evolution of multi-stage felsic melts in eastern Gangdese belt: constraints from](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0195) [U–Pb zircon dating and Hf isotopic composition. Lithos 127, 54–67](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0195).

Guo, L., Zhang, H.F., Harris, N., Parrish, R., Xu, W.C., Shi, Z.L., 2012. [Paleogene crustal anatexis and metamorphism in Lhasa terrane, eastern Himalayan syntaxis: evidence from](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0205) [U–Pb zircon ages and Hf isotopic compositions of the Nyingchi Complex. Gondwana Research 21, 100–111](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0205).

Guo, L., Zhang, H.F., Harris, N., Pan, F.B., Xu, W.C., 2013. [Late Cretaceous (~81](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0200) [Ma) hightemperature metamorphism in the southeastern Lhasa terrane: implication for the Neo-Tethys ocean ridge subduction. Tectonophysics 608, 112–126](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0200).

Guo, L., Zhang, H.F., Harris, N., Xu, W.C., Pan, F.B., 2015. Late Devonian–Early Carboniferous magmatism in the Lhasa terrane and its tectonic implications: evidences from detrital zircons in the Nyingchi Complex. Lithos http://dx.doi.org[/10.1016/j.lithos.2015.1006. 1018](http://dx.doi.org/10.1016/j.lithos.2015.1006.1018) (in press).

Guynn, J., Gehrels, G., 2010. [Comparison of Detrital Zircon Age Distributions Using the](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0215) [K–S Test: Tucson. University of Arizona, Arizona LaserChron Center (16 pp.)](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0215).

Hofmann, M., Linnemann, U., Rai, V., Becker, S., Gärtner, A., Sagawe, A., 2011. [The India and South China cratons at the margin of Rodinia](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0220) [—](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0220) [synchronous Neoproterozoic magmatism revealed by LA-ICP-MS zircon analyses. Lithos 123, 176–187](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0220).

Hoskin, P.W.O., Schaltegger, U., 2003. [The composition of zircon and igneous and metamorphic petrogenesis. Reviews in Mineralogy and Geochemistry 53, 27–62](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0225).

Hu, D.G., Wu, Z.H., Jiang, W., Shi, Y.R., Ye, P.S., Liu, Q.S., 2005. [SHRIMP zircon](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0230) [U–Pb age and Nd isotopic study on the Nyainqentanglha Group in Tibet. Science in China Series DEarth Sciences 48, 1377–1386](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0230).

Hu, Z.C., Liu, Y.S., Gao, S., Liu, W.G., Zhang, W., Tong, X.R., Lin, L., Zong, K.Q., Li, M., Chen, H.H., Zhou, L., Yang, L., 2012. [Improved in situ Hf isotope ratio analysis of zircon using newly designed X skimmer cone and jet sample cone in combination with the addition of nitrogen by laser ablation multiple collector ICP-MS. Journal of Analytical Atomic Spectrometry 27, 1391–1399](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0235).

Ji, W.Q., Wu, F.Y., Chung, S.L., Li, J.X., Liu, C.Z., 2009. [Zircon](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0245) [U–Pb geochronology and Hf isotopic constraints on petrogenesis of the Gangdese batholith, southern Tibet. Chemical Geology 262, 229–245](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0245).

Ji, W.Q., Wu, F.Y., Chung, S.L., Liu, C.Z., 2012. [Identification of Early Carboniferous granitoids from Southern Tibet and implications for terrane assembly related to the Paleo-Tethyan evolution. The Journal of Geology 120, 531–541](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0240).

Kapp, J.L.D., Harrison, T.M., Kapp, P., Grove, M., Lovera, O.M., Lin, D., 2005. [Nyainqentanglha Shan: a window into the tectonic, thermal, and geochemical evolution of the Lhasa block, southern Tibet. Journal of Geophysical Research-Solid Earth 110, B08413](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0250).

Kaur, P., Chaudhri, N., Raczek, I., Kröner, A., Hofmann, A.W., Okrusch, M., 2011. [Zircon ages of late Palaeoproterozoic (ca. 1.72–1.70](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0255) [Ga) extension-related granitoids in NE Rajasthan, India: regional and tectonic significance. Gondwana Research 19, 1040–1053](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0255).

Kirkland, C.L., Spaggiari, C.V., Pawley, M.J., Wingate, M.T.D., Smithies, R.H., Howard, H.M., Tyler, I.M., Belousova, E.A., Poujol, M., 2011. [On the edge:](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0260) [U–Pb, Lu–Hf, and Sm–Nd data suggests reworking of the Yilgarn craton margin during formation of the Albany–Fraser Orogen. Precambrian Research 187, 223–247](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0260).

Kohn, M.J., Paul, S.K., Corrie, S.L., 2010. [The lower Lesser Himalayan sequence:](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0265) [a Paleoproterozoic arc on the northern margin of the Indian plate. Geological Society of America Bulletin 122, 323–335](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0265).

Le Fort, P., Rai, S.M., 1999. [Pre-Tertiary felsic magmatism of the Nepal Himalaya: recycling of continental crust. Journal of Asian Earth Sciences 17, 607–628](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0270).

Liao, Q.N., Li, D.W., Lu, L.A., Yuan, Y.M., Chu, L.L., 2008. [Paleoproterozoic granitic gneisses of the Dinggye and LhagoiKangri areas from the higher and northern Himalaya, Tibet: geochronology and implications. Science in China Series D-Earth Sciences 51, 240–248](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0275).

Lin, Y.H., Zhang, Z.M., Dong, X., Shen, K., Lu, X., 2013. [Precambrian evolution of the Lhasa terrane, Tibet: constraint from the zircon](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0280) [U–Pb geochronology of the gneisses. Precambrian Research 237, 64–77](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0280).

Liu, Y., Yang, Z.Q., Wang, M., 2007. [History of zircon growth in a high-pressure granulite within the eastern himalayan syntaxis, and tectonic implications. International Geology Review 49, 861–872](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0290).

Liu, Y., Liu, H.F., Theye, T., Massonne, H.J., 2009. [Evidence for oceanic subduction at the NE Gondwana margin during Permo-Triassic times. Terra Nova 21, 195–202](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf9005).

Liu, Y.S., Gao, S., Hu, Z.C., Gao, C.G., Zong, K.Q., Wang, D.B., 2010. [Continental and oceanic crust recycling-induced melt-peridotite interactions in the Trans-North China Orogen:](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0295) [U–Pb dating, Hf isotopes and trace elements in Zircons from mantle xenoliths. Journal of Petrology 51, 537–571](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0295).

Liu, Y., Siebel, W., Theye, T., Massonne, H.-J., 2011. [Isotopic and structural constraints on the late Miocene to Pliocene evolution of the Namche Barwa area, eastern Himalayan syntaxis, SE Tibet. Gondwana Research 19, 894–909](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0285).

Long, S., McQuarrie, N., Tobgay, T., Rose, C., Gehrels, G., Grujic, D., 2011. [Tectonostratigraphy of the Lesser Himalaya of Bhutan: implications for the alongstrike stratigraphic continuity of the northern Indian margin. Geological Society of America Bulletin 123, 1406–1426](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0300).

Ludwig, K.R., 2003. [User's Manual for Isoplot 3.0: A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special, Publication No.4](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0635).

Malone, S.J., Meert, J.G., Banerjee, D.M., Pandit, M.K., Tamrat, E., Kamenov, G.D., Pradhan, V.R., Sohl, L.E., 2008. [Paleomagnetism and detrital zircon geochronology of the Upper Vindhyan sequence, Son Valley and Rajasthan, India: a ca. 1000 ma closure age for the Purana Basins? Precambrian Research 164, 137–159](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0305).

McKenzie, N.R., Hughes, N.C., Myrow, P.M., Xiao, S., Sharma, M., 2011. [Correlation of Precambrian–Cambrian sedimentary successions across northern India and the utility of isotopic signatures of Himalayan lithotectonic zones. Earth and Planetary Science Letters 312, 471–483](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0320).

McKenzie, N.R., Hughes, N.C., Myrow, P.M., Banerjee, D.M., Deb, M., Planavsky, N.J., 2013. [New age constraints for the Proterozoic Aravalli-Delhi successions of India and their implications. Precambrian Research 238, 120–128](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0315).

McKenzie, N.R., Hughes, N.C., Gill, B.C., Myrow, P.M., 2014. [Plate tectonic influences on Neoproterozoic–early Paleozoic climate and animal evolution. Geology 42, 127–130](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0310). McQuarrie, N., Robinson, D., Long, S., Tobgay, T., Grujic, D., Gehrels, G., Ducea, M., 2008. [Preliminary stratigraphic and structural architecture of Bhutan: implications for the along strike architecture of the Himalayan system. Earth and Planetary Science Letters 272, 105–117](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0330).

McQuarrie, N., Long, S.P., Tobgay, T., Nesbit, J.N., Gehrels, G., Ducea, M.N., 2013. [Documenting basin scale, geometry and provenance through detrital geochemical data: lessons from the Neoproterozoic to Ordovician Lesser, Greater, and Tethyan Himalayan strata of Bhutan. Gondwana Research 23, 1491–1510](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0325).

Metcalfe, I., 1996. [Gondwanaland dispersion, Asian accretion and evolution of eastern Tethys. Australian Journal of Earth Sciences 43, 605–623](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0335).

Mottram, C.M., Argles, T.W., Harris, N.B.W., Parrish, R.R., Horstwood, M.S.A., Warren, C.J., Gupta, S., 2014. [Tectonic interleaving along the Main Central Thrust, Sikkim Himalaya. Journal of the Geological Society 171, 255–268](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0340).

Mukherjee, A., Bickford, M.E., Hietpas, J., Schieber, J., Basu, A., 2012. [Implications of](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0345) [a newly dated ca. 1000-Ma rhyolitic tuff in the Indravati Basin, Bastar Craton, India. Journal of Geology 120, 477–485](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0345).

Myrow, P.M., Hughes, N.C., Paulsen, T.S., Willlams, I.S., Parcha, S.K., Thompson, K.R., Bowring, S.A., Peng, S.C., Ahluwalia, A.D., 2003. [Integrated tectonostratigraphic analysis of the Himalaya and implications for its tectonic reconstruction. Earth and Planetary Science Letters 212, 433–441](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0355).

Myrow, P.M., Hughes, N.C., Goodge, J.W., Fanning, C.M., Williams, I.S., Peng, S., Bhargava, O.N., Parcha, S.K., Pogue, K.R., 2010. [Extraordinary transport and mixing of sediment across Himalayan central Gondwana during the Cambrian–Ordovician. Geological Society of America Bulletin 122, 1660–1670](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0350).

Pan, F.B., Zhang, H.F., Xu, W.C., Guo, L., Wang, S., Luo, B.J., 2014. [U–Pb zircon chronology, geochemical and Sr–Nd isotopic composition of Mesozoic–Cenozoic granitoids in the SE Lhasa terrane: petrogenesis and tectonic implications. Lithos 192–195, 142–157](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0360).

Parrish, R.R., Hodges, K.V., 1996. [Isotopic constraints on the age and provenance of the Lesser and Greater Himalayan sequences, Nepalese Himalaya. Geological Society of America Bulletin 108, 904–911](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0365).

Patranabis-Deb, S., Bickford, M.E., Hill, B., Chaudhuri, A.K., Basu, A., 2007. [SHRIMP ages of zircon in the uppermost tuff in Chattisgarh Basin in central India require similar to 500-Ma adjustment in Indian proterozoic stratigraphy. Journal of Geology](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0370) [115, 407–415](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0370).

Pradhan, V.R., Meert, J.G., Pandit, M.K., Kamenov, G., Mondal, M.E.A., 2012. [Paleomagnetic and geochronological studies of the mafic dyke swarms of Bundelkhand craton, central India: implications for the tectonic evolution and paleogeographic reconstructions. Precambrian Research 198–199, 51–76](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0375).

Ran, B., Wang, C., Zhao, X., Li, Y., He, M., Zhu, L., Coe, R.S., 2012. [New paleomagnetic results of the early Permian in the Xainza area, Tibetan Plateau and their paleogeographical implications. Gondwana Research 22, 447–460](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0380).

Ratre, K., De Waele, B., Biswal, T.K., Sinha, S., 2010. [SHRIMP geochronology for the 1450](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0385) [Ma Lakhna dyke swarm: its implication for the presence of Eoarchaean crust in the Bastar Craton and 1450–517](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0385) [Ma depositional age for Purana basin (Khariar), Eastern Indian Peninsula. Journal of Asian Earth Sciences 39, 565–577](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0385).

Rekha, S., Upadhyay, D., Bhattacharya, A., Kooijman, E., Goon, S., Mahato, S., Pant, N.C., 2011. [Lithostructural and chronological constraints for tectonic restoration of Proterozoic accretion in the Eastern Indian Precambrian shield. Precambrian Research 187, 313–333](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0390).

Richards, A., Argles, T., Harris, N., Parrish, R., Ahmad, T., Darbyshire, F., Draganits, E., 2005. [Himalayan architecture constrained by isotopic tracers from clastic sediments. Earth and Planetary Science Letters 236, 773–796](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0395).

Richards, A., Parrish, R., Harris, N., Argles, T., Zhang, L., 2006. [Correlation of lithotectonic units across the eastern Himalaya, Bhutan. Geology 34, 341–344](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0400).

Roy, A., Chakraborti, K., 2008. [Precambrian mafic–ultramafic magmatism in central Indian suture zone. Journal of the Geological Society of India 72, 123–140](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0405).

Rubatto, D., 2002. [Zircon trace element geochemistry: partitioning with garnet and the link between](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0410) [U–Pb ages and metamorphism. Chemical Geology 184, 123–138](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0410).

Scherer, E., Munker, C., Mezger, K., 2001. [Calibration of the lutetium–hafnium clock. Science 293, 683–687](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0415).

Schulz, B., Klemd, R., Bratz, H., 2006. [Host rock compositional controls on zircon trace element signatures in metabasites from the Austroalpine basement. Geochimica Et Cosmochimica Acta 70, 697–710](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0420).

Smits, R.G., Collins, W.J., Hand, M., Dutch, R., Payne, J., 2014. [A Proterozoic Wilson cycle identified by Hf isotopes in central Australia: implications for the assembly of Proterozoic Australia and Rodinia. Geology 42, 231–234](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0425).

Sun, S.S., McDonough, W.F., 1989. [Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. Geological Society, London, Special Publications 42, 313–345](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0430).

Turner, C.C., Meert, J.G., Pandit, M.K., Kamenov, G.D., 2014. [A detrital zircon](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0435) [U–Pb and Hf isotopic transect across the Son Valley sector of the Vindhyan Basin, India: implications for basin evolution and paleogeography. Gondwana Research 26, 348–364.](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0435)

Upadhyay, D., 2008. [Alkaline magmatism along the southeastern margin of the Indian shield: implications for regional geodynamics and constraints on craton–Eastern Ghats Belt suturing. Precambrian Research 162, 59–69](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0440).

Upadhyay, D., Raith, M.M., 2006a. [Intrusion age, geochemistry and metamorphic conditions of a quartz–monzosyenite intrusion at the craton–Eastern Ghats Belt contact near Jojuru, India. Gondwana Research 10, 267–276](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0450).

Upadhyay, D., Raith, M.M., 2006b. [Petrogenesis of the Kunavaram alkaline complex and the tectonothermal evolution of the neighboring Eastern Ghats Belt granulites, SE India. Precambrian Research 150, 73–94](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0455).

Upadhyay, D., Raith, M., Mezger, K., Bhattacharya, A., Kinny, P., 2006a. [Mesoproterozoic rifting and Pan-African continental collision in SE India: evidence from the Khariar alkaline complex. Contributions to Mineralogy and Petrology 151, 434–456](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0445).

Upadhyay, D., Raith, M.M., Mezger, K., Hammerschmidt, K., 2006b. [Mesoproterozoic riftrelated alkaline magmatism at Elchuru, Prakasam Alkaline Province, SE India. Lithos 89,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0460) [447–477](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0460).

Vermeesch, P., 2012. [On the visualisation of detrital age distributions. Chemical Geology 312–313, 190–194](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0465).

Vervoort, J.D., Blichert-Toft, J., 1999. [Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time. Geochimica Et Cosmochimica Acta 63, 533–556](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0470).

Vijaya Kumar, K., Rathna, K., 2008. [Geochemistry of the mafic dykes in the Prakasam Alkaline Province of Eastern Ghats Belt, India: implications for the genesis of continental rift-zone magmatism. Lithos 104, 306–326](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0480).

Vijaya Kumar, K., Frost, C.D., Frost, B.R., Chamberlain, K.R., 2007. [The Chimakurti, Errakonda, and Uppalapadu plutons, Eastern Ghats Belt, India: an unusual association of tholeiitic and alkaline magmatism. Lithos 97, 30–57](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0475).

Wang, J.L., Zhang, Z.M., Dong, X., Liu, F., Yu, F., Wang, W., Xu, F.J., Shen, K., 2009. [Discovery of Late Cretaceous garnet two-pyroxene granulite in the southern Lhasa terrane, Tibet and its tectonic significances. Acta Petrologica Sinica 1695–1706](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0640).

Webb, A.A.G., Yin, A., Dubey, C.S., 2013. [U–Pb zircon geochronology of major lithologic units in the eastern Himalaya: implications for the origin and assembly of Himalayan rocks. Geological Society of America Bulletin 125, 499–522](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0490).

Wen, D.R., Liu, D.Y., Chung, S.L., Chu, M.F., Ji, J.Q., Zhang, Q., Song, B., Lee, T.Y., Yeh, M.W., Lo, C.H., 2008. [Zircon SHRIMP](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0495) [U–Pb ages of the Gangdese Batholith and implications for Neotethyan subduction in southern Tibet. Chemical Geology 252, 191–201](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0495).

Xu, R.H., Scharer, U., Allégre, C.J., 1985. [Magmatism and metamorphism in the Lhasa Block (Tibet): a geochronological study. Journal of Geology 93,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0500) [41–57](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0500).

Xu, W.C., Zhang, H.F., Parrish, R., Harris, N., Guo, L., Yuan, H.L., 2010. [Timing of granulitefacies metamorphism in the eastern Himalayan syntaxis and its tectonic implications. Tectonophysics 485, 231–244](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0515).

Xu, Z., Ji, S., Cai, Z., Zeng, L., Geng, Q., Cao, H., 2012. [Kinematics and dynamics of the Namche Barwa Syntaxis, eastern Himalaya: constraints from deformation, fabrics and geochronology. Gondwana Research 21, 19–36](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0520).

Xu, W.C., Zhang, H.F., Harris, N., Guo, L., Pan, F.B., 2013a. [Rapid Eocene erosion, sedimentation and burial in the eastern Himalayan syntaxis and its geodynamic significance. Gondwana Research 23, 715–725.](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0505)

Xu, W.C., Zhang, H.F., Harris, N., Guo, L., Pan, F.B., Wang, S., 2013b. [Geochronology and geochemistry of Mesoproterozoic granitoids in the Lhasa terrane, south Tibet: implications for the early evolution of Lhasa terrane. Precambrian Research 236, 46–58.](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0510)

Yang, J.S., Xu, Z.Q., Li, Z.L., Xua, X.Z., Li, T.F., Ren, Y.F., Li, H.Q., Chen, S.Y., Robinson, P.T., 2009. [Discovery of an eclogite belt in the Lhasa block, Tibet: a new border for Paleo-Tethys? Journal of Asian Earth Sciences 34, 76–89](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0525).

Yin, A., 2006. [Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. Earth-Science Reviews 76,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0530) [1–131](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0530).

Yin, A., Harrison, T.M., 2000. [Geologic evolution of the Himalayan–Tibetan orogen. Annual Review of Earth and Planetary Sciences 28, 211–280](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0550).

Yin, A., Dubey, C.S., Kelty, T.K., Gehres, G.E., Chou, C.Y., Grove, M., Lovera, O., 2006. [Structural evolution of the Arunachal Himalaya and implications for asymmetric development of the Himalayan orogen. Current Science 90, 195–206](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0535).

Yin, A., Dubey, C.S., Kelty, T.K., Webb, A.A.G., Harrison, T.M., Chou, C.Y., Celerier, J., 2010a. [Geologic correlation of the Himalayan orogen and Indian craton: Part 2. Structural geology, geochronology, and tectonic evolution of the Eastern Himalaya. Geological Society of America Bulletin 122, 360–395](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0540).

Yin, A., Dubey, C.S., Webb, A.A.G., Kelty, T.K., Grove, M., Gehrels, G.E., Burgess, W.P., 2010b. [Geologic correlation of the Himalayan orogen and Indian craton: Part 1. Structural geology,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0545) [U–Pb zircon geochronology, and tectonic evolution of the Shillong Plateau and its neighboring regions in NE India. Geological Society of America Bulletin 122, 336–359](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0545).

Yoshida, M., Upreti, B.N., 2006. [Neoproterozoic India within East Gondwana: constraints from recent geochronologic data from Himalaya. Gondwana Research 10,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0555) [349–356](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0555).

Zhang, L., Wu, Y., 2012. [Origin and metamorphic evolution of the Nyingchi Complex, eastern Lhasa terrane, southern Tibet: constraint from the zircon](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0565) [U–Pb geochronology. Acta Petrologica Sinica 28, 1674–1688](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0565).

Zhang, H.F., Xu, W.C., Zong, K.Q., Yuan, H.L., Harris, N., 2008. [Tectonic evolution of metasediments from the Gangdise terrane, Asian plate, Eastern Himalayan Syntaxis, Tibet. International Geology Review 50, 914–930](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0560).

Zhang, H.F., Harris, N., Guo, L., Xu, W.C., 2010a. [The significance of Cenozoic magmatism from the western margin of the eastern syntaxis, southeast Tibet. Contributions to Mineralogy and Petrology 160, 83–98](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf9000).

Zhang, Z.M., Zhao, G.C., Santosh, M., Wang, J.L., Dong, X., Liou, J.G., 2010b. [Two stages of granulite facies metamorphism in the eastern Himalayan syntaxis, south Tibet: petrology, zircon geochronology and implications for the subduction of Neo-Tethys and the Indian continent beneath Asia. Journal of Metamorphic Geology 28, 719–733](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0595).

Zhang, Z.M., Dong, X., Liu, F., Lin, Y., Yan, R., He, Z., Santosh, M., 2012a. [The making of Gondwana: discovery of 650 Ma HP granulites from the North Lhasa, Tibet. Precambrian Research 212–213, 107–116](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0570).

Zhang, Z.M., Dong, X., Santosh, M., Liu, F., Wang, W., Yiu, F., He, Z., Shen, K., 2012b. [Petrology and geochronology of the Namche Barwa Complex in the eastern Himalayan syntaxis, Tibet: constraints on the origin and evolution of the north-eastern margin of the Indian Craton. Gondwana Research 21, 123–137](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0575).

Zhang, Z.M., Dong, X., Xiang, H., Liou, J.G., Santosh, M., 2013. [Building of the Deep Gangdese Arc, South Tibet: paleocene plutonism and granulite-facies metamorphism. Journal of Petrology 54, 2547–2580](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0580).

Zhang, Z.M., Dong, X., Santosh, M., Zhao, G.C., 2014. [Metamorphism and tectonic evolution of the Lhasa terrane, Central Tibet. Gondwana Research 25, 170–189](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0590).

Zhang, Z.M., Xiang, H., Dong, X., Ding, H., He, Z., 2015. [Long-lived high-temperature granulite-facies metamorphism in the Eastern Himalayan orogen, south Tibet. Lithos 212–215,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0585) [1–15](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0585).

Zhu, D.C., Mo, X.X., Zhao, Z.D., Niu, Y., Wang, L.Q., Chu, Q.H., Pan, G.T., Xu, J.F., Zhou, C.Y., 2010. [Presence of Permian extension- and arc-type magmatism in southern Tibet: paleogeographic implications. Geological Society of America Bulletin 122, 979–993](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0600).

Zhu, D.C., Zhao, Z.D., Niu, Y., Dilek, Y., Mo, X.X., 2011a. [Lhasa terrane in southern Tibet came from Australia. Geology 39, 727–730](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0610).

Zhu, D.C., Zhao, Z.D., Niu, Y., Mo, X.X., Chung, S.L., Hou, Z.Q., Wang, L.Q., Wu, F.-Y., 2011b. [The Lhasa Terrane: record of a microcontinent and its histories of drift and growth. Earth and Planetary Science Letters 301, 241–255](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0620).

Zhu, D.C., Zhao, Z.D., Niu, Y., Dilek, Y., Wang, Q., Ji, W.H., Dong, G.C., Sui, Q.L., Liu, Y.S., Yuan, H.L., Mo, X.X., 2012a. [Cambrian bimodal volcanism in the Lhasa Terrane, southern Tibet: record of an early Paleozoic Andean-type magmatic arc in the Australian proto-Tethyan margin. Chemical Geology 328, 290–308](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0615).

Zhu, D.C., Zhao, Z.D., Niu, Y., Wang, Q., Dilek, Y., Dong, G.C., Mo, X.X., 2012b. [Origin and Paleozoic tectonic evolution of the Lhasa terrane. Geological Journal of China Universities 18,](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0625) [1–15](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0625).

Zhu, D.C., Zhao, Z.D., Niu, Y., Dilek, Y., Hou, Z.Q., Mo, X.X., 2013. [The origin and preCenozoic evolution of the Tibetan Plateau. Gondwana Research 23, 1429–1454](http://refhub.elsevier.com/S1342-937X(15)00193-8/rf0605).