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Detrital zircon U–Pb geochronology, trace-element and Hf isotope geochemistry of the metasedimentary rocks in the Eastern Himalayan syntaxis: Tectonic and paleogeographic implications

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Abstract

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 alkaline and mafic rocks belt in the southeastern India is a potential provenance. Most 1.50–1.65 Ga zircons have positive $\varepsilon_{\text{Hf}}(t)$ values (+1.2 to +9.0), and most 1.70–1.80 Ga zircons have negative $\varepsilon_{\text{Hf}}(t)$ values (–7.1 to –1.9), which are compatible with

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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.

Keywords: Detrital zircon; Eastern Himalayan syntaxis; Greater Himalayan Sequence; South Lhasa terrane; Paleogeography

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; Gehrels et al., 2011; McQuarrie et al., 2013; Myrow et al., 2003; Yin and Harrison, 2000; Zhang et al., 2012a, 2014; Zhu et al., 2011a, 2011b, 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 (Burrett et al.,

2014; Dong et al., 2010; Gehrels et al., 2011; Metcalfe, 1996; Yin and Harrison, 2000). However, recent studies argued that the Lhasa terrane was located adjacent to Northwest Australia (Ferrari et al., 2008; Ran et al., 2012; Zhu et al., 2011a). 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 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 tectono-stratigraphic 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 (Kohn et al., 2010; Long et al., 2011; McQuarrie et al., 2008, 2013). The lower LHS consists of Late Paleoproterozoic to 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; Kohn et al., 2010; Long et al., 2011; McKenzie et al., 2011; McQuarrie et al., 2008, 2013; Myrow et al., 2010; Yin, 2006). The GHS is mainly composed 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 (Dong et al., 2011; Hu et al., 2005; Kapp et al., 2005; Xu et al., 1985; Zhang et al., 2012a, 2014; Zhu et al., 2012a). 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 (Chu et al., 2006; Coulon et al., 1986; Guo et al., 2011; Ji et al., 2009; Pan et al., 2014; Wen et al., 2008; Zhu et al., 2011b). Its metamorphic basement is exposed in the eastern part of the South Lhasa terrane (Dong et al., 2010; Guo et al., 2011; Lin et al., 2013; Xu et al., 2013b; Zhang et al., 2008).

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, 2013b; Zhang et al., 2008, 2010c). The Nyingchi Complex is composed of orthogneiss, paragneiss, amphibolite, marble, schist, quartzite, migmatite, and minor granulites (Booth et al., 2009; Dong et al., 2010; Geng et al., 2006; Guo et al., 2011, 2012, 2013; Wang et al., 2009; Zhang et al., 2010, 2013, 2014). The Bome Complex has similar lithological assemblage to that of the Nyingchi Complex except for the lack of granulites (Xu et al., 2013a, 2013b). 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; Dong et al., 2010; Guo et al., 2012, 2013; Lin et al., 2013; Wang et al., 2009; Xu et al., 2013a; Zhang et al., 2010, 2013, 2014). Detrital zircon geochronological studies revealed that the metasedimentary rocks have various depositional ages ranging from Paleozoic to Cenozoic (Dong et al., 2010; Guo et al., 2012, 2013; Xu et al., 2013a; Zhang et al., 2008; Zhang and Wu, 2012). In this study, we report that the Nyingchi Complex contains >499 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; Guo et al., 2008; Liu et al., 2007, 2011; Xu et al., 2010, 2012; Zhang et al., 2010, 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 granulite-facies 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 peak-metamorphism of the high-pressure granulites occurred at ~40–30 Ma, and the high-pressure granulites underwent a long-lived high-temperature 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 2c). Both the metasedimentary rocks and granitic gneiss are strongly foliated (Fig. 2b and 2c). 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 K-feldspar, quartz and minor plagioclase (Fig. 2c and Fig. 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

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 (Gyynn 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 >0.05 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 (Gyynn and Gehrels, 2010).

3.2 Zircon Lu-Hf isotopes

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 MC-ICP-MS instrument and analytical method are the same as 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 ^{176}Lu and the chondritic ratios of $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{176}\text{Lu}/^{177}\text{Hf}$ used in calculations are $1.865 \times 10^{-11}/\text{year}$ (Scherer et al., 2001), and 0.282772 and 0.0332 (Blichert-Toft and Albarede, 1997), respectively. The single-stage model age (T_{DM1}) was calculated relative to the depleted mantle with a present-day $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.28325 and $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0384 (Griffin et al., 2000), and two-stage model ages (T_{DM2}) were calculated by assuming a mean $^{176}\text{Lu}/^{177}\text{Hf}$ value of 0.015 for the average continental crust (Vervoort and Blichert-Toft, 1999). Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios and $\varepsilon_{\text{Hf}}(t)$ 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, trace-element and Hf isotope data are given in the electronic supplements as Table A1, A2, and A3, respectively. For statistical purposes, zircon grains with discordance <10% 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 modelled 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 (<10 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 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.

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 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, 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 Metagneous 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 twenty-seven 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 $^{206}\text{Pb}/^{238}\text{U}$ 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 zircon from our metasedimentary samples have high Th/U ratios (>0.10), and exhibit fractionated REE patterns with positive Ce anomalies and marked negative Eu anomalies (Fig. 7a–d), indicating they are 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 (<0.10) 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 recognise 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 Ne-syenites is >80% (Belousova et al., 2002; Griffin et al., 2004). On basis of the classification and regression trees analysis (Belousova et al., 2002), the modelled rock types of detrital zircons from Nyingchi Complex and Namche Barwa Complex include granitoids (<65% and 70–75% SiO₂), dolerite, and minor basalt, carbonatite, >75% 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 trace-element 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 Metagneous 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 $\epsilon_{\text{Hf}}(t)$ values ranging from -19.4 to +10.0 (Table A3, Fig. 6c), which are similar to those ($\epsilon_{\text{Hf}}(t) = -9.5 - +14.5$) of detrital zircons from the Namche Barwa Complex (Table A3, Fig. 6c). The $\epsilon_{\text{Hf}}(t)$ 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 $\epsilon_{\text{Hf}}(t)$ 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 $\epsilon_{\text{Hf}}(t)$ values (+1.2 to +9.0), and most 1.75–1.85 Ga zircons have negative $\epsilon_{\text{Hf}}(t)$ 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 $\epsilon_{\text{Hf}}(t)$ values of -4.6 to -0.3 and T_{DM2} of 2.45–2.71 Ga. Sample T610 has $\epsilon_{\text{Hf}}(t)$ values of +1.4 – +7.3 and T_{DM2} of 1.85–2.24 Ga. Sample T616 has $\epsilon_{\text{Hf}}(t)$ values of +0.5 – +5.4 and T_{DM2} 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 (Cawood et al., 2012; Dickinson and Gehrels, 2009). 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 (Dong et al., 2010; Guo et al., 2012; Zhang et al., 2008; Zhang and Wu, 2012). Compared with the Paleozoic strata from the Lhasa terrane (Dong et al., 2010; Gehrels et al., 2011; Guo et al., 2012; Zhang et al., 2008; Zhang and Wu, 2012; Zhu et al., 2011b), 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.

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 <600 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 (DeCelles et al., 2000; Gehrels et al., 2003; Le Fort and Rai, 1999). 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) (Chakungal et al., 2010; Guo et al., 2008; Kohn et al., 2010; Liao et al., 2008; 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 ϵ_{Nd} values and containing abundant Neoproterozoic–Paleozoic (~1.0 Ga and ~0.5 Ga) detrital zircon, whereas the LHS yielding more negative ϵ_{Nd} values and containing no detrital zircon younger than 1.6 Ga (Ahmad et al., 2000; Argles et al., 2003; DeCelles et al., 2000; Mottram et al., 2014; Parrish and Hodges, 1996; Richards et al., 2005, 2006). 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 (Long et al., 2011; McKenzie et al., 2011; McQuarrie et al., 2008, 2013; Mottram et al., 2014; Myrow et al., 2003, 2010; Webb et al., 2013; Yin et al., 2010a).

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 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 (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, 2010b), 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 East Antarctic and South Australian Cratons (Cawood and Korsch, 2008; Clark et al., 2000; 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 active-margin magmatic activity (Smits et al., 2014). Secondly, the 1.30–1.45 Ga detrital zircon define a broad band of $\varepsilon_{\text{Hf}}(t)$ (–19.4 to +5.2), and most of them have more negative $\varepsilon_{\text{Hf}}(t)$ 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 (Ratre et al., 2010; Upadhyay, 2008; Upadhyay et al., 2006a, 2006b; Upadhyay and Raith, 2006a, 2006b; Vijaya Kumar et al., 2007; Vijaya Kumar and Rathna, 2008). 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 modelled 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; McKenzie et al., 2011, 2013; Turner et al., 2014; Yin et al., 2010b). 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; Mukherjee et al., 2012; Patranabis-Deb et al., 2007; Pradhan et al., 2012; Rekha et al., 2011; Roy and Chakraborti, 2008; Yin et al., 2010a). 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 Aravalli–Delhi 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; Bhowmik et al., 2011, 2012; Bora et al., 2013; Guo et al., 2008; Yin et al., 2010a; Zhang et al., 2012b). 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; Chakungal et al., 2010; Guo et al., 2008; Kaur et al., 2011; Kohn et al., 2010; Yin et al., 2010a; 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 (Lin et al., 2013; Yin et al., 2010a). 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. (2015) 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 (McKenzie et al., 2011, 2013; McQuarrie et al., 2013; Myrow et al., 2010; Yin et al., 2010b), 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 an north-facing active margin (Fig. 10) (Cawood et al., 2007; Ding et al., 2015; Garzanti et al., 1986; Gehrels et al., 2011; McQuarrie et al., 2013; Zhu et al., 2012a). 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 (Guo et al., 2015; Zhu et al., 2010, 2012b, 2013). 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.

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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).

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 locations of 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.

Fig. 3. Photomicrographs for the metasedimentary and orthogneisses samples collected from the Eastern Himalayas syntaxis 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.

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 $\varepsilon_{\text{Hf}}(t)$ 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.

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 $\epsilon_{\text{HF}}(t)$ 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.

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).

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.

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., 2011b, 2013; Turner et al., 2014; Yin et al., 2010b) and Lhasa terrane (Zhu et al., 2011; 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 Shillong Group) and South Lhasa terrane. The yellow band highlights the ~1.2 Ga age peak.

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.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

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-02-1 3-06-7 (n = 99)	AY-02-13 -06-9B (n = 105)	AY-02-1 3-06-8 (n = 111)	AY9160 314A (n = 81)	AY9170 315 (n = 84)	AY2461 2 (n = 31)	AY2044 18 (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.

Graphical abstract

Research highlights

- ▶ The Nyingchi Complex contain >499 Ma metasedimentary rocks.
- ▶ The metasedimentary rocks in the Namche Barwa Complex and Nyingchi Complex have common sources.
- ▶ The Namche Barwa Complex is the northeastern extension of the Greater Himalayan Sequence.
- ▶ The South Lhasa terrane was linked to the northern India prior to Cambrian.