

Late Devonian-Early Carboniferous magmatism in the Lhasa terrane and

its tectonic implications: Evidences from detrital zircons in the

Nyingchi Complex

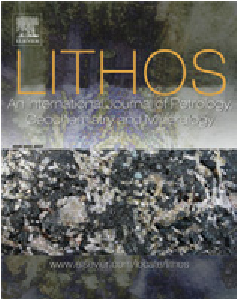
Lithos 245 (2016) 4

[7](http://dx.doi.org/10.1016/j.lithos.2015.06.018)

[–](http://dx.doi.org/10.1016/j.lithos.2015.06.018)

[5](http://dx.doi.org/10.1016/j.lithos.2015.06.018)

[9](http://dx.doi.org/10.1016/j.lithos.2015.06.018)



Contents lists available at

ScienceDirec

[t](http://www.sciencedirect.com/science/journal/00244937)

Lithos

journal homepage:

www.elsevier.com/locate/litho

[s](http://www.elsevier.com/locate/lithos)

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

a State Key Laboratory of Geological Processes and Mineral Resources and School of Earth Sciences, China University of Geosciences, Wuhan 430074, People’s Republic of China b Department of Environmental, Earth and Ecosystems, The Open University, Milton Keynes, MK7 6AA, UK c Ocean college, Zhejiang University, Hangzhou 310058, People’s Republic of China

|  |  |  |
| --- | --- | --- |
| a r t i c l e | i n f o | a b s t r a c t |

|  |  |
| --- | --- |
| Article history:  Received 26 March 2015  Accepted 29 June 2015 Available online 4 July 2015  Keywords:  Lhasa terrane  Detrital zircon  Zircon trace-element  Back-arc basin  Tectonic evolution | The Late Paleozoic tectonic evolution of the Lhasa terrane remains poorly understood due to the paucity of the Late Paleozoic magmatic rocks exposed at the surface. Detrital zircons in the sedimentary rocks can provide a record of magmatic rocks that have been eroded. Here we report detrital zircon U-Pb ages, trace-element and Hf isotopic data of metasedimentary rocks from the Nyingchi Complex in the eastern Himalayan syntaxis. Detrital zircons from the metasedimentary rocks yield major age populations of 330–364 Ma, 490–800 Ma, 1000–1200 Ma, and 1500–1800 Ma. The weighted mean ages of the youngest three detrital zircons indicate Carboniferous (~330 Ma) depositional age for their sedimentary protoliths. Provenance analysis indicates that the sedimentary detritus was sourced from the Lhasa terrane itself. The presence of abundant 330–364 Ma detrital zircons indicates that the Lhasa terrane was characterized by Late Devonian-Early Carboniferous magmatism. The trace-element compositions of the 330–364 Ma detrital zircons indicate that their magmatic host rocks mainly include mafic rocks and granitoids, and minor carbonatite. Some mafic host rocks probably formed in rift-related tectonic setting, and the others formed in arc-related tectonic settings. The granitic host rocks were S-type granites. The 330–391 Ma zircons have negative εHf(t) values (−19.3 to −2.5), suggesting that their magmatic host rocks resulted from partial melting of the enriched mantle or ancient crustal materials. Combined with previous studies, we propose that the Late Devonian-Early Carboniferous magmatic rocks in the Lhasa terrane probably formed in an arc-back-arc system which resulted from the southward subduction of the Paleo-Tethys oceanic crust. The back-arc basin developed as the Sumdo Paleo-Tethys ocean, which began to shrink as oceanic crust subducted northwards underneath the North Lhasa terrane during the Late Carboniferous-Permian and finally closed during the Triassic.  © 2015 Elsevier B.V. All rights reserved. |

# Introduction

The Himalayan–Tibetan Plateau is an amalgamation of individual terranes that detached from northern Gondwana and accreted onto southern Asia in a series of collision during Paleozoic and Cenozoic (Allègre et al., 1984; Dewey et al., 1988; Gehrels et al., 2011; Yin and Harrison, 2000; Zhu et al., 2013). The Lhasa terrane, bounded by the Bangong–Nujiang suture zone in the north and the Indus–Yarlung Tsangpo suture zone in the south (Fig. 1a), is generally considered to have rifted from the northern Gondwanaland in the Triassic or the Middle to Late Jurassic, and drifted northward across the Tethyan ocean before it collided with the Qiangtang terrane in Late Jurassic or Early Cretaceous (Dewey et al., 1988; Gehrels et al., 2011; Yin and Harrison,

|  |
| --- |
| ⁎ Corresponding author.  E-mail address: lguo@cug.edu.cn (L. Guo).  <http://dx.doi.org/10.1016/j.lithos.2015.06.018>0024-4937/© 2015 Elsevier B.V. All rights reserved. |

2000). Recent discoveries of the Permian–Triassic garnet glaucophane blueschist in Pana (Liu et al., 2009), the Permian MORB-type eclogite belt in Sumdo (Chen et al., 2008; Cheng et al., 2012; Li et al., 2009b; Yang et al., 2009; Zeng et al., 2009) and spatially associated Carboniferous ophiolite (Chen et al., 2009) indicate the presence of a Paleo-Tethys ocean between the South and North Lhasa terranes, although Metcalfe (2013) argue that the eclogite was a part of arc constructed on the Lhasa terrane. This Paleo-Tethys ocean has been termed the Sumdo Paleo-Tethys or North Gangdese Ocean (Xu et al., 2013b; Yang et al., 2009). Therefore, the Lhasa terrane has a complex tectonic evolution history (Metcalfe, 2013; Pan et al., 2012; Zhang et al., 2014; Zhu et al., 2013), which has attracted considerable attention of many geologists (e.g., Chen et al., 2008, 2009; Cheng et al., 2012; Dong et al., 2010b, 2011a, 2014; Geng et al., 2007a, 2007b, 2009; Ji et al., 2012; Li et al., 2009b; Lin et al., 2013b; Weller et al., 2015; Wu et al., 2013; Yang et al., 2009, 2014; Zeng et al., 2009; Zhang et al., 2011, 2014; Zhu et al., 2009, 2010, 2013). However, when and how the Sumdo

|  |
| --- |
| Fig. 1. (a) Tectonic framework of the Lhasa terrane (modified from Li et al., 2012; Yang et al., 2009; Zhu et al., 2011a), showing the location of this study area in the Eastern Himalayan syntaxis. The locations of the Sumdo eclogite belt (Chen et al., 2008; Cheng et al., 2012; Yang et al., 2009; Zeng et al., 2009), Late Devonian-Permian magmatic rocks in the Lhasa terrane (Dong et al., 2010b, 2014; Geng et al., 2007a, 2007b, 2009; Ji et al., 2012; Wang et al., 2008; Wu et al., 2013; Zhu et al., 2009, 2010, 2013), Qiangtang terrane (Jiang et al., 2015; Pullen et al., 2011; Zhu et al., 2013), Indus-Yarlung Tsangpo Suture zone (Dai et al., 2011), and Longmuco-Shuanghu suture zone (Zhai et al., 2013), Triassic medium pressure metamorphic rocks (Dong et al., 2011a; Lin et al., 2013b; Weller et al., 2015) and peraluminous granite belt (Li et al., 2012; Zhang et al., 2007) are also labeled. Abbreviations: IYTS = Indus-Yarlung Tsangpo Suture; NGS = Northern Gangdese Suture; BNS = Bangonghu-Nujiang Suture; LSS = Longmuco-Shuanghu Suture; JSS = Jinshajiang Suture. (b) Simplified geological map of the Eastern Himalayan syntaxis, showing the locations of the studied samples. The cross-section (A-B) is modified from Zhang et al. (2013). |

Paleo-Tethys ocean opened remains unclear. Hence, Late Paleozoic magmatism in the Lhasa terrane can provide an important constraint on its tectonic evolution. Although Late Devonian-Permian magmatic rocks in the Lhasa terrane have been reported (Dong et al., 2010b, 2014; Geng et al., 2007a, 2007b, 2009; Ji et al., 2012; Wang et al., 2008; Wu et al., 2013; Zhu et al., 2009, 2010), these studies on the Late Paleozoic magmatic rocks are too limited to fully explore their geodynamic setting.

Zircon is a robust mineral such that its trace-element and isotopic (e.g., U-Pb, Hf, and O isotopes) compositions can survive the geologic processes of erosion, transportation, diagenesis, metamorphism, and even crustal melting, and is commonly preserved in sedimentary rocks (Fedo et al., 2003). Detrital zircons can provide a cryptic record of magmatic rocks that may have been eroded away providing both geochemical insights from trace elements and isotopic compositions (e.g., Veevers, 2007; Veevers and Saeed, 2007; Veevers et al., 2006; Wu et al., 2010). The zircon trace-element and isotopic compositions can define broad categories of magmatic rocks from which the zircons crystallized, and therefore provide valuable petrogenetic information (e.g., Belousova et al., 2002; Hoskin and Ireland, 2000; Hoskin and Schaltegger, 2003; Nardi et al., 2013; Wang et al., 2012; Wilde et al., 2001). Previous studies have shown that the metasedimentary rocks from the Nyingchi Complex in the eastern South Lhasa terrane contain abundant Late Devonian-Early Carboniferous detrital zircons (Dong et al., 2010a; Guo et al., 2012; Zhang and Wu, 2012). Analysis of such detrital zircons provides a means by which tectono-thermal events that are otherwise absent from the lithological record may be reconstructed, and this information can be used to unravel details of the Late Paleozoic tectonic and geodynamic evolution of the Lhasa terrane in which their magmatic host rocks formed. This study integrates U-Pb geochronology, trace-element analyses, and Hf isotope analyses of detrital zircons and discusses the Late Devonian-Early Carboniferous evolution of the Lhasa terrane.

# Geological background

The Lhasa terrane can be divided into the South and North Lhasa terranes, separated by the Carboniferous–Permian North Gangdese suture zone (Fig. 1a), as represented by the Permian-Triassic garnet glaucophane blueschist in Pana (Liu et al., 2009), the Permian eclogite belt in Sumdo (Chen et al., 2008; Cheng et al., 2012; Li et al., 2009b; Yang et al., 2009; Zeng et al., 2009) and spatially associated Carboniferous ultramafic massifs (Chen et al., 2009). The geochemical features of the ultramafic rocks show that their protoliths were harzburgite. These ultramafic massifs may represent a dismembered ophiolite (Chen et al., 2009). The Sumdo eclogite belt extends over 100 km from east to west. The protoliths of the Sumdo eclogites show geochemical characteristics of N-MORB basalts (Yang et al., 2009; Zeng et al., 2009) or back-arc basin basalts (Cheng et al., 2012; Li et al., 2009b). They have protolith ages of 306–290 Ma (Cheng et al., 2012; Li et al., 2009b), indicating that the Sumdo Paleo-Tethyan ocean opened no later than ~306 Ma. The peak metamorphic P-T conditions of the Sumdo eclogite were estimated at 600–790 °C and 2.5-3.8 GPa based on the garnet-omphacite thermometry and garnet-omphacitephengite barometry, respectively (Cheng et al., 2012; Yang et al., 2009, 2014; Zhang et al., 2011). The peak metamorphic ages were estimated at 266–239 Ma (Chen et al., 2008; Cheng et al., 2012; Yang et al., 2009; Zeng et al., 2009), indicating that the Sumdo Paleo-Tethyan ocean began to close before ~266 Ma. In addition, a Triassic (225–200 Ma) medium pressure (0.6–0.9 GPa) amphibolite-facies metamorphic belt, which is typical of Barrovian-type metamorphism, was recognized from Yangbajing in the west to Basongco in the east between the South and North Lhasa terranes (Fig. 1a) (Dong et al., 2011a; Lin et al., 2013b; Weller et al., 2015; Zhang et al., 2014). This belt probably resulted from the closure of the Sumdo Paleo-Tethyan ocean and subsequent collision between the South and North Lhasa terranes (Dong et al., 2011a; Lin et al., 2013b; Weller et al., 2015; Zhang et al., 2014).

The North Lhasa terrane is underlain by ancient basement rocks that experienced multiple episodes of metamorphic overprinting and magmatism from the Neoproterozoic to Cenozoic times (Dong et al., 2011a, 2011b; Hu et al., 2005; Kapp et al., 2005; Xie et al., 2014; Xu et al., 1985; Zhang et al., 2012b, 2014). This basement is covered by the widespread Carboniferous-Permian and Late Jurassic-Early Cretaceous volcano-sedimentary rocks, and minor Ordovician-Devonian and Triassic limestones (Zhu et al., 2012a, 2013). The CarboniferousPermian strata unconformably overlie the Devonian and Precambrian rocks. The Carboniferous sediments represent deep-marine transgressive deposits, indicating a marginal rifting setting (Geng et al., 2007a, 2009). The Carboniferous-Permian volcanic and intrusive rocks are scattered along the southern margin of the North Lhasa terrane from Coqen County in the west to Ranwu Town in the east (Fig. 1a) (Geng et al., 2007a, 2007b, 2009; Wang et al., 2008; Zhu et al., 2009, 2010). The Carboniferous volcanic rocks include basalts, dacites, and rhyolites, forming a bimodal volcanic suite (Geng et al., 2007a). The basalts show geochemical characteristics of continental flood basalts and sourced from partial melting of enriched mantle, indicating that they formed in a rift setting (Geng et al., 2007a). Some Carboniferous basalts display geochemical characteristics of island-arc volcanic rocks (Wang et al., 2008). The Permian basalts exhibit a calc-alkaline, high-alumina basalt affinity, with significant negative Nb-Ta-Ti anomalies, indicating that they probably formed in an active continental margin arc system (Fig. 1a) (Geng et al., 2007b, 2009; Wang et al., 2008; Zhu et al., 2009, 2010). Abundant Triassic granites occur along the south margin of North Lhasa terrane from Coqen to Bome County (Li et al., 2009a, 2012; Zhang et al., 2007; Zhu et al., 2011b). These granites are peraluminous and have negative zircon εHf(t) values, indicating that they resulted from partial melting of ancient crustal materials in a syn- or post-collisional setting (Li et al., 2009a, 2012; Zhang et al., 2007). The Late Jurassic-Early Cretaceous magmatic rocks are widespread in the North Lhasa terrane, and may have resulted from the southward subduction of the Bangong-Nujiang Tethyan oceanic slab (Chen et al., 2014; Zhu et al., 2011b, and references therein).

The South Lhasa terrane is dominated by the Late Triassic-Cenozoic Gangdese batholith and Linzizong volcanic succession resulting from the northward subduction of the Neo-Tethyan oceanic crust beneath the Lhasa terrane (Chu et al., 2006; Coulon et al., 1986; Guo et al., 2011; Ji et al., 2009; Kang et al., 2014; Lee et al., 2009; Ma et al., 2013; Mo et al., 2008; Pan et al., 2014; Wen et al., 2008; Zhu et al., 2011b). A few Cambrian and Late Devonian-Early Carboniferous magmatic rocks have been reported in the Jiacha and Langxian areas in the eastern South Lhasa terrane (Fig. 1a) (Dong et al., 2010b, 2014; Ji et al., 2012; Wu et al., 2013). The Late Devonian-Early Carboniferous (371–345 Ma) magmatic rocks include granitic gneisses (Dong et al., 2010b, 2014; Ji et al., 2012; Wu et al., 2013) and amphibolites which had experienced amphibolite-facies metamorphism at ~105 Ma (Dong et al., 2014). The protoliths of the amphibolites, showing within-plate basalt affinities, originated form partial melting of the enriched mantle (Dong et al., 2014). The granitic gneisses are metaluminous or peraluminous, with zircon εHf(t) values of −8.6 to −0.8, suggesting that they were derived from partial melting of ancient continental crust (Dong et al., 2014; Ji et al., 2012; Wu et al., 2013).

In the eastern Himalayan syntaxis, the South Lhasa terrane is separated from the Namche Barwa Complex of northeastern Indian plate by the Yarlung-Tsangpo suture zone (Fig. 1b). The South Lhasa terrane consists of the high-grade metamorphic sequence (Nyingchi Complex), Carboniferous − Triassic strata and 165–22 Ma granitoids and mafic rocks (Booth et al., 2009; Burg et al., 1997; Dong et al., 2010a; Geng et al., 2006; Guo et al., 2011, 2013; Zhang et al., 2010a, 2013). The Nyingchi Complex is a tectonic mélange and mainly consists of schists, migmatite, orthogneisses, paragneisses and metasandstone, with minor quartzite, calc-silicate rocks, marble and granulite (Dong et al., 2010a; Guo et al., 2011, 2012, 2013; Lin et al., 2013a; Zhang et al., 2008, 2010b, 2013, 2015). Due to the lack of detailed geological and geochemical investigation, the age and origin of the protoliths of the metamorphic rocks from the Nyingchi Complex have not yet been well documented. The Nyingchi Complex was previously considered to be the Precambrian basement of the Lhasa terrane (Geng et al., 2006). However, the recent studies show that the orthogneisses from the Nyingchi Complex have protolith crystallization ages ranging from Paleoproterozoic (~1782 Ma) to Cambrian (~496 Ma) (Dong et al.,

2010a; Lin et al., 2013a), and the metasedimentary rocks from the Nyingchi Complex have maximum protolith depositional ages ranging from Paleozoic to Cenozoic (Dong et al., 2010a; Guo et al., 2012, 2013; Zhang and Wu, 2012; Zhang et al., 2008). The Nyingchi Complex underwent upper amphibolite-facies, locally to granulite-facies metamorphism during the Late Mesozoic to Cenozoic (Booth et al., 2009; Guo et al., 2012; Guo et al., 2013; Lin et al., 2013a; Zhang et al., 2010b).

# Analytical methods

3.1. Zircon U-Pb dating and trace-element analysis

Zircon grains were separated from the metasedimentary samples using heavy liquid and magnetic separation techniques. The grain selection was randomised in order to avoid the preference for large detrital zircon grains. All grain-size fractions (80–250 m) were selected during the analysis. Zircon cathodoluminescence (CL) images were used to check the internal structures of individual zircon grains and to guide U-Pb dating, trace-element and Hf isotope analysis. U-Pb dating and trace-element analysis 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 (GPMR), China University of Geosciences, Wuhan. Laser sampling was performed using a GeoLas 2005. An Agilent 7500a ICP-MS instrument was used to acquire ion-signal intensities. A beam diameter of 32 μm was used. Zircon 91500 was used as an external standard for correcting mass discrimination and isotope fractionation. NIST610 glass was analyzed as external standard for trace-element content calibration. Detailed operating conditions for the laser ablation system and the ICP-MS instrument and data reduction are as described by Hu et al. (2008) and 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 results of the zircon UPb dating and trace-element composition are given in the supplements as Tables A1 and A2, respectively. For statistical purposes, zircons with discordance b10% were accepted. We use 206Pb/238U ages for zircons b1000 Ma and 207Pb/206Pb ages for zircons N1000 Ma. The U-Pb concordia plots were processed using the ISOPLOT program of Ludwig (2003). The distributions of detrital zircon ages are visualized using the program of DensityPlotter version 4.3 based on kernel density estimation (Vermeesch, 2012).

3.2. Zircon Lu-Hf isotope

Zircon Lu-Hf isotope measurements were performed on the dated zircons using a Neptune Plus MC-ICP-MS in combination with a Geolas 2005 excimer ArF laser ablation system, at the state Key Laboratory of GPMR, China University of Geosciences, 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 176Lu and the chondritic ratios of 176Hf/177Hf and 176Lu/177Hf used in calculations are 1.865 × 10−11/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.

# Samples and analytical results

4.1. Metasedimentary rock samples

Three metasedimentary rock samples (T629, T630, and T772) were collected from the Nyingchi Complex in the eastern Himalayan syntaxis area (Fig. 1b). Sample T629 is a two-mica K-feldspar gneiss mainly consisting of quartz (85%), biotite (6%), muscovite (4%), and K-feldspar (5%) (Fig. 2a). The two-mica K-feldspar gneiss is intruded by the Middle Jurassic (~165 Ma) granitic gneiss (Guo et al., 2011). Sample T630 is a metasandstone mainly composed of quartz (96%), biotite (2%), and muscovite (2%) (Fig. 2b). Sample T772 is also a metasandstone mainly consisting of quartz (85%), plagioclase (13%), and biotite (2%) (Fig. 2c). Guo et al. (2012) reported the U-Pb ages and Hf isotopic composition of detrital zircons for the paragneiss sample T642 from the Nyingchi Complex (Fig. 1b). In this study, we report the trace-element compositions of the dated detrital zircons from this paragneiss.

4.2. Zircon U-Pb ages

Detrital zircon grains in the metasedimentary rock samples (T629, T630 and T772) from the Nyingchi Complex are rounded or subrounded in shape, and range from 80 to 250 μm in size (Fig. 3). Most zircons exhibit core-rim structures in the CL images (Fig. 3). The boundaries between the cores and rims are irregular or embayed, suggesting possible resorption and new growth (Fig. 3). The cores display oscillatory, sector, or no zoning (Fig. 3), indicating both magmatic and metamorphic origins (Corfu et al., 2003). The rims are narrow (most b20 μm) and exhibit planar or no zoning (Fig. 3), which is typical for metamorphic zircons (Corfu et al., 2003).

Ninety-seven analyses on ninety zircon grains from the two-mica K-feldspar gneiss (T629) were carried out, amongst which eighty-nine analyses are from the cores and eight analyses are from the metamorphic rims. Eighty-five core analyses are concordant or near-concordant (Fig. 4a), and yield U-Pb ages ranging from 162 Ma to 3305 Ma, with age populations of 310–377 Ma, 490–800 Ma, 1000–1200 Ma, 1500–1800 Ma, and 2550–2700 Ma (Fig. 4a). The youngest detrital zircon age is 162 ± 2 Ma (T629-58, 98% concordance, Table A1). The weighted mean age of the youngest three grains, that overlap in age at the 2σ level, is 325 ± 48 Ma (MSWD = 19). Eight analyses on the metamorphic rims have low Th/U ratios of 0.02-0.01, and yield 206Pb/238U ages of 71.0-48.4 Ma (Fig. 4b). The youngest seven analyses yield a weighted mean 206Pb/238U ages of 50.7 ± 1.2 Ma (MSWD = 1.00, Fig. 4b).

Eighty-seven analyses were undertaken on eighty-six zircon grains from the metasandstone (T630): eighty-six analyses on the cores and one analysis on the metamorphic rim. Eighty of the 86 analyses on the cores have concordant or near-concordant ages ranging from 330 Ma to 2443 Ma (Fig. 4c), with age population of 330–390 Ma, 1037–1172 Ma, 1409–1587 Ma, and 1650–1817 Ma (Fig. 4c). The youngest detrital zircon age is 330 ± 3 Ma (T630-43, 99% concordance, Table A1). The weighted mean age of the youngest three grains, that overlap in age at 2σ, is 333 ± 3 Ma (MSWD =

1.20). One analysis on the metamorphic rim yield a 206Pb/238U age of 53.4 ± 1.8 Ma (Fig. 4c, Table A1), which is identical within uncertainty to the metamorphic age of the two-mica K-feldspar gneiss (T629).

Ninety analyses were carried out on the cores of detrital zircons from the metasandstone (T772), in which eighty-seven analyses are concordant or near-concordant (Fig. 4d). They yield U-Pb ages of 234–2421 Ma, with age populations of 332–407 Ma, 1017–1243 Ma,

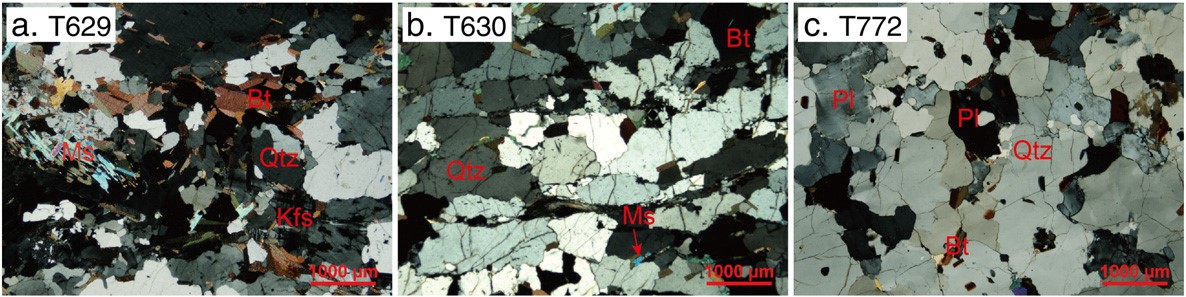
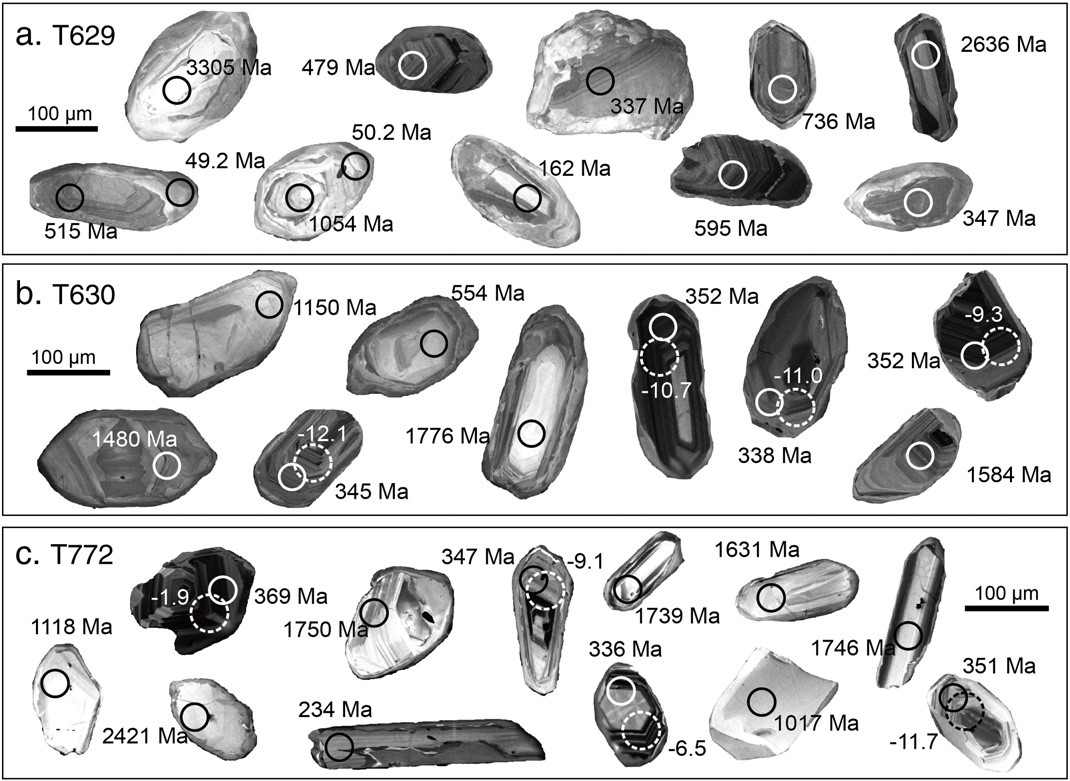


Fig. 2. Photomicrographs for the metasedimentary samples collected from the Nyingchi Complex in the eastern Himalayan syntaxis. (a) Two-mica K-feldspar gneiss T629; (b) Metasandstone T630; (c) Metasandstone T772. Mineral abbreviations: Bt = biotite; Kfs = K-feldspar; Ms = muscovite; Pl = plagioclase; Qtz = quartz.

Fig. 3. Typical zircon cathodoluminescence (CL) images for the studied samples. (a) Two-mica K-feldspar gneiss T629; (b) Metasandstone T630; (c) Metasandstone T772. 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.

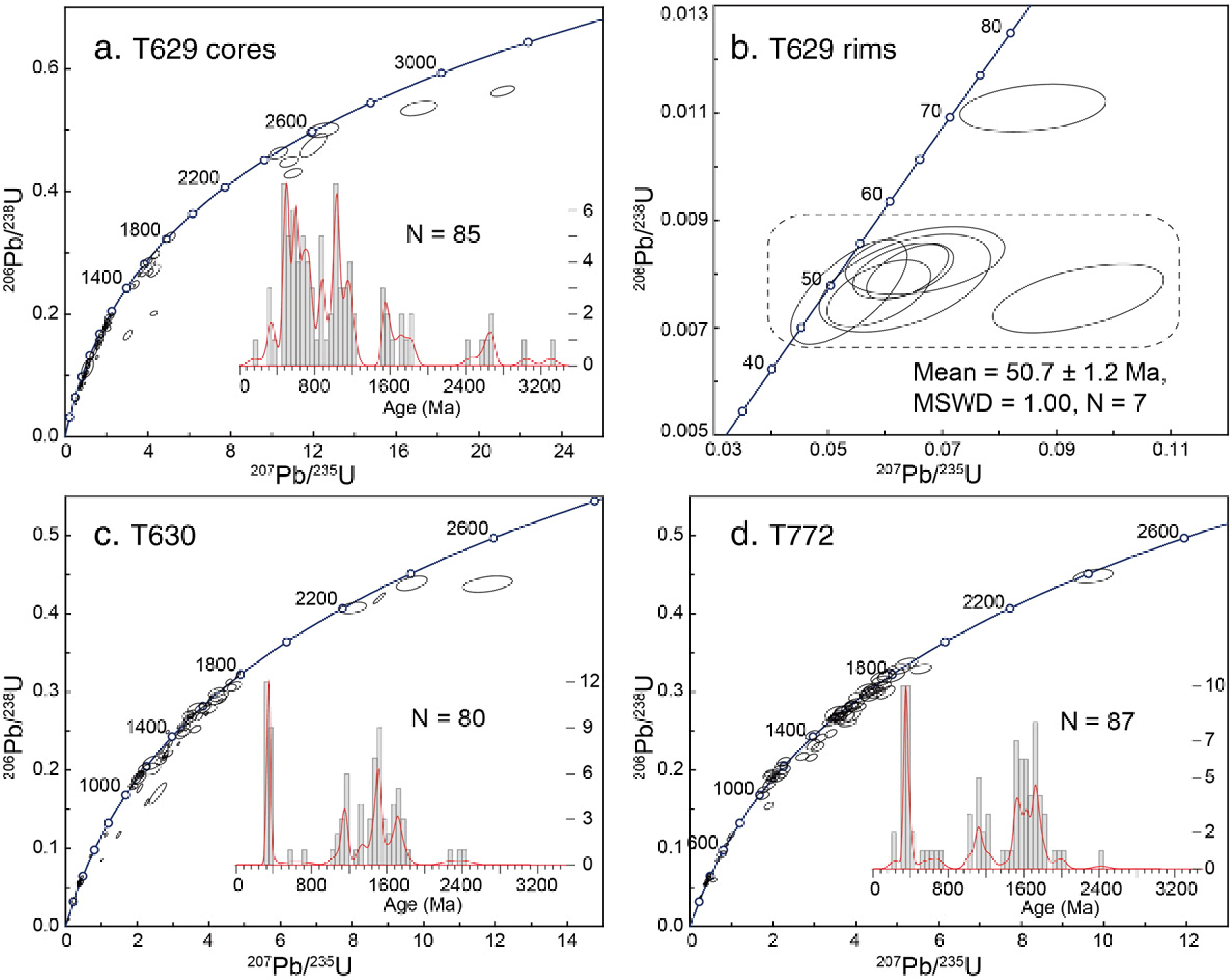


Fig. 4. Zircon U-Pb concordia diagrams (a-d) for the studied metasedimentary rocks. The insets show U-Pb age spectra plotted as histograms and kernel density estimation plots (Vermeesch, 2012).

and 1500–1831 Ma (Fig. 4d). The youngest detrital zircon age is 234 ± 3 Ma (T772-36, 97% concordance, Table A1). The weighted mean age of the youngest three grains, that overlap in age at 2σ, is 335 ± 4 Ma (MSWD = 0.20). Detrital zircons from the paragneiss (T642) have U-Pb ages ranging from 333 Ma to 2965 Ma, with age populations at 330–362 Ma, 440–625 Ma, 1057–1283 Ma, and 1500–1850 Ma

(Guo et al., 2012).

4.3. Zircon trace-element

Most cores of detrital zircons from the studied metasedimentary samples have high Th/U ratios (N0.10, Table A2), and show fractionated chondrite-normalized REE patterns with positive Ce anomalies and negative Eu anomalies (Fig. 5), indicating they are magmatic zircon (Hoskin and Schaltegger, 2003). Few cores have low Th/U ratios (b0.10) and LREE contents (Fig. 5, Table A2), indicating a metamorphic origin (Hoskin and Schaltegger, 2003). The metamorphic rims of detrital zircons from T629 and T630 have lower Th/U ratios (0.01-0.03) and LREE contents than those of the cores (Table A2, Fig. 5a and b).

Forty-two zircon grains with ages of 391–310 Ma have high Th/U ratios (0.13-2.82) and steep chondrite-normalized REE patterns with marked positive Ce anomalies and negative Eu anomalies (Fig. 5), typical of magmatic zircons (Hoskin and Schaltegger, 2003). The traceelement compositions of magmatic zircon can be used to recognise broad categories of magmatic rocks that represent the crystallized melts from which the zircons crystallized (Belousova et al., 2002). The 391–310 Ma zircons plot into the fields of granitoids, mafic rocks, carboniferous, syenite, and lamproites which tend overlap in the Y-U, Ce/Ce\*-Eu/Eu\*, Y-Yb/Sm, Y-Nb/Ta, Y-Ce/Ce, Nb-Ta, and Hf-Y bivariate discriminant diagrams (not shown) (Belousova et al., 2002). Classification and regression trees analysis was applied to classify each individual zircon grain in terms of its rock type more precisely (Belousova et al., 2002). Twenty-four grains were classified as mafic rocks (basalt and dolerite) and sixteen grains were classified as granitoids (b65% and 70-75% SiO2 granitoids, Table A2). Two grains were classified as carbonatite on the basis of the low Lu content (b20.7 ppm).

4.4. Zircon Hf isotope

A total of thirty-eight Hf isotopic analyses were carried out on the dated detrital zircons from the metasandstones T630 and T772 (Table A3). Thirty-six analyses were on the 391–330 Ma zircons, and the other two were on the ~1213 Ma and ~407 Ma zircons (spots T772-07 and T772-08). The ~1213 zircon yielded εHf(t) values of +5.9, and the ~407 Ma zircon yielded εHf(t) values of −9.0 (Table A3). Combined with results from a previous study (Guo et al., 2012), the 391–330 Ma zircons define a isotopic array that shifts towards progressively more negative εHf(t) values from 391 Ma to 330 Ma (Fig. 6). Except for spot T630-05 (~390 Ma), the 391–368 Ma detrital zircons have higher εHf(t) values (−6.8 to +2.5) than those of the 364–330 Ma (−19.3 to −6.5) (Fig. 6).

# Discussion

5.1. Depositional ages and metamorphic timing of the metasedimentary rocks

The maximum depositional ages of the metasedimentary rocks can be constrained by the youngest concordant detrital zircons, providing that their U–Pb system of the investigated zircons have not been disturbed during subsequent metamorphic events. The youngest concordant zircons in the metasedimentary rocks from the Nyingchi Complex in this study yielded ages of 162 ± 2 Ma for sample T629, 330 ± 3 Ma for sample T630, and 234 ± 3 Ma for sample T772

|  |
| --- |
| Fig. 5. The chondrite-normalized rare earth elements (REE) patterns of detritalzircons from the studied metasedimentary rocks. Chondrite normalization values from Sun and McDonough (1989). |

(Table A1). However, it is likely that the U–Pb system of grains T62958 and T772-36 were reset by a non-zero age Pb loss because the primary magmatic zoning of these grains are partially obliterated by the subsequent metamorphism (Fig. 3a and c). It is also possible that the core-rim interfaces were sampled for these analyses which would also lead to intermediate ages (Fig. 3a and c). Dickinson and Gehrels (2009) proposed that the mean age of the youngest three or more grains that overlap in age at 2σ provides an age that is the most consistently compatible with depositional age. The weighted mean ages of the

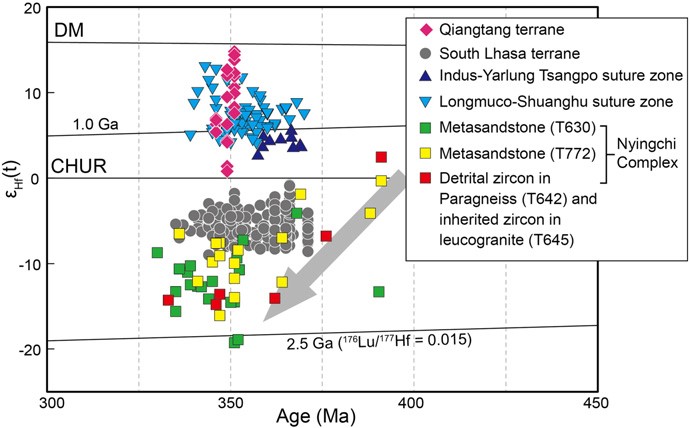


Fig. 6. Plots of εHf(t) values versus U-Pb ages of the 391–330 Ma detrital zircons from the metasedimentary rocks from Nyingchi Complex (Guo et al., 2012; this study). For comparison, the available Late Devonian-Early Carboniferous magmatic rocks from the Qiangtang terrane (Jiang et al., 2015), South Lhasa terrane (Dong et al., 2014; Ji et al., 2012; Wu et al., 2013), Indus-Yarlung Tsangpo suture zone (Dai et al., 2011), and Longmuco-Shuanghu suture zone (Zhai et al., 2013) are also plotted. CHUR = chondritic uniform reservoir; and DM = depleted mantle.

youngest three grains that overlap in age at 2σ from sample T629, T630, and T772 are 325 ± 48 Ma, 333 ± 3 Ma, and 335 ± 4 Ma, respectively. These weighted mean ages are identical within errors, suggesting that their protoliths probably were deposited during the Carboniferous (~330 Ma).

Detrital zircons in the metasedimentary rocks show core-rim structures (Fig. 3). The rims exhibit planar or no zoning, and have low Th/U ratios and LREE contents than those of cores (Fig. 5a and b), which are consistent with the characteristics of metamorphic zircon (Corfu et al., 2003; Hoskin and Schaltegger, 2003). They yielded metamorphic age of ~50 Ma (Fig. 4b, Table A1), which is compatible with the Eocene metamorphism and crustal anatexis in the Nyingchi Complex (Dong et al., 2010a; Guo et al., 2011, 2012; Zhang and Wu, 2012; Zhang et al., 2013).

5.2. Provenance of the metasedimentary rocks and its paleogeographic implication

Considerable debate surrounds the Paleozoic-Early Mesozoic paleogeographic position of the Lhasa terrane in the Eastern Gondwana. It is generally considered that both the Lhasa and Qiangtang terranes located on the northern margin of Indian plate (model I), with the Qiangtang terrane rifting during the Permian followed by the Lhasa terrane during the Late Triassic (Allègre et al., 1984; Burrett et al., 2014; Gehrels et al., 2011; Metcalfe, 2011; Yin and Harrison, 2000). However, competing studies have proposed that the Lhasa terrane was adjacent to Northwest Australia in the Late Precambrian-Devonian and Late Permian-Triassic periods (model II) (Audley-Charles, 1983, 1984; Ferrari et al., 2008; Zhu et al., 2011a, 2012b, 2013), and Zhu et al. (2010, 2013) proposed that the Lhasa terrane was an isolated microcontinent within the Paleo-Tethys ocean basin during the Carboniferous to Early Permian (model III). Detrital zircons from the metasedimentary rocks in the Nyingchi Complex define a distinctive age population of 390–330 Ma (Fig. 7a) (Dong et al., 2010a; Guo et al., 2012; Zhang and Wu, 2012; this study), that provides an important provenance indicator thus shedding light on the Late Paleozoic paleogeographic position of the Lhasa terrane.

According to the paleogeographic model I, the potential source for the Carboniferous sedimentary rocks in the Nyingchi Complex include the Indian plate and Qiangtang terrane. The Carboniferous-Permian and Jurassic strata of Tethyan Himalayan sequence formed as a passive margin sequence along the northern margin of India (Brookfield, 1993; Yin, 2006), and were mainly shed from India and Antarctica plates (Gehrels et al., 2011, and references therein). The absence of the 390–330 Ma detrital zircons in the Tethyan Himalayan sequence (Fig. 7b) (Aikman et al., 2008; Li et al., 2010; Webb et al., 2013; Zhu et al., 2011a, and references therein) excludes the possibility that the Indian plate was the provenance of the Carboniferous sedimentary rocks from the Nyingchi Complex. Although Upper Triassic strata from the Tethyan Himalayan sequence contain 390–330 Ma detrital zircons (Fig. 7b), the paleocurrent data and detrital zircon Hf isotopic composition indicate that they were derived from the Lhasa terrane (Li et al., 2010). Late Devonian-Early Carboniferous (364–346 Ma) magmatic rocks have been recognized in the Qiangtang terrane (Jiang et al., 2015; Pullen et al., 2011; Zhu et al., 2013). If the sediments were derived from the Qiangtang terrane, Carboniferous-Triassic strata from the Southern Qiangtang terrane should also contain 390–330 Ma zircons. However, this is not the case, and the 390–330 Ma age population is absent (Fig. 7c) (Gehrels et al., 2011, and references therein). In addition, the 364–346 Ma detrital zircons have negative εHf(t) values (Fig. 6) which is distinct from those of the zircons from the 351–349 Ma volcanic rocks in the Qiangtang terrane (Jiang et al., 2015). Therefore, the Qiangtang terrane provenance can be excluded. In the same way, although the Late Devonian-Carboniferous magmatic rocks were widespread in the Eastern Australia (e.g., Klootwijk, 2013; Murgulov et al., 2013), the absence of the 390–330 Ma detrital zircons in PermianTriassic strata from the West Australia (Fig. 7d) (Cawood and Nemchin, 2000; Lewis and Sircombe, 2013; Veevers et al., 2005) indicates that the Eastern Australia did not supply clastic materials to the Lhasa terrane during the Late Permian-Triassic periods on basis of the paleogeographic model II.

Dai et al. (2011) reported a ~364 Ma gabbro from the Indus-Yarlung Tsangpo suture zone (IYTSZ, Fig. 1a), and Zhai et al. (2013) reported 357–345 Ma gabbros and plagiogranites in the Longmuco-Shuanghu suture zone (LSSZ, Fig. 1a). It is unlikely that the 390–330 Ma detrital zircons in the Nyingchi Complex sourced from the IYTSZ or LSSZ, because (1) all the 390–330 Ma detrital zircons plot into the continental zircon field (Fig. 8) in the Hf-U/Yb and Y-U/Yb discriminant diagrams (Grimes et al., 2007); (2) they have negative εHf(t) values which is distinct from those of the zircons from the Late Devonian-Early Carboniferous gabbros and plagiogranites in the IYTSZ or LSSZ (Fig. 6) (Dai et al., 2011; Zhai et al., 2013).

Late Devonian-Early Carboniferous magmatic rocks have been reported from both the South and North Lhasa terranes (Fig. 1a). The 371–341 Ma granitic gneisses and amphibolites occur in Langxian and Jiacha areas in the eastern South Lhasa terrane (Fig. 1a) (Dong et al., 2010b, 2014; Ji et al., 2012; Wu et al., 2013). In addition, the Devonian-Carboniferous inherited zircons in the Gangdese batholith and associated volcanic rocks (Chu et al., 2011; Chung et al., 2009; Quidelleur et al., 1997; Wen et al., 2008; Zhu et al., 2011b), and detrital zircons in the modern river sediment (Zhang et al., 2012a) indicate that magmatic rocks of Late Devonian-Early Carboniferous age were widespread in the South Lhasa terrane (Ji et al., 2012). The Carboniferous volcanic rocks in the North Lhasa terrane were distributed from Shiquanhe in the west to Bome in the east (Fig. 1a) (Geng et al., 2007a; Wang et al., 2008). Moreover, the Triassic Mailonggang Formation sandstones from the North Lhasa terrane contain abundant 380–330 Ma detrital zircons (Fig. 7e) (Li et al., 2014). The petrographic study show that the sandstones are poorly sorted with mostly angular to subangular shapes, indicating low maturity and relatively proximal provenance (Li et al., 2014). The detrital heavy mineral assemblage (zircon, apatite, tourmaline, rutile, anatase, leucoxene, magnetite, and limonite) in the sandstones indicates an orogenic provenance. Detrital zircon U-Pb ages and Hf isotopic compositions are consistent with derivation of these rocks from nearby Triassic magmatic rocks and basements in the Late PermianTriassic Sumdo-Cuoqin orogenic belt within the Lhasa terrane (Li et al., 2014). We therefore propose that the most likely provenance for the 390–330 Ma detrital zircons from the metasedimentary rocks in the Nyingchi Complex is the Lhasa terrane itself (South and North

|  |
| --- |
| Fig. 7. Detrital zircon U-Pb age kernel density estimation plots for (a) Neoproterozoic and Late Paleozoic strata from the Nyingchi Complex in the South Lhasa terrane (Dong et al., 2010a; Guo et al., 2012; Zhang and Wu, 2012; Zhang et al.,2008; this study and our unpublished data); (b) Carboniferous-Jurassic strata from the Tethys HimalayanSequence (Aikman et al., 2008; Gehrels et al., 2011, and references therein; Li et al., 2010; Webb et al., 2013; Zhu et al., 2011a); (c) Carboniderous-Triassic strata from South Qiangtang terrane (Gehrels et al., 2011, and references therein); (d) Permian-Triassic strata from Western Australia (Cawood and Nemchin, 2000; Veevers et al., 2005); and (e) Carboniferous-Jurassic strata from the North Lhasa terrane (Gehrels et al., 2011, and references therein; Li et al., 2014; Zhu et al., 2011a). The gray band highlights the 390–330 Ma age population. |

Lhasa terranes). This speculation is supported by some of the 390–330 Ma detrital zircons having Hf isotopic composition similar to those of the zircons from the Late Devonian-Early Carboniferous magmatic rocks in the eastern South Lhasa terrane (Fig. 6) (Dong

et al., 2014; Ji et al., 2012; Wu et al., 2013). The discrepancies of detrital zircon age spectra for Carboniferous-Triassic strata between the Lhasa terrane and other terranes (Tethyan Himalaya of northern

|  |
| --- |
| Fig. 8. Zircon U/Yb-Hf and U/Yb-Y diagrams. Fields for continental and oceanic zircon are from Grimes et al. (2007). |

India, West Australia, and Southern Qiangtang terrane) indicate that

these terranes were not tectonically linked during CarboniferousTriassic. This speculation is consistent with the suggestion that the Lhasa terrane was an isolated microcontinent (model III) within the Paleo-Tethys ocean during Late Paleozoic time (Zhu et al., 2010, 2013).

The older detrital zircon age populations of 490–800 Ma, 1000–1200 Ma, and 1500–1800 Ma from the metasedimentary rocks in the Nyingchi Complex probably sourced from the Early Paleozoic (Dong et al., 2010a; Zhu et al., 2012a), Neoproterozoic (Hu et al., 2005), Mesoproterozoic (Xu et al., 2013a), and Paleoproterozoic (Lin et al., 2013a) magmatic rocks in the Lhasa terrane. In addition, these older detrital zircons have similar age spectra to those of detrital zircons in Neoproterozoic-Early Paleozoic strata from the South and North Lhasa terranes (Fig. 7a and e). Therefore, they also probably recycled from Neoproterozoic-Early Paleozoic sedimentary rocks (Gehrels et al., 2011; Zhu et al., 2011a; Our unpublished data).

5.3. Late Devonian-Early Carboniferous magmatism in the Lhasa terrane

As discussed above, the 390–330 Ma detrital zircons in the Nyingchi Complex are inferred to have been derived from the Lhasa terrane, suggesting that the Lhasa terrane was characterized by Late Devonian-Early Carboniferous magmatism. Although the Late Devonian-Early Carboniferous magmatic rocks have been reported in the Lhasa terrane (Dong et al., 2014; Geng et al., 2007a; Ji et al., 2012; Wang et al., 2008, 2013; Wu et al., 2013), their petrogenesis and tectonic-setting remain unclear. The trace-element composition of magmatic zircon is sensitive to the composition of its magmatic host rock and crystallization environment (e.g., Belousova et al., 2002; Grimes et al., 2007; Hoskin and Ireland, 2000; Hoskin and Schaltegger, 2003; Nardi et al., 2013; Schulz et al., 2006; Wang et al., 2012). The trace-element composition of magmatic zircons has been used to identify the petrogenesis of their host rocks (e.g., I-, S-, and A-type granites) (Breiter et al., 2014; Nardi et al., 2013; Wang et al., 2012), and can provide insights into the tectonic setting in which their magmatic host rocks formed (Grimes et al., 2007; Schulz et al., 2006). Therefore, the trace-element composition of the 390–330 Ma detrital magmatic zircons in the Nyingchi Complex provides a means to unravel the tectonic setting of the Late DevonianEarly Carboniferous magmatism in the Lhasa terrane.

The trace-element compositions of the 390–330 Ma detrital zircons indicate that they were derived from mafic rocks, granitoids and minor carbonatites (Belousova et al., 2002). The trace-element compositions of zircons from mafic rocks can discriminate between N-MORB-, volcanic-arc basalt (VAB)-, or within-plate-basalt (WPA)type host rocks (Schulz et al., 2006). On the basis of trace-element discriminant diagrams (Schulz et al., 2006), detrital zircons derived from mafic rocks can be divided into older (391–377 Ma) and younger (364–332 Ma) groupings. Detrital zircons of the older group plot into the VAB-type mafic rocks field (Fig. 9), indicating that their magmatic host rocks formed in a volcanic arc-related setting in Middle-Late Devonian. Detrital zircons of the younger group plot into the VAB- and WPAtype mafic rocks fields (Fig. 9), suggesting that their magmatic host rocks were produced within the volcanic arc and within-plate settings during Late Devonian-Early Carboniferous. No zircons plot into the MORB-type rock field (Fig. 9), which is consistent with the results based on the Hf-U/Yb and Y-U/Yb discriminant diagrams (Fig. 8) (Grimes et al., 2007). Detrital zircons derived from granitoids mainly plot in the S-type granitoids field (Fig. 10) based on the Pb-Th and

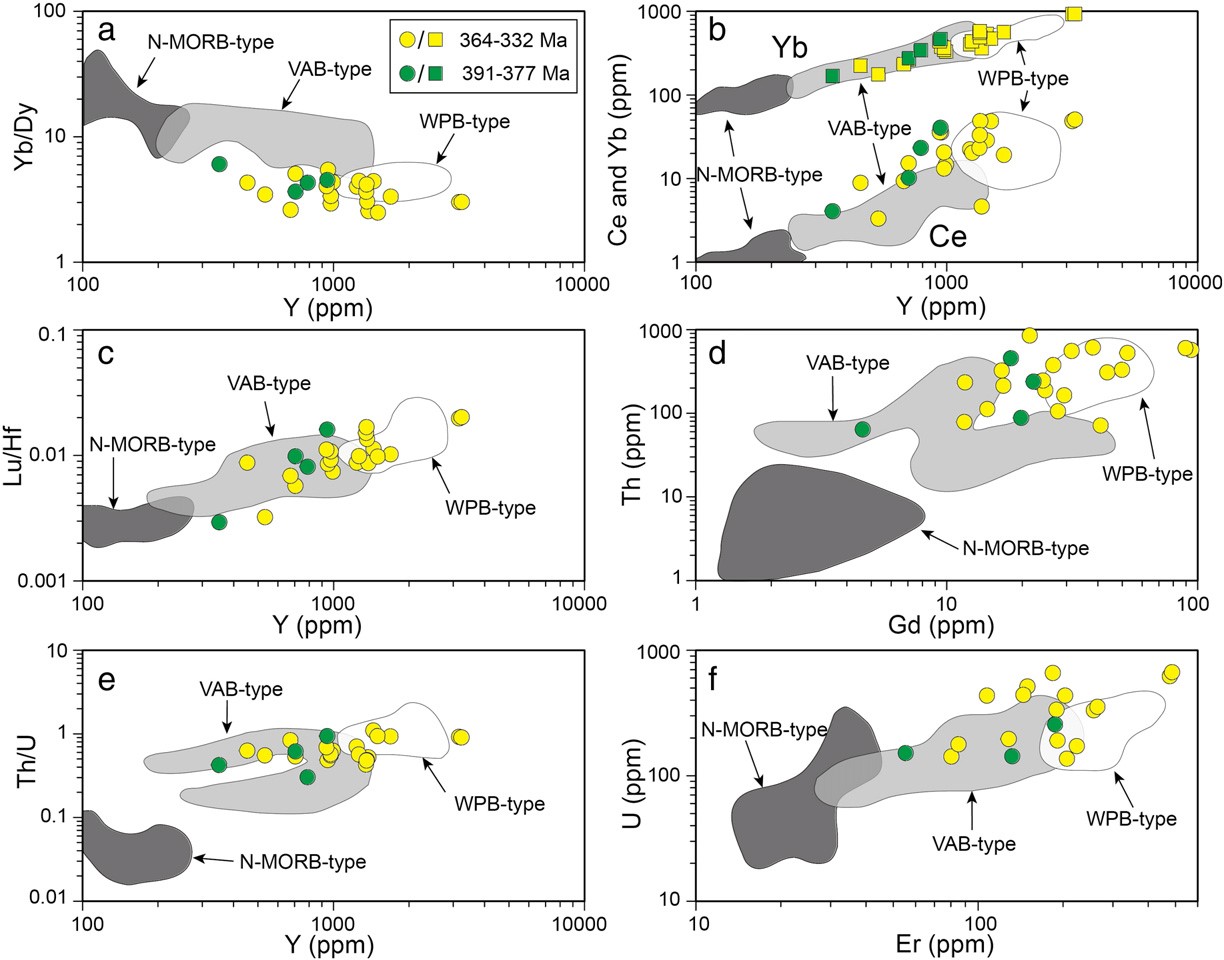


Fig. 9. Tectonic setting discrimination diagrams using the trace-element composition of zircons from mafic rocks (Schulz et al., 2006). Twenty-four 391–332 Ma detrital zircon grains whose magmatic host rocks were mafic rocks (dolerite and basalt) (Belousova et al., 2002) were plotted.

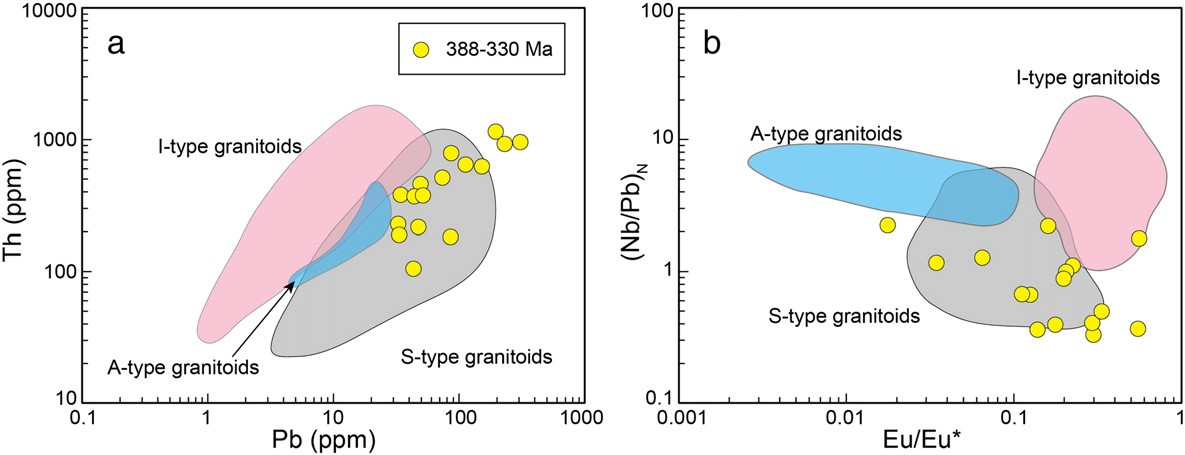


Fig. 10. (a) Th-Pb and (b) (Nb/Pb)N-Eu/Eu\* diagrams for sixteen 388–330 Ma detrital zircon grains whose magmatic host rocks were granitoids. Fields of I-, S-, and A-type granites are from

Wang et al. (2012).

Eu/Eu\*-(Nb/Pb)N discriminant diagrams (Wang et al., 2012). The 391–368 Ma detrital zircons have higher εHf(t) values than those of the 364–330 Ma detrital zircons (Fig. 6), indicating that their magmatic host rocks sourced from partial melting of the depleted mantle or juvenile crustal materials, consistent with an arc-related setting. The 364–330 Ma detrital zircons have negative εHf(t) values (Fig. 6), indicating that their magmatic host rocks probably resulted from partial melting of the enriched mantle, or their original magma involving a significant component of ancient crustal materials.

These results show that the volcanic-arc magmatism, rifting-related magmatism, and crustal anatexis coexisted in the Lhasa terrane during the Late Devonian-Early Carboniferous. This is consistent with previous studies of the Late Devonian-Carboniferous magmatic rocks (Dong et al., 2014; Geng et al., 2007a; Ji et al., 2012; Wang et al., 2008; Wu et al., 2013). Wang et al. (2008) reported the Carboniferous arc volcanic rocks in the North Lhasa terrane, which resulted from southward subduction of the Paleo-Tethys oceanic crust. Geng et al. (2007a) found that some Carboniferous basalts in the North Lhasa terrane have similar geochemical characteristics to those of continental flood basalts, and proposed that they formed in a rift setting. These basalts have markedly negative εNd(t) values (as low as −12), indicating that they were derived from partial melting of enriched mantle (Geng et al., 2007a). The 371–341 Ma magmatic rocks from the South Lhasa terrane form bimodal magmatic associations (Dong et al., 2014; Ji et al., 2012; Wu et al., 2013). The mafic rocks show geochemical signatures of within-plate basalts and have negative zircon εHf(t) values (Fig. 6), indicating that their magmas originated from an enriched mantle (Dong et al., 2014). The felsic rocks include metaluminous and peraluminous granitoids (Dong et al., 2014; Ji et al., 2012; Wu et al., 2013). All the granitoids have negative εHf(t) values (Fig. 6), suggesting that they resulted from partial melting of ancient crustal materials (Dong et al., 2014; Ji et al., 2012; Wu et al., 2013). In summary, the arc volcanic rocks are mainly distributed in the North Lhasa terrane (Wang et al., 2008). The riftingrelated magmatic rocks occurred across both the South and North Lhasa terrane (Dong et al., 2014; Geng et al., 2007a; Ji et al., 2012; Wu et al., 2013).

5.4. Tectonic implications

The discoveries of the Permian Sumdo eclogite belt and of spatially associated Carboniferous ophiolite indicate that the Lhasa terrane can be divided into the South and North Lhasa terranes, separating by the Sumdo Paleo-Tethys ocean (Chen et al., 2008, 2009; Cheng et al., 2012; Li et al., 2009b; Yang et al., 2009; Zeng et al., 2009). When and how the Sumdo Paleo-Tethys ocean opened and how it evolved remain unclear. The coeval occurrences of the Late Devonian-Early Carboniferous volcanic-arc magmatism, riftingrelated magmatism, and crustal anatexis in the Lhasa terrane indicate that these tectono-thermal events probably formed in an arc-back-arc system. This speculation is supported by following studies: (1) Carboniferous sediments in the North Lhasa terrane unconformably overlie the Devonian and Precambrian rocks and represent deep-marine transgressive deposits, indicating a marginal rifting setting (Geng et al., 2007a, 2009); (2) Geng et al. (2007a) and Dong et al. (2014) considered that the Carboniferous bimodal magmatic associations in the North and South Lhasa terranes formed in the back-arc extensional setting; (3) Ji et al. (2012) and Wu et al. (2013) proposed that the Early Carboniferous granitoids from Langxian and Jiacha areas in the South Lhasa terrane were derived from reworking of ancient basement in a back-arc extensional setting associated with outboard subduction; (4) The protoliths of the Sumdo eclogites exhibit geochemical characteristics of back-arc basin basalt (Cheng et al., 2012; Li et al., 2009b). Therefore, we considered that the Sumdo Paleo-Tethys ocean developed from this back-arc basin in Late Devonian-Early Carboniferous.

Cheng et al. (2012) suggested that opening of the Sumdo back-arc basin was related to the northward subduction of the Paleo-Tethys oceanic crust beneath the South Lhasa terrane. However, the DevonianCarboniferous arc magmatism is absent in South Lhasa terrane. The North Lhasa terrane contains the Carboniferous arc magmatic rocks (Wang et al., 2008) and bimodal volcanic rocks (Geng et al., 2007a). Therefore, this arc-back-arc system probably was related to the southward subduction Paleo-Tethys oceanic crust (Fig. 11a) (Zhu et al., 2013). The roll-back of oceanic slab would have caused the upwelling of asthenosphere and back-arc rifting, which resulted in the Late Devonian-Early Carboniferous bimodal magmatism both in the South and North Lhasa terranes (Fig. 11b). This back-arc basin subsequently evolved into a mature ocean (Sumdo Paleo-Tethys ocean) before the Early Permian (Fig. 11c), as indicated by the ~303 Ma MORB-type eclogite (Yang et al., 2009; Zeng et al., 2009). The Sumdo Paleo-Tethys ocean began to close no later than ~265 Ma (Chen et al., 2008; Cheng et al., 2012; Yang et al., 2009). The northward subduction of the Sumdo Paleo-Tethys oceanic crust resulted in the Permian arc magmatism in the North Lhasa terrane (Geng et al., 2007b, 2009; Wang et al., 2008; Zhu et al., 2009, 2010) and the ultrahigh-pressure metamorphism of the oceanic slab (Fig. 11d) (Chen et al., 2008; Cheng et al., 2012; Li et al., 2009b; Yang et al., 2009; Zeng et al., 2009). The final closure of the Sumdo Paleo-Tethys ocean probably occurred during the Late Triassic (Fig. 11e). The collision between South and North Lhasa terranes led to the Triassic high-grade metamorphism (Dong et al., 2011a; Lin et al., 2013b; Weller et al., 2015; Zhang et al., 2014) and widespread crustal anatexis (Li et al., 2009a, 2012; Zhang et al., 2007; Zhu et al., 2011b).

|  |
| --- |
| Fig. 11. Late Paleozoic-Early Mesozoic tectonic model for the Lhasa terrane. Details are in Section 5.4. |

# Conclusions

Detrital zircons from the metasedimentary rocks in the Nyingchi Complex in the eastern South Lhasa terrane define four age populations of 330–364 Ma, 490–800 Ma, 1000–1200 Ma, and 1500–1800 Ma. The weighted mean ages of the youngest three detrital zircons indicate Carboniferous (~330 Ma) depositional age for their sedimentary protoliths. The protoliths of the metasedimentary rocks were derived from the Lhasa terrane itself (South and North Lhasa terranes). The presence of abundant 330–364 Ma detrital zircons indicates that the Lhasa terrane was characterized by Late Devonian-Early Carboniferous magmatism. The zircon trace-element signature and Hf isotopic composition indicate that the magmatic host rocks of the 364–330 Ma detrital zircons formed in an arc-back-arc system, which resulted from the southward subduction of the Paleo-Tethys oceanic crust during Late Devonian-Early Carboniferous. This back-arc basin subsequently developed into the Sumdo Paleo-Tethys ocean.

Supplementary data to this article can be found online at [http://dx.](http://dx.doi.org/10.1016/j.lithos.2015.06.018)

[doi.org/10.1016/j.lithos.2015.06.018.](http://dx.doi.org/10.1016/j.lithos.2015.06.018)

# Acknowledgments

This research is supported by the Natural Science Foundation of China (grants: 41073046 and 41303023), and SinoProb 04–02 (2101105). We thank Prof. Di-Cheng Zhu for the comments and editorial handling. We thank Dr. Elena Belousova, Dr. Inga Sevastjanova, and another anonymous reviewer for their constructive comments that greatly improved the manuscript. We also thank Dr. Zhao-Chu Hu for LA-ICP-MS zircon U-Pb dating and LA-MC-ICP-MS zircon Hf isotopic analyses.

# References

Aikman, A.B., Harrison, T.M., Lin, D., 2008. [Evidence for early](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0005) [(N44](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0005) [Ma) Himalayan crustal thickening, tethyan Himalaya, southeastern Tibet. Earth and Planetary Science Letters 274, 14–23.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0005)

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/S0024-4937(15)00227-3/rf0010).

Audley-Charles, M.G., 1983. [Reconstruction of eastern Gondwanaland. Nature 306, 48–50](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0015). Audley-Charles, M.G., 1984. [Cold Gondwana, warm Tethys and the Tibetan Lhasa block. Nature 310 (165-165)](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0020).

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/S0024-4937(15)00227-3/rf0025).

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/S0024-4937(15)00227-3/rf0030).

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.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0035) [Geological Society of America Bulletin 121, 385–407](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0035).

Breiter, K., Lamarao, C.N., Borges, R.M.K., Dall'Agnol, R., 2014. [Chemical characteristics of zircon from A-type granites and comparison to zircon of S-type granites. Lithos 192, 208–225](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0040).

Brookfield, M.E., 1993. [The Himalayan passive margin from Precambrian to cretaceous times. Sedimentary Geology 84,](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0045) [1–35.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0045)

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/S0024-4937(15)00227-3/rf0050)

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/S0024-4937(15)00227-3/rf0055) [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/S0024-4937(15)00227-3/rf0055)

Cawood, P.A., Nemchin, A.A., 2000. [Provenance record of a rift basin: U/Pb ages of detrital zircons from the Perth Basin, Western Australia. Sedimentary Geology 134, 209–234.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0060)

Chen, S.Y., Yang, J.S., Xu, X.Z., Li, H.Q., Yang, Y.H., 2008. [Study of Lu-Hf geochemical tracing and LA-ICPMS U-Pb isotopic dating of the Sumdo eclogite from the Lhasa block, Tibet. Acta Petrologica Sinica 1528–1538](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0070).

Chen, S.Y., Yang, J.S., Li, Y., Xu, X.Z., 2009. [Ultramafic blocks in Sumdo Region, Lhasa Block, Eastern Tibet Plateau: An ophiolite unit. Journal of Earth Science 20, 332–347](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0065).

Chen, Y., Zhu, D.-C., Zhao, Z.-D., Meng, F.-Y., Wang, Q., Santosh, M., Wang, L.-Q., Dong, G.-C., Mo, X.-X., 2014. [Slab breakoff triggered ca. 113 Ma magmatism around Xainza area of the Lhasa Terrane, Tibet. Gondwana Research 26, 449–463](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0075).

Cheng, H., Zhang, C., Vervoort, J.D., Lu, H., Wang, C., Cao, D., 2012. [Zircon](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0080) [U–Pb and garnet Lu–Hf geochronology of eclogites from the Lhasa Block, Tibet. Lithos 155, 341–359.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0080)

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 U-Pb and Hf isotope constraints on the Mesozoic tectonics and crustal evolution of southern Tibet. Geology 34, 745–748.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0090)

Chu, M.-F., Chung, S.-L., O'Reilly, S.Y., Pearson, N.J., Wu, F.-Y., Li, X.-H., Liu, D., Ji, J., Chu, C.-H., Lee, H.-Y., 2011. [India's hidden inputs to Tibetan orogeny revealed by Hf isotopes of Transhimalayan zircons and host rocks. Earth and Planetary Science Letters 307, 479–486](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0085).

Chung, S.L., Chu, M.F., Ji, J.Q., O'Reilly, S.Y., Pearson, N.J., Liu, D.Y., Lee, T.Y., Lo, C.H., 2009. [The nature and timing of crustal thickening in Southern Tibet: Geochemical and zircon Hf isotopic constraints from postcollisional adakites. Tectonophysics 477, 36–48.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0095)

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/S0024-4937(15)00227-3/rf0100)

Coulon, C., Maluski, H., Bollinger, C., Wang, S., 1986. [Mesozoic and Cenozoic volcanic rocks from central and southern Tibet:](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0105) [39Ar-40Ar dating, petrological characteristics and geodynamical significance. Earth and Planetary Science Letters 79, 281–302.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0105)

Dai, J., Wang, C., Hébert, R., Li, Y., Zhong, H., Guillaume, R., Bezard, R., Wei, Y., 2011. [Late Devonian OIB alkaline gabbro in the Yarlung Zangbo Suture Zone: Remnants of the Paleo-Tethys? Gondwana Research 19, 232–243.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0110)

Dewey, J.F., Shackleton, R.M., Chengfa, C., Yiyin, S., 1988. [The tectonic evolution of the Tibetan plateau. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences 327, 379–413](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0115).

Dickinson, W.R., Gehrels, G.E., 2009. [Use of 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/S0024-4937(15)00227-3/rf0120).

Dong, X., Zhang, Z., Santosh, M., 2010a. [Zircon U-Pb chronology of the Nyingtri group, southern Lhasa terrane, Tibetan plateau: implications for grenvillian and PanAfrican provenance and Mesozoic-Cenozoic metamorphism. Journal of Geology 118, 677–690.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0135)

Dong, X., Zhang, Z.M., Geng, G.S., Liu, F., Wang, W., Yu, F., 2010b. [Devonian magmatism from the southern Lhasa terrane, Tibetan Plateau. Acta Petrologica Sinica 26, 2226–2232.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0145)

Dong, X., Zhang, Z., Liu, F., Wang, W., Yu, F., Shen, K., 2011a. [Zircon U-Pb geochronology of the Nyainqentanglha Group from the Lhasa terrane: New constraints on the Triassic orogeny of the south Tibet. Journal of Asian Earth Sciences 42, 732–739.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0130)

Dong, X., Zhang, Z., Santosh, M., Wang, W., Yu, F., Liu, F., 2011b. [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/S0024-4937(15)00227-3/rf0140).

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/S0024-4937(15)00227-3/rf0125)

Fedo, C.M., Sircombe, K.N., Rainbird, R.H., 2003. [Detrital zircon analysis of the sedimentary record. Reviews in Mineralogy and Geochemistry 53, 277–303.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0150)

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/S0024-4937(15)00227-3/rf0155).

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/S0024-4937(15)00227-3/rf0160).

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/S0024-4937(15)00227-3/rf0170)

Geng, Q., Wang, L., Pan, G., Jin, Z., Zhu, D., Liao, Z., Li, G., Li, F., 2007a. [Carboniferous marginal rifting in Gangdese: volcanic rocks and stratigraphic constraints, Xizang (Tibet), Chia. Acta Geologica Sinica 81, 1259–1276](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0165).

Geng, Q.R., Wang, L.Q., Pan, G.T., Jin, Z.M., Zhu, D.C., Liao, Z.L., Li, G.M., Li, F.Q., 2007b. [Volcanic rock geochemistry and tectonic implication of the Luobadui Formation on the Gangdese zone, Xizang (Tibet). Acta Petrologica Sinica 23, 2699–2714.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0180)

Geng, Q.R., Sun, Z.M., Pan, G.T., Zhu, D.C., Wang, L.Q., 2009. [Origin of the Gangdise (Transhimalaya) Permian arc in southern Tibet: Stratigraphic and volcanic geochemical constraints. Island Arc 18, 467–487.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0175)

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/S0024-4937(15)00227-3/rf0185)

Grimes, C.B., John, B.E., Kelemen, P.B., Mazdab, F.K., Wooden, J.L., Cheadle, M.J., Hanghoj, K., Schwartz, J.J., 2007. [Trace element chemistry of zircons from oceanic crust:](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0190) [A method for distinguishing detrital zircon provenance. Geology 35, 643–646](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0190).

Guo, L., Zhang, H.-F., Harris, N., Pan, F.-B., Xu, W.-C., 2011. [Origin and evolution of multistage felsic melts in eastern Gangdese belt: Constraints from](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0195) [U–Pb zircon dating and Hf isotopic composition. Lithos 127, 54–67.](http://refhub.elsevier.com/S0024-4937(15)00227-3/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/S0024-4937(15)00227-3/rf0205) [U–Pb zircon ages and Hf isotopic compositions of the Nyingchi Complex. Gondwana Research 21, 100–111.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0205)

Guo, L., Zhang, H.-F., Harris, N., Pan, F.-B., Xu, W.-C., 2013. [Late Cretaceous (~81](http://refhub.elsevier.com/S0024-4937(15)00227-3/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/S0024-4937(15)00227-3/rf0200)

Hoskin, P.W.O., Ireland, T.R., 2000. [Rare earth element chemistry of zircon and its use as](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0210) [a provenance indicator. Geology 28, 627–630.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0210)

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/S0024-4937(15)00227-3/rf0215)

Hu, D.G., Wu, Z.H., Jiang, W., Shi, Y.R., Ye, P.S., Liu, Q.S., 2005. [SHRIMP zircon 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/S0024-4937(15)00227-3/rf0220)

Hu, Z.C., Gao, S., Liu, Y.S., Hu, S.H., Chen, H.H., Yuan, H.L., 2008. [Signal enhancement in laser ablation ICP-MS by addition of nitrogen in the central channel gas. Journal of Analytical Atomic Spectrometry 23, 1093–1101](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0225).

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/S0024-4937(15)00227-3/rf0230).

Ji, W.Q., Wu, F.Y., Chung, S.L., Li, J.X., Liu, C.Z., 2009. [Zircon U-Pb geochronology and Hf isotopic constraints on petrogenesis of the Gangdese batholith, southern Tibet. Chemical Geology 262, 229–245](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0240).

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 paleotethyan evolution. Journal of Geology 120, 531–541](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0235).

Jiang, Q.-y., Li, C., Su, L., Hu, P.-y., Xie, C.-m., Wu, H., 2015. [Carboniferous arc magmatism in the Qiangtang area, northern Tibet: Zircon](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0585) [U–Pb ages, geochemical and Lu–Hf isotopic characteristics, and tectonic implications. Journal of Asian Earth Sciences 100, 132–144.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0585)

Kang, Z.-Q., Xu, J.-F., Wilde, S.A., Feng, Z.-H., Chen, J.-L., Wang, B.-D., Fu, W.-C., Pan, H.-B., 2014. [Geochronology and geochemistry of the Sangri Group Volcanic Rocks, Southern Lhasa Terrane: Implications for the early subduction history of the Neo-Tethys and Gangdese Magmatic Arc. Lithos 200–201, 157–168.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0245)

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/S0024-4937(15)00227-3/rf0250)

Klootwijk, C., 2013. [Middle-Late Paleozoic Australia-Asia convergence and tectonic extrusion of Australia. Gondwana Research 24,](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0255) [5–54.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0255)

Lee, H.Y., Chung, S.L., Lo, C.H., Ji, J.Q., Lee, T.Y., Qian, Q., Zhang, Q., 2009. [Eocene Neotethyan slab breakoff in southern Tibet inferred from the Linzizong volcanic record. Tectonophysics 477, 20–35.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0260)

Lewis, C.J., Sircombe, K.N., 2013. [Use of U-Pb geochronology to delineate provenance of North West Shelf sediments, Australia. In: Keep, M., Moss, S.J. (Eds.), The Sedimentary Basins of Western Australia IV. Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth WA, pp.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0265) [1–27](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0265).

Li, H.Q., Xu, Z.Q., Yang, J.S., Cai, Z.H., Chen, S.Y., Tang, Z.M., 2009a. [Records of Indosinian Orogenesis in Lhasa Terrane, Tibet. Journal of Earth Science 20, 348–363](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0285).

Li, Z.L., Yang, J.S., Xu, Z.Q., Li, T.F., Xu, X.Z., Ren, Y.F., Robinson, P.T., 2009b. [Geochemistry and Sm-Nd and Rb-Sr isotopic composition of eclogite in the Lhasa terrane, Tibet, and its geological significance. Lithos 109, 240–247.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0290)

Li, G., Liu, X., Alex, P., Wei, L., Liu, X., Huang, F., Zhou, X., 2010. [In-situ detrital zircon geochronology and Hf isotopic analyses from Upper Triassic Tethys sequence strata. Earth and Planetary Science Letters 297, 461–470.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0270)

Li, H., Xu, Z., Yang, J., Tang, Z., 2012. [Indosinian Orogenesis in the Lhasa Terrane, Tibet: New Muscovite 40Ar-39Ar Geochronology and Evolutionary Process. Acta Geologica Sinica - English Edition 86, 1116–1127.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0280)

Li, G., Sandiford, M., Liu, X., Xu, Z., Wei, L., Li, H., 2014. [Provenance of Late Triassic sediments in central Lhasa terrane, Tibet and its implication. Gondwana Research 25, 1680–1689](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0275).

Lin, Y.-H., Zhang, Z.-M., Dong, X., Shen, K., Lu, X., 2013a. [Precambrian evolution of the Lhasa terrane, Tibet: Constraint from the zircon](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0295) [U–Pb geochronology of the gneisses. Precambrian Research 237, 64–77.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0295)

Lin, Y.-H., Zhang, Z.-M., Dong, X., Xiang, H., Yan, R., 2013b. [Early Mesozoic metamorphism and tectonic significance of the eastern segment of the Lhasa terrane, south Tibet. Journal of Asian Earth Sciences 78, 160–183](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0300).

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/S0024-4937(15)00227-3/rf0305)

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: U-Pb Dating, Hf Isotopes and Trace Elements in Zircons from Mantle Xenoliths. Journal of Petrology 51, 537–571](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0310).

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/S0024-4937(15)00227-3/rf0590).

Ma, L., Wang, Q., Wyman, D.A., Jiang, Z.-Q., Yang, J.-H., Li, Q.-L., Gou, G.-N., Guo, H.-F., 2013. [Late Cretaceous crustal growth in the Gangdese area, southern Tibet: Petrological and Sr–Nd–Hf–O isotopic evidence from Zhengga diorite–gabbro. Chemical Geology 349–350, 54–70](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0315).

Metcalfe, I., 2011. [Tectonic framework and Phanerozoic evolution of Sundaland. Gondwana Research 19,](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0320) [3–21.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0320)

Metcalfe, I., 2013. [Gondwana dispersion and Asian accretion: Tectonic and palaeogeographic evolution of eastern Tethys. Journal of Asian Earth Sciences 66,](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0325) [1–33.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0325)

Mo, X.X., Niu, Y.L., Dong, G.C., Zhao, Z.D., Hou, Z.Q., Zhou, S., Ke, S., 2008. [Contribution of syncollisional felsic magmatism to continental crust growth: A case study of the Paleogene Linzizong volcanic Succession in southern Tibet. Chemical Geology 250, 49–67.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0330)

Murgulov, V., Griffin, W.L., O'Reilly, S.Y., 2013. [Carboniferous and Permian granites of the northern Tasman orogenic belt, Queensland, Australia: insights into petrogenesis and crustal evolution from an in situ zircon study. International Journal of Earth Sciences 102, 647–669.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0335)

Nardi, L.V.S., Formoso, M.L.L., Muller, I.F., Fontana, E., Jarvis, K., Lamarao, C., 2013. [Zircon/ rock partition coefficients of REEs, Y, Th, U, Nb, and Ta in granitic rocks: Uses for provenance and mineral exploration purposes. Chemical Geology 335,](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0340) [1–7](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0340).

Pan, G., Wang, L., Li, R., Yuan, S., Ji, W., Yin, F., Zhang, W., Wang, B., 2012. [Tectonic evolution of the Qinghai-Tibet Plateau. Journal of Asian Earth Sciences 53,](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0350) [3–14](http://refhub.elsevier.com/S0024-4937(15)00227-3/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/S0024-4937(15)00227-3/rf0345)

Pullen, A., Kapp, P., Gehrels, G.E., Ding, L., Zhang, Q., 2011. [Metamorphic rocks in central Tibet: Lateral variations and implications for crustal structure. Geological Society of America Bulletin 123, 585–600](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0355).

Quidelleur, X., Grove, M., Lovera, O.M., Harrison, T.M., Yin, A., Ryerson, F.J., 1997. [Thermal evolution and slip history of the Renbu Zedong Thrust, southeasterm Tibet. Journal of Geophysical Research - Solid Earth 102, 2659–2679](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0360).

Scherer, E., Munker, C., Mezger, K., 2001. [Calibration of the Lutetium-Hafnium Clock. Science 293, 683–687.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0365)

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/S0024-4937(15)00227-3/rf0370).

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/S0024-4937(15)00227-3/rf0595).

Veevers, J.J., 2007. [Pan-Gondwanaland post-collisional extension marked by 650–500](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0375) [Ma alkaline rocks and carbonatites and related detrital zircons: A review. Earth-Science Reviews 83,](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0375) [1–47.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0375)

Veevers, J.J., Saeed, A., 2007. [Central Antarctic provenance of Permian sandstones in Dronning Maud Land and the Karoo Basin: Integration of U-Pb and TDM ages and host-rock affinity from detrital zircons. Sedimentary Geology 202, 653–676.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0385)

Veevers, J.J., Saeed, A., Belousova, E.A., Griffin, W.L., 2005. [U-Pb ages and source composition by Hf-isotope and trace-element analysis of detrital zircons in Permian sandstone and modem sand from southwestern Australia and a review of the paleogeographical and denudational history of the Yilgam Craton. Earth-Science Reviews 68, 245–279.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0390)

Veevers, J.J., Belousova, E.A., Saeed, A., Sircombe, K., Cooper, A.F., Read, S.E., 2006. [PanGondwanaland detrital zircons from Australia analysed for Hf-isotopes and trace elements reflect an ice-covered Antarctic provenance of 700–500](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0380) [Ma age, T-DM of](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0380) [2.01.0](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0380) [Ga, and alkaline affinity. Earth-Science Reviews 76, 135–174](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0380).

Vermeesch, P., 2012. [On the visualisation of detrital age distributions. Chemical Geology 312–313, 190–194](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0395).

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/S0024-4937(15)00227-3/rf0400).

Wang, L.-Q., Pan, G.-T., Zhu, D.-C., Zhou, C.-Y., Yuan, S.-H., Zhang, W.-P., 2008. [CarboniferousPermian island arc orogenesis in the Gangdise belt, Tibet, China: evidence from volcanic rocks and geochemistry. Geological Bulletin of China 27, 1509–1534](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0405).

Wang, Q., Zhu, D.-C., Zhao, Z.-D., Guan, Q., Zhang, X.-Q., Sui, Q.-L., Hu, Z.-C., Mo, X.-X., 2012. [Magmatic zircons from I-, S- and A-type granitoids in Tibet: Trace element characteristics and their application to detrital zircon provenance study. Journal of Asian Earth Sciences 53, 59–66.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0415)

Wang, L., Zeng, L.S., Gao, L.E., Chen, Z.Y., 2013. [Early Cretaceous high Mg-# and high Sr/Y clinopyroxene-bearing diorite in the southeast Gangdese batholith, Southern Tibet. Acta Petrologica Sinica 29, 1977–1994](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0410).

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/S0024-4937(15)00227-3/rf0420).

Weller, O.M., St-Onge, M.R., Searle, M.P., Waters, D.J., Rayner, N., Chen, S., Chung, S.L., Palin, R.M., 2015. [Quantifying the](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0425) [P–T–t conditions of north–south Lhasa terrane accretion: new insight into the pre-Himalayan architecture of the Tibetan plateau. Journal of Metamorphic Geology 33, 91–113.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0425)

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 U-Pb ages of the Gangdese Batholith and implications for Neotethyan subduction in southern Tibet. Chemical Geology 252, 191–201.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0430)

Wilde, S.A., Valley, J.W., Peck, W.H., Graham, C.M., 2001. [Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. Nature 409, 175–178.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0435)

Wu, F.Y., Ji, W.Q., Liu, C.Z., Chung, S.L., 2010. [Detrital zircon U-Pb and Hf isotopic data from the Xigaze fore-arc basin: Constraints on Transhimalayan magmatic evolution in southern Tibet. Chemical Geology 271, 13–25.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0440)

Wu, X.Y., Wang, Q., Zhu, D.C., Zhao, Z.D., Chen, Y., Sea, L.L., Zheng, J.P., Mo, X.X., 2013. [Origin of the Early Carboniferous granitoids in the southern margin of the Lhasa Terrane and its implication for the opening of the Songdo Tethyan Ocean. Acta Petrologica Sinica 29, 3716–3730](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0445).

Xie, C., Li, C., Wu, Y., Wang, M., Hu, P., 2014. [40Ar/39Ar thermochronology constraints on jurassic tectonothermal event of nyainrong microcontinent. Journal of Earth Science 25,](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0450) [98–108.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0450)

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/S0024-4937(15)00227-3/rf0455) [41–57.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0455)

Xu, W.-C., Zhang, H.-F., Harris, N., Guo, L., Pan, F.-B., Wang, S., 2013a. [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/S0024-4937(15)00227-3/rf0460)

Xu, Z.Q., Yang, J.S., Li, W.C., Li, H.Q., Cai, Z.H., Yan, Z., Ma, C.Q., 2013b. [Paleo-Tethys system and accretionary orogen in the Tibet Plateau. Acta Petrologica Sinica 29, 1847–1860.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0465)

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/S0024-4937(15)00227-3/rf0470)

Yang, X.L., Zhang, L.F., Zhao, Z.D., Zhu, D.C., 2014. [Metamorphic evolution of glaucophane eclogites from Sumdo, Lhasa block of Tibetan Plateau: Phase equilibria and metamorphic P-T path. Acta Petrologica Sinica 30, 1505–1519](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0475).

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/S0024-4937(15)00227-3/rf0480) [1–131](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0480).

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/S0024-4937(15)00227-3/rf0485)

Zeng, L., Liu, J., Gao, L.e., Chen, F., Xie, K., 2009. [Early Mesozoic High-pressure Metamorphism Within the Lhasa Block, Tibet and Implications for Regional Tectonics. Earth Science Frontiers 16, 140–151](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0490).

Zhai, Q.-g., Jahn, B.-m., Wang, J., Su, L., Mo, X.-X., Wang, K.-l., Tang, S.-h., Lee, H.-y., 2013. [The Carboniferous ophiolite in the middle of the Qiangtang terrane, Northern Tibet: SHRIMP](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0600) [U–Pb dating, geochemical and Sr–Nd–Hf isotopic characteristics. Lithos 168–169, 186–199](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0600).

Zhang, L., Wu, Y., 2012. [Origin and metamorphic evolution of the Nyingchi Complex, eastern Lhasa terrane, southern Tibet: Constraint from the zircon U-Pb geochronology. Acta Petrologica Sinica 28, 1674–1688.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0520)

Zhang, H., Xu, W., Guo, J., Zong, K., Cai, H., Yuan, H., 2007. [Indosinian orogenesis of the Gangdise Terrane: Evidences from zircon U-Pb dating and petrogenesis of granitoids. Earth Science - Journal of China University of Geosciences 32, 155–166.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0505)

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/S0024-4937(15)00227-3/rf0510)

Zhang, H., Harris, N., Guo, L., Xu, W., 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/S0024-4937(15)00227-3/rf0500)

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/S0024-4937(15)00227-3/rf0545)

Zhang, D., Zhang, L., Zhao, Z., 2011. [A study of metamorphism of Sumdo eclogite in Tibet, China. Earth Science Frontiers 18, 116–126](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0495).

Zhang, J.Y., Yin, A., Liu, W.C., Wu, F.Y., Lin, D., Grove, M., 2012a. [Coupled U-Pb dating and Hf isotopic analysis of detrital zircon of modern river sand from the Yalu River (Yarlung Tsangpo) drainage system in southern Tibet: Constraints on the transport processes and evolution of Himalayan rivers. Geological Society of America Bulletin 124, 1449–1473](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0515).

Zhang, Z., Dong, X., Liu, F., Lin, Y., Yan, R., He, Z., Santosh, M., 2012b. [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/S0024-4937(15)00227-3/rf0525)

Zhang, Z., 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/S0024-4937(15)00227-3/rf0535).

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/S0024-4937(15)00227-3/rf0540)

Zhang, Z., Dong, X., Xiang, H., Ding, H., He, Z., Liou, J.G., 2015. [Reworking of the Gangdese magmatic arc, southeastern Tibet: post-collisional metamorphism and anatexis. Journal of Metamorphic Geology 33,](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0530) [1–21](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0530).

Zhu, D.C., Mo, X.X., Niu, Y.L., Zhao, Z.D., Wang, L.Q., Pan, G.T., Wu, F.Y., 2009. [Zircon U-Pb dating and in-situ Hf isotopic analysis of Permian peraluminous granite in the Lhasa terrane, southern Tibet: Implications for Permian collisional orogeny and paleogeography. Tectonophysics 469, 48–60](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0580).

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/S0024-4937(15)00227-3/rf0550).

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/S0024-4937(15)00227-3/rf0560).

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/S0024-4937(15)00227-3/rf0570)

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/S0024-4937(15)00227-3/rf0565).

Zhu, D., Zhao, Z., Niu, Y., Wang, Q., Dilek, Y., Dong, G., Mo, X., 2012b. [Origin and Paleozoic tectonic evolution of the Lhasa terrane. Geological Journal of China Universities 18, 1–15.](http://refhub.elsevier.com/S0024-4937(15)00227-3/rf0575)

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/S0024-4937(15)00227-3/rf0555).