Late Triassic orogenic assembly of the Tibetan Plateau: constraints from magmatism and metamorphism in the east Lhasa terrane

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Running title: Collisional orogeny of Paleo-Tethys ocean in the east Lhasa terrane

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ABSTRACT

The early Mesozoic evolution of the Lhasa terrane, which represents a major component of the Himalayan-Tibetan orogen, remains highly controversial. In particular, geological units and events documented either side of the eastern Himalayan syntaxis (EHS correlated. Here, we report new petrological, geochemical and geochronological data for co-genetic peraluminous S-type granites and metamorphic rocks (gneiss and schist) from the Motuo–Bomi–Chayu region of the eastern Lhasa terrane, located on the eastern flank of the EHS. Zircon U–Pb dating indicates that these units record both Late Triassic m (216–206 Ma) and metamorphic (209–198 Ma) episodes. The granites were derived from a Paleoproterozoic crustal source with negative $\varepsilon_{Hf}(t)$ values (−5.5 to −16.6) and T_{DM2} model ages of 1.51–1.99 Ga, and are interpreted to have formed by crustal anatexis of nearby metasediments during The gneisses and schists experienced similar upper amphibolite-facies peak metamorphism and associated partial melting, followed by decompressi metamorphism. These rocks were buried to lower-crustal depths and then exhumated to the surface in a collisional orogenic setting during plate convergence. From comparison of these data to other metamorphic belts with similar grades and coeval granitic magmatism widespread in the central-east Lhasa terrane, we propose that the studied co-genetic magmatism and metamorphism in the Motuo–Bomi–Chayu region record Late Triassic accretion of the North Lhasa and South Lhasa terranes, which represents the first evidence of the Paleo-Tethys Ocean (PTO) closure in this part of Asia. These data provide new constraints on the spatial and temporal evolution of the Paleo-Tethyan Wilson Cycle and provide a 'missing link' to correlate the geology and the history of the Lhasa terrane continental crust on either side of the EHS.

Keywords: collisional-orogenesis; Lhasa terrane; magmatism and metamorphism; Paleo-Tethys Ocean; Zircon U–Pb geochronology

INTRODUCTION

The Himalayan Range and Tibetan Plateau formed due to collision between the Indian and Asian plates and closure of the Neo-Tethys Ocean at approximately 50 Ma (Tapponnier *et al.*, 1986; O'Brien *et al.*, 2001; Najman *et al.*, 2010; Zhang *et al.*, 2012a; St-Onge *et al.*, 2013; Ding *et al.*, 2016), although this orogeny merely represents the youngest of multiple accretion events that have occurred along the southern margin of Eurasia since the Paleozoic (e.g. Kapp *et al.*, 2007; Yin & Harrison, 2000; Zhang *et al.*, 2014a). From north to south, the Tibetan Plateau includes the Songpan-Ganzi, Qiangtang, Lhasa, and Himalaya terranes, which are separated by the Jinsha, Bangong-Nujiang and Indus-Yarlung Tsangpo suture zones, respectively (Fig. 1a; Burg and Chen, 1984; Xu *et al.*, 1985, 2006, 2015; Searle *et al.*, 1987; Dewey *et al.*, 1988; Murphy *et al.*, 1997; Mo *et al.*, 2003, 2005, 2006, 2007, 2008; Pan *et al.*, 2004, 2006, 2012; Zhang *et al.*, 2012b, c, 2013, 2014a, b, c; Zhu *et al.*, 2013, 2015, 2016; Palin *et al.*, 2014, 2015; Ding *et al.*, 2015, 2016). The Lhasa terrane records geological evidence of Paleoproterozoic magmatism (Zhang & Santosh, 2012; Lin *et al.*, 2013a), Mesoproterozoic magmatism (Lin *et al.*, 2013b), opening of the Mozambique Ocean during the Neoproterozoic (Dong *et al.*, 2011a; Zhang *et al.*, 2012b, 2014a), assembly of Gondwana and subduction of the Proto-Tethyan ocean during the Early Paleozoic (Li *et al.*, 2008; Dong *et al.*, 2009; Ji *et al.*, 2009; Zhu *et al.*, 2012, 2013; Hu *et al.*, 2013; Ding *et al.*, 2015), subduction and closure of the Paleo-Tethys ocean (PTO) from the Permian to the Triassic (Yang *et al.*, 2006, 2007, 2009; Li *et al.*, 2009a, b, 2012; Zeng *et al.*, 2009; Dong *et al.*, 2011b, 2015; Lin *et al.*, 2013b; Cheng *et al.*, 2012, 2015; Weller *et al.*, 2015, 2016a, b; Chen *et al.*, 2017), and finally the formation and destruction of the Bangong-Nujiang Tethyan and Neo-Tethyan oceans during the Mesozoic and Cenozoic, respectively (Allègre *et al.*, 1984; Ding *et al.*, 2003; Mo *et al.*, 2003, 2005, 2006, 2007, 2008; Hou *et al.*, 2004, 2006; Zhu *et al.*, 2009, 2011, 2012, 2013, 2015, 2016; Zhan *et al.*, 2010, 2013, 2014c; Zhang & Santosh, 2012; Guan *et al.*, 2012; Palin *et al.*, 2014, 2015; Shui *et al.*, 2017).

Understanding the evolution of the PTO is s tectonothermal history of the Lhasa terrane – and thus the Tibetan Plateau as a whole – as the PTO suture zone divides its central-east portions into northern and southern blocks with distinct geological histories (Fig. 1a; Yang *et al.*, 2006, 2007, 2009; Zhang *et al.*, 2014a; Cheng *et al.*, 2015; Weller *et al.*, 2015, 2016a; Chen *et al.*, 2017). Previous studies of Permian to Early Jurassic magmatic and high-grade metamorphic rocks located in central-east Lhasa terrane (westward of the eastern Himalayan syntaxis) suggest PTO subduction and ocean-closure in this region (Kapp *et al.*, 2005; Yang *et al.*, 2006, 2007, 2009; Li *et al.*, 2009a, b, 2012; Zeng *et al.*, 2009; Zhang *et al.*, 2014a; Cheng *et al.*, 2015; Weller *et al.*, 2015, 2016a, b; Chen *et al.*, 2017). However, it is still unclear (1) if these events continued into the east Lhasa terrane, eastward of the eastern Himalayan syntaxis (EHS); (2) where the actual location of the PTO orogenic belt is in this region; and (3) the metamorphic and magmatic events in this area. Together, these represent an important gap in our understanding of the early evolution of this major orogenic system.

In this paper, we present new petrological, geochemical, and geochronological data for co-genetic amphibolite-facies metasediments and S-type granites from the Motu Chayu region of the east Lhasa terrane, eastern flank of the EHS constraints on the timing and style of collisional orogeny and PTO closure during the Early Mesozoic. These integrated data represent the first robust constraints on the locat timing of North-South Lhasa microblock accretion east of the EH constraints for tectonic reconstructions of terrane evolution in southeast Asia prior to India-Asia collision.

GEOLOGICAL BACKGROUND AND SAMPLES

The east-west oriented Lhasa terrane, southern Tibet, is 100–300 km wide and over 2000 km long (Fig. 1a). It is composed dominantly of Precambrian crystalline metamorphic basement overlain by Paleozoic to Mesozoic marine strata, volcanic rocks and metasediments, and is intruded by Mesozoic and Cenozoic plutons (e *et al.*, 2004, 2006, 2012; Metcalfe, 2006; Zhu *et al.*, 2009, 2011, 2012, 2016; Zhang *et al.*, 2010, 2012b, 2013, 2014a). The presence of Precambrian basement is shown by the discovery of Neoproterozoic granitic and mafic rocks and amphibolite- to granulite-fac metamorphic rocks in northern block, and Paleo- to Meso-Proterozoic gra southern block, although these rocks were also furth Neoproterozoic (Dong *et al.*, 2011a, 2020; Zhang *et al.*, 2012b, 2014a; Lin *et al.*, 2013a; Hu *et al.*, 2019 and references therein).

The study region discussed here is located in the easternmost segment of the terrane, east/southeast of Namche Barwa, near to the towns of Motuo, Bomi, and ((Fig. 1b). This area is characterized by regionally amphibolite-facies lithologies, Late Paleozoic to Cenozoic s intrusions, and the exposed roots of the Gangdese Batholith (Fig. 1b). These metamorphic rocks consist mainly of orthogneiss, schist, marble, migmatite and together are referred to as the Bom *et al.*, 1999; Xie *et al.*, 2007; Dong *et al.*, 2011c, 2015). The radiogenic 2264–2145 Ma, 1330–900 Ma and 600–520 Ma obtained by traditional dating methods show that remnants of Precambrian metamorphic baseme *et al.*, 1999; Xie *et al.*, 2007; Dong *et al.*, 2011c, 2015), although recent metamorphic zircon U–Pb ages of ca. 217 Ma and ca. 22–16 Ma suggest that these rocks also experienced Mesozoic and Cenozoic thermal overprinting (Dong *et al.*, 2011c, 2015). Late Paleozoic sediments, Mesozoic marine sediments, and minor Cenozoic sedimentary rocks mainly occur in the northeast, although Late Paleozoic sediments do not contact the Mesozoic strata and the Cenozoic sedimentary rocks unconformably overlie the Mesozoic sediments, indicating punctuated tectonics in this region. The Late Paleozoic se Devonian marine sediments and Carboniferous-Permian volcanic ro marine clastic rocks, running *et al.*, 2004; Wang *et al.*, 2008). Carboniferous, Triassic and Jurassic granites were recently recognized in this area, although these rocks have been partly transformed into orthogneiss during Mesozoic and Cenozoi *et al.*, 2004; Li *et al.*, 2013a; Dong *et al.*, 2015). The Gangdese batholith is predominantly composed of Cretaceous to Neogene granitoids, which formed as continental arc magm during subduction and closure of the Neo-Tethyan ocean (Chu *et al.*, 2009; Dong *et al.*, 2013; Li *et al.*, 2013b).

The samples documented here comprise magmatic and metamorphic rocks coll from two regions of the east Lhasa terrane (east of the EHS), but also located ~150 km apart: granites and metapelitic schists were collected from ~35 km southwes metapelitic gneisses were collected from ~25 km southwest of Bomi (Fig. 1b). This region has been relatively understudied in comparison with outcrops west of the EHS and so th degree to which geological units and tectonic events correlate either side of uncertain. Outcrop and petrological information for each sample is Mineral abbreviations are after Whitney and Evans (2010).

ANALYTICAL METHODS

Mineral composition

Mineral compositions were acquired using a JEOL JXA 8900 electron microprobe (EMP housed at the Institute of Geology, Chinese Academy of Geological Beijing. Operating conditions comprised a 15-kV accelerating voltage, 5-nA beam current, 5-µm probe diameter, and count time of 10 s for peak and background, Natur biotite, plagioclase, and K-feldspar and synthetic silica calibrations and a ZAF correction was used. Analytical uncertainties SiO_2, TiO_2, Al_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, and total are <1% at abundances >1 wt. % and <8% at abundances <1 wt. %. Compositional data collected for garnet, biotite, plagioclase, K-feldspar, and cordierite in all rock types are given in Supplementary Tables 1–5.

Whole-rock composition

All magmatic samples collected from the Chayu area were analysed for major an element contents, which are shown in Supplementary table 6. Whole-rock compositions were obtained at the National Research Center, CAGS, Beijing. Standards GBW07103, GBW07121, and GBW07122 were used to monitor analytical quality control. Major-elements oxides, including loss on ignition (fluorescence (XRF) on a Rigaku-3080 analyser, which has an analytica <0.5%. Concentrations of trace elements Zr, Nb, Cr, Sr, Ba, Ni, Rb and Y were determined using a Rigaku-2100 XRF analyser, which has an analytical uncertainty of <3–5%. Ot trace elements and rare earth elements (REEs) were determined by induct plasma mass spectrometry (ICP-MS) using a TJA-PQ-ExCell. Detailed description o ICP–MS method has been reported by Liang *et al.* (2000). Analytical uncertainties for ICP-MS are 1–5% at abundances >1 ppm and 5–10% at abundances <1 ppm.

Zircon U–Pb and Hf isotopes and trace element analysis

Radiogenic isotope geochronology was performed on four of gra metasediment samples to determine the timing of key tect Motuo–Bomi–Chayu region of the east Lhasa terrane. Zircon grains were separated from each sample by magnetic and conventional heavy-liquid techniques at the Hebei Institute of Regional Geology and Mineral Investigation. Cathodoluminescence (CL) images were taken on a HITACHI S2250-N scanning electron microscope at the SHRIMP Unit at the Institute of Geology, CAGS. Zircon U–Pb isotope and trace element analysis were p simultaneously on an Agilent 7500 ICP-MS equipped with a 193 nm ArF-excimer laser at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan). Detailed operating conditions for the ICP-MS instrum laser ablation system are as reported by Liu *et al.* (2010). Zircon 91500 was used as external standard for U–Pb dating, which was analysed twice for every 5 analyses of the samples. SRM610 were used as external standard for the trace element analysis. Time drifts of U–Th–Pb isotopic ratios were corrected using a linear interpolation (with time) for every five analyses according to the variations of zircon 91500. Zircon GJ-1 was used standard to monitor the stability and accuracy of the acquired U–Pb data. Silic (^{29}Si) was used as an internal standard. The U–Pb and trace element data were processed by ICPMSDataCal (Liu *et al.*, 2010) and Isoplot (Lugwig, 2003) was used to calculate isotopic ages and construct concordia diagrams. LA-ICP-MS U–Pb data and the trace element compositions of the magmatic and metamorphi metasediments are presented in Supplementary table 7.

In situ Hf isotope compositions of zircon were obtained by a Neptune MC-ICP-MS at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan). The laser had a beam diameter of 44 μm, a frequency of 8 H energy of 60 mJ, and a fluence of 5.3 J/cm^2. Analytical spots were chosen on the same domains with LA-ICP-MS spots. The zircon standards GJ-1 (Elhlou *et al.*, 2006) and 91500 (Blichert, 2008) were analysed as reference materials ^{176}Hf/^{177}Hf ratios of 0.282012 ± 11 (1σ, n = 4) and 0.282305 ± 10 (1σ, n = 10), respectively. These values match the recommend 1, Elhlou *et al.*, 2006; 0.282308 ± 6 for 91500, Blic ^{176}Hf/^{177}Hf ratios were calculated using the ^{176}Lu decay constant of 1.867 × 10^{-11} y^{-1} (Soderlund *et al.*, 2004). The $\varepsilon_{Hf}(t)$ values were calculated usi ^{176}Hf/^{177}Hf ratio of 0.282785 and ^{176}Lu/^{177}Hf ratio of 0.0336 (Bouvier *et al.*, 2008). The depleted-mantle-Hf model ages (T_{DM}) were calculated with respect to a depleted present-day mantle ^{176}Hf/^{177}Hf ratio of 0.28325 and ^{176}Lu/^{177}Hf ratio of 0.0384 (Griffin *et al.*, 2000). The Hf crustal model ages (T_{DM2}) of each zircon were calculated by assuming its parental magma to have been derived from an average continental crust with ^{176}Lu/^{177}Hf = 0.015 (Griffin *et al.*, 2002). *In-situ* Lu–Hf isotopic ratios from two granites are presented in Supplementary table 8.

RESULTS

Petrology

Magmatic rocks

Magmatic rocks collected from the Chayu area include undefo T15–46–7, T15–46–8 and T15–46–9) and weakly deformed T15–46–1, T15–46–3, T15–46–4, T15–46–5, T15–47–2 and T15–47–4). The undeformed granite displays a phaneritic texture and contains quartz (40–50%), K-feldspar (20–30%), plagioclase (20–25%), biotite (2–3%) and muscovite (2–3%), with accessory zircon, apatite, and sphene (Fig. 2a and c). The weakly deformed granites display a slight foliation in outcrop and consist of quartz (40–45%), K-feldspar (20–25%), plagioclase (25–30%), biotite (3–5%) and variable muscovite, garnet, and accessory minerals zircon and apatite (Fig. 2b and d). The finely crystall quartz, feldspar and biotite grains, which (Fig. 2d).

Metamorphic rocks

Two high-grade gneisses (T15–32–3 and T15–33–7) were collected from southwest o Bomi. They show prominent foliation in outcrop and comprise pale plagioclase-rich (Pl-rich) quartzofeldspathic leucosomes, which are generally aligned subparallel to the foliation, and dark melanosomes. The (Pl-rich) leucosomes range from millimeter thickness and often occur as interlayers or small- to large-scale lenses (Fig. 3 diagnostic of partial melting during metamorphism and locally mi T15–32–3 is a metapelitic gneiss containing biotite, muscovite, quartz, pla garnet, with minor sillimanite, ilmenite and chlorite (Fig. 4a and b). Large porphyroblasts of garnet are set in a matrix with a foliation defined by oriented mica and quartzofeldspathic domains (Fig. 4a). Chlorite partially pseudomorphs biotite and garnet (Fig. 4a), suggesting a retrograde origin. Sample T15–33–7 has a similar miner T15–32–3, but contains additional K-feldspar (Fig. 4c). In sample T15–33–7, muscovite occurs as both large lath-like porphyroblasts and randomly orientated fine-grained (Fig. 4d), which suggest a retrograde origin (Ashworth, 1975, 1979; Tyler & 1982). Cuspate quartz also exhibits very small dihedral angles against plagioclase (Fig. 4e), and K-feldspar grains are surrounded by plagioclase rims (Fig. 4f). These microstruc features suggest the presence of partial melt during metamorphism (e.g. Holness & Clemens, 1999; Holness & Sawyer, 2008; Feisel *et al.*, 2018).

Two metapelitic schists (T15–43–1 and T15–43–3) were collected from southwest of Chayu. They have the appearance of stromatic migmatitic rocks and consist of millimeter to centimeter thick white-beige felsic domains (leucosomes), which occur as concordant layers or small-scale rootless folds, alternating with grey domai feldspathic material with interstitial biotite (Fig. 3b). These outcrop features imply that these rocks experienced partial melting and the melt did not migra Sample T15–43–1 is a garnet-two-mica schist containing garnet porphyroblasts with biotite, muscovite, plagioclase, quartz and minor ilmenite as matrix minera Muscovite occurs both as flakes that are aligned within the foliation and as larger, unfoliated and subhedral to euhedral grains against garnet rims (Fig. 5a and b). These microstructural relationships indicate two generations of muscovite growth (cf. Ashworth, 1975, 1979; Tyler & Ashworth, 1982). Garnet rims and internal fractures are o aggregates of biotite, muscovite, and plagioclase (Fig. retrogression. Sample T15–43–3 is a garnet-sillimanite-cordierite schist containing biotite, plagioclase, K-feldspar, q 5c–f). The foliation is defined by aligned fibrous/prismatic sillimanite and biotite flakes that wrap around coarse K-feldspar, plagioclase and quartz in the matrix. Garnet porphyroblasts have inclusion-rich cores, containing biotite, plagioclase and quartz, whereas rim domai are mostly inclusion-free (Fig. 5d and f). Some ga pseudomorphed at their rims by biotite and cordierite (Fig. 5d). Minor perthite occurs in the matrix, exhibiting micro-exsolved lamellae of plagioclase hosted by K-feldspar (Fig. 5e), and polymineralic inclusions of biotite + plagioclase + quartz are occasionally preserved in garnet cores (Fig. 5f), suggesting the studied rocks under Holness & Clemens, 1999; Waters, 2001; Holness & Sawyer, 2008; Zhang *et al.*, 2017; Feisel *et al.*, 2018). In all samples, garnet rims are partly replaced by biotite + plagioclase ± muscovite aggregates (Figs **4a**, b, e), recording back-reaction involving mel crystallization (e.g., Waters, 2001; Kriegsman & Alvarez-Valero, 2010).

Mineral chemistry

Bomi gneiss

Bomi gneiss samples T15–32–3 and T15–33–7 contain garnet porphyroblasts of composition $X_{Fe76–78}X_{Mg10–12}X_{Ca3–5}X_{Mn8–9}$ ($X_{Fe} = Fe^{2+}/(Fe^{2+} + Mn + Mg + Ca)$, with X_{Ca}, X_{Mg} and X_{Mn} defined according to X_{Fe}) and $X_{Fe72–73}X_{Mg14–16}X_{Ca4–5}X_{Mn8–9}$ respectively (Supplementary tab Porphyroblasts in both samples thus lack systematic compositional zonation from c rim. Matrix biotite has an X_{Mg} [= Mg/(Mg + Fe)] of 0.35–0.42 in sample T15–32–3 and 0.45–0.49 in T15–33–7. The Ti contents of each are 0.15–0.18 and 0.20–0.23 cations per formula unit (cpfu) based on an 11-oxygen calculation, respectively (Supplementary ta 2). Plagioclase in sample T15–32–3 is oligoclase with X_{Ca} [= Ca/(Ca + K + Na)] of

0.18–0.23, and also oligoclase with X_{Ca} = 0.26–0.29 in sample T15–33–7, whereas those surrounding K-feldspar are albite with X_{Ca} = 0.02–0.03 (Supplementary and K-feldspar has X_{Na} [= Na/(Ca + K + Na)] of 0.11–0.12 (Supplementary table 4).

These petrographic observations and patterns in mineral chemistry sugg Bomi gneisses contained a p Grt + Sil + Bt + Ms + Pl + Qz ± Ilm + melt for sample T15–32–3 and Grt + Sil + Bt + Kfs + Pl + Qz + melt for sample T15–33–7. Retrograde cooling and exhumation likely initiated growth of secondary Ms, Chl, and Ab surrounding some K-feldspar grains.

Chayu schist

Garnet porphyroblasts from Chayu schist sa characteristics, with homogenous broad cores and weakly zoned rims. Co T15–43–1 have compositions $X_{Fe72–74}X_{Mg15}X_{Ca13–16}X_{Mn8–9}$, which change to out compositions $X_{Fe73–74}X_{Mg12–14}X_{Ca3–4}X_{Mn9–12}$ (Supplementary table 1; Fig. 6a). By contrast, garnet porphyroblasts in sample T15–43–3 have core compositions of $X_{Fe73–74}X_{Mg11–12}X_{Ca2–3}X_{Mn11–13}$, and rim compositions of $X_{Fe70–72}X_{Mg10–11}X_{Ca2–3}X_{Mn15–19}$ (Supplementary table 1; Fig. 6b). These patterns are diagnostic of diffusion-driven homogenization at peak metamorphic conditions, followed by diffusion-controlled retrograde resorption during exhumation, which led to compositional inflections in outer rim domains (e.g. Florence & Spear, 1991; Spear, 1991, 1993; Kohn & Spear, 2000; Caddick *et al.*, 2010).

In sample T15–43–1, biotite grains in the matrix and adjacent to garnet rims X_{Mg} values of 0.50–0.51 and 0.48–0.52, respectively, although the former have higher Ti contents (~0.08) than those at the rims (0.10–0.14) (Supplementary table 2; Fig. 6c). These compositional patterns confirm minor breakdown of garnet durin conditions, leading to biotite formation during retrogression. Plagioclase grains in the matrix and adjacent to garnet rims have similar compositions X_{Ca} = 0.23–0.30, (Supplementary table 3). In sample T15–43–3, biotite inclusions within garnet cores have relative contents of 0.16–0.18 cpfu and low X_{Mg} values of 0.46–0.49, whereas biotites in the matrix have a relatively low Ti content (0.12–0.15 cpfu) and high X_{Mg} values of 0.54–0.59 (Supplementary table 2; Fig. 6d). Plagioclase in the matrix exhibits X_{Ca} = 0.17–0.24 (Supplementary table 3) and K-feldspar in the matrix has X_{Na} = 0.14–0.20 (Supplementary table 4). Cordierite grains adjacent to garnet rims h X_{Mg} values of 0.56–0.59 (Supplementary table 5).

These petrographic observations and patterns in mineral chemistry sugg Chayu schists preserve petrographic eviden In sample T15–41–1, the peak metamorphic st and foliation-forming matrix minerals (Grt + Bt ± Ms + Ilm + Pl + Qz) and retrograde metamorphism induced comp (e.g. Mn spikes; cf. Kohn & Spear, 2000) and peripheral breakdown to form secondary muscovite, biotite and plagioclase. In sample T15–43–3, peak metamorphism is characterized by garnet cores and their associate Sil + Kfs + Bt + Pl + Qz.Akin to sampleT15–43–1, retrograde cooling induced garnet rims resorption and recrystallization to biotite and plagioclase, although here additional cordierite formed during decompression. These mineral assemblages and reaction textures indicate that all samples experienced a similar *P*–*T* conditions quantified using thermobarometry (see below).

Whole-rock geochemistry

Allgranites have high SiO_2 (69.05–76.12 wt. %), Al_2O_3 (12.33–14.58 wt. %) and $Na_2O + K_2O$ (4.36–8.59 wt. %) contents, and low $Fe_2O_3^T$ (0.64–4.24 wt. %), MgO (0.11–2.96 wt. %), CaO (0.73–2.50 wt. %) and MnO (0.02–0.07 wt. %) contents (Supplementary table 6). Most are weakly peraluminous with A/CNK values T15–46–1 and T15–46–4 has an atypically higher value of 1.21 and 1.20 resp (Supplementary table 6).

On a primitive mantle-normalized spider diagram (Fig. 7a), all samples are enriched in large ion lithophile elements (LILE), such as Rb, Th, U and K, and depleted in some high field strength elements (HFSE), such as Nb, Ta, Sr and Ti. In addition, B depleted compared to Rb and Th. When normalized to chondritic values, all grani strongly enriched and show similar fractionated REE pattern ($(La/Yb)_N$ = 5.45–46.36), with LREE-enrichment, HREE-depletio anomalies (δEu = 0.32–0.63), although sample T15–46–7 is only moderately enrich (Supplementary table 6; Fig. 7b).

Zircon U–Pb ages and Hf isotope

Zircons from granites T15–46–3, T15–46–5, T15–46–7, and T15–47–2 show similar internal structures, are colourless to pale brown, euhedral to subhedral prismatic in form (70–170 μm long), and have regular oscillatory zoning with inherited detrital cores in CL images (Fig. 9a–d). Most of the analysed zircon spots have relatively high Th/U ratios (>0 contents, and are characterized by fractionated REE patterns with LREE depletion, HREE enrichment, and negative Eu anomalies (Supplementary table 7; Fig. 10a) structure and compositional features suggest a magmatic origin (Hoskin and Schal 2003). Zircon data from these four samples yielded near-consistent 206Pb/238U ages, with weighted mean ages ranging from 216 Ma to 206 Ma (Fig. 11a–d). These ages ar interpreted to represent magma emplacement/crystallization age.

Zircons from the gneiss and schist samples T15–32–3, T15–33–7, T15–43–1, and T15–43–3 are mostly colourless, oval or sub-rounded in shape, and show well-preserved core-rim zonation (Fig. 9e–f). Inherited cores have a variable size, irregular form and random zoning, implying that zircon cores are detrital/xenocrystic and the protoliths of the studied samples are sedimentary rocks. In contrast, metamorphic rims show weak patchy zoning (or have no zoning at all), and have relatively low Th/U ratios, low REE contents and fractionated REE patterns with depleted LREE, flat HREE an (Supplementary table; Fig. 10b), typical of a metamorphic origin (Hoskin & Schaltegger, 2003). The analysed spots of the metamorphic rims yielded near-concordant $^{206}Pb/^{238}U$ ages, with weighted means of 198 ± 3.3 Ma, 202 ± 3.4 Ma, 209 ± 2.8 Ma and 203 ± 3.1 Ma for T15–32–3, T15–33–7, T15–43–1, and T15–43–3, respectively (Fig. 11e–h).

Together, these data are interpreted to record Late Triassic cru 216–206 Ma and regional metamorphism at 209–198 Ma in the east Lhasa terrane.

Zircons from two Late Triassic granites in the east Lhasa terrane (sa T15–46–3 and T15–46–5) have initial $^{176}Hf/^{177}Hf$ ratios ranging from 0.282308 to 0.282525 and variable negative $\varepsilon_{Hf}(t)$ values (ε −8.6 to −16.2). These va T_{DM2} model ages of 1.99–1.51 Ga (Supplementary table; Fig. 12), indicating Paleoproterozoic crustal magma source.

DISCUSSION

Metamorphic *P–T* path of gneiss and schist

In order to constrain the tectonothermal evolution of metamorphic sampl diagram-based thermobarometry and conventional techniques were employed to *P–T* conditions for various stages of their prograde, peak and retrogr evolutions.

In general, bulk-rock-specific phase diagrams (pseudosections) c precise constraints on *P–T* conditions of metamorphism than conventional techni (cf. Powell & Holland, 2008), thus allowing discrete changes in crustal depth and thermal state during the burial and exhumation cycle to be defined (e.g. Weller *et al*, 2015; Palin *et al*, 2018). Typical uncertainties associated with cation exchange thermometers an transfer barometers are at least ± 50 °C and ± 1 kbar at 1. S.D., which is primarily a function of uncertainty on thermodynamic end-member data and inaccuracies in the descriptio activity-composition (*a–x*) relations describing elemental mixi (e.g. Green *et al*, 2016; Waters, 2019). While uncertainty on the absolute po assemblage field boundaries on any individual pseudosection are of a similar magnitude to those for conventional techniques (Powell & Holland, 2008; Palin *et al.*, 2016), as all phase diagrams in this study were calculated using the same t *a–x* relations, similar absolute errors cancel, and the calculated phase equilibria shown below are relatively precise to within ±0.2 kbar and ±10–15 °C (Worley & Powell, 2000). Su values allow distinct *P*–*T* differences to be determined, discrimination of depths of burial and calculated geotherms performed with confidence (Hernández-Uribe *et al*, 2018; Hernández-Uribe & Palin, 2019; Li *et al.*, 2018). Nonetheless, conventional techniques must be employed in scenarios where the bulk-rock composition of a rock is not representative of reaching 'equilibration' volume, such as for retrograde breakdown within porphyroblast st *et al*, 2013; Waters, 2019). As such, the conditions of late-stage retrograde metamorphism were identified using conventional techniques explicitly considering the minerals that formed during these events: not the surrounding peak metamorphic assemblage.

Phase equilibria modelling

All pseudosections were calculated using Perple_X (Connolly, 2005; versi internally consistent thermodynamic dataset ds-55 of Holland and Powell system MnO–Na_2O–CaO–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O–TiO_2 (MnNCKFMASH The following *a–x* relationships were employed: biotite (Tajčm plagioclase and K-feldspar (Holland & Powell, 2003), ga staurolite, chlorite, ilmenite and silicate melt (White *et al.*, 2014). Kyanite, sillimanite, quartz, and rutile are treated as pure phases. Pseudosections were calculated using XRF-derived bulk-rock compositions (Supplementary table 6) and fluid was considered as pure H_2O. All iron was considered as ferrous due to the lack Fe^{3+}-rich minerals in the schists and gneisses.

Quantitative *P–T* pseudosections calculated for gneisses T15–32–3 between 600–800 °C and 4–9 kbar and T15–33–7 between 600–850 °C and 3–9 kbar are shown in Fig. 8a and b, respectively. Quartz a *P–T* range and garnet is stable in both except for low-*P* conditions, where cordierite is stable instead. The measured H_2O contents for each sample saturate the solidus in each case, which is located at ~660–690 °C (Fig. 8a and b).

For sample T15–32–3, the o Bt + Ms + Pl + Grt + Sil + Qz + melt is stable in a relatively broad fie 4.9–8.7 kbar and 670–745 °C (Fig. 8a), although isopleths for garnet inner-rim composition (X_{Mg} = 0.10–0.12) constrain peak conditions within this range to a minimum pressure

~6 kbar (pink field in Fig. 8a). Retrograde effects where garnet compositions h modified by diffusional cation exchange with matrix phases are not considered here when determining peak metamorphic conditions. As such, sample T15–32–3 likely equilibrated at 5.7–7.5 kbar and 675–725 °C. For sample T15–33–7, the observed peak mineral assemblage of Grt + Sil + Kfs + Bt + Pl + melt + Qz is calculated to be stable 3.2–9.6 kbar and 675–820 °C (Fig. 8b). This range was reduced by matching observed and calculated garnet composition (X_{Mg} 0.14–0.16), (X_{Ca} 0.04–0.05) and biotite Ti contents (0.20–0.23 cpfu), as Ca in garnet and Ti in biotite have slow diffusi measured concentrations should represent those obtained at peak metamorphism. Isopleths delineating these ranges constrain peak *P*–*T* conditions to 5.3–6.7 kbar and 750–765 °C (pink field in Fig. 8b).

The calculated *P*–*T* pseudosection for garnet-biotite schist sample T15–43–1 shows that quartz, plagioclase and bi *P*–*T* range, and garnet is stable everywhere except for <3.1 kbar and 675–685 °C. The fluid-saturated solidus is located at 670–690 °C, and the muscovite-out/sillimanite-in reaction has a positive slope between 630 °C and 750 °C. The observed peak-metamorphic assemblage (Grt + Bt + Ms + Pl + Qz + melt) is stable at 5.4–10 kbar and 675–730 °C, and garnet core X_{Mg} and plagioclase X_{Ca} isopleths constrain peak *P*–*T* conditions to be >7.9 kbar and 690–720 °C (pink field in Fig. 8c). Retrograde alteration at garnet rims, forming coarse aggregates of biotite, plagioclase, and muscovite, but no sillimanite, constrain retrogression to have a steep angle in *P*–*T* space. If heating had continued, or decompression had occurred isothermally, sillimanite would be expected to form within strain although this is not observed. Sample T15–43–3 contains sillimanite in the matrix, but is otherwise mineralogically similar to sample T15–43–1. In a calculated *P*–*T* pseudosection for T15–43–3, the interpreted peak assemblage of Grt + Sil + Kfs + Bt + Pl + Qz + melt is stable at 4.6–9 kbar and 710–800 °C, whereas the retrograde-metamorphic assemblage Grt + Sil + Kfs + Crd + Bt + Pl + Qz yields a *P*–*T* range of 3.6–5.4 kbar and 705–800 °C (Fig. 8d). The highest Ti content of biotite isopleths was used to provide the m temperature and constrain the peak metamorphic *P*–*T* conditions of 4.6–8.7 kbar and 710–765 °C (pink field in Fig. 8d) and retrograde-metamorphic *P*–*T* conditions of 3.6–4.9 kbar and 727–760 °C (blue field in Fig. 8d).

These calculated phase relations infer a comm *P*–*T* path for metamorphic rocks from the Bomi and Chayu regions, which formed alo similar geothermal gradients and reached similar *P*–*T* conditions (Fig. 8e and f), despite being located ~150 km apart along strike.

Geothermobarometry

The garnet–biotite (GB) thermometer (Holdaway, 2000) and garnet–biotite–plagioclase–quartz (GBPQ) barometer (Wu *et al*., 2004) were applied to calculate the pe retrograde-metamorphic *P–T* conditions of the studied gneisses and schists. These result were used both as an independent check on the conditions calculated via phase analysis and due to local disequilibrium that may have developed d retrograde recrystallization, which obviates pseudosection modeling from interpr *P–T* conditions of retrograde exhumation far below the solidus.

For gneiss samples, flat garnet core compositions are interpreted to be the resu homogenization of cations at the thermal peak of metamorphism (e.g. Caddick et al., 2010). Garnet core compositions alongside those of matrix biotite and plagioclase produced peak-metamorphic *P–T* conditions of 6.1–6.7 kbar and 673–717 °C (sample T15–32–3; yellow-filled circle in Fig. 8a) and 5.3–6.4 kbar and 703–727 °C (sample T15–33–7; yellow-filled circle in Fig. 8b) using these calibrations. For schist samples, the garnet porphyroblasts show compositional zoning, and their cores and rims are interpreted to be formed during the peak and retrograde metamorphism respectively. Therefore, compositions matrix biotite and plagioclase that are not adjacent to garnet grains were selected to calculate the peak-metamorphic *P–T* conditions. These calibrations produced 5.5–6.1 kbar and 673–688 °C for sample T15–43–1 (yellow-filled circle in Fig. 8c), and garnet rim compositions were combined with compositions of neocrystalline biotite and plagioclase to constrain retrograde metamorphic *P–T* conditions of 3.9–4.5 kbar and 627–645 °C, shown by a blue-filled circle in Fig. 8c. No result T15–43–3.

These peak metamorphic *P–T* conditions calculated via thermobarometry are similar to those constrained by phase equilibria modelling, although the calculated pressures of schist sample T15–43–1 are significantly lower than those estimated via pseudosection analysis Given that full bulk-rock compositions are not appropriate to forward-model mineralogical changes occurring in discrete domains, such as garnet strain sh metamorphic *P–T* conditions for sample T15–43–1 determined by thermobarometry are considered most reliable in this case. These conditions lie below the fluid-saturated solidus and are interpreted to correlate with the retrograde closure temperature for effective cation exchange between garnet and the adjacent matrix (Ehlers *et al*., 1994).

Late Triassic metamorphism in the east Lhasa terrane

Petrological observations, zircon geochronology, and phase equilibria modelling show that a major metamorphic episode affected the Motuo–Bomi–Chayu region of the eastern Lhasa terrane during the Late Triassic. Gneiss *P–T* conditions (5.7–7.5 kbar and 675–725 °C) to gneiss sample T15–33–7 (5.3–6.7 kbar and 750–765 °C), and these are considered as peak metamorphism in the Bomi area. Given their proximity with no evident structural discontinuities between outcrops, both sample have experienced the same tectonothermal evolution, even if the former preser temperature than the latter. The occurrence of fine-grained and large lath-like porphyroblasts of retrograde muscovite formed in sample T15–33–7, alongside the absence of cordier constrains the post-peak exhumation history to involve decompressional cooling, as shown in Fig. 8e. By contrast, schists from the Chayu area ~150 km to the southeast underv retrograde *P–T* path characterized by near-isothermal decompression at high temperatures, causing the growth of cordierite and the consumption of garnet, and then cooling towards to the inferred early prograde field (Fig. 8f). The studied gneisses and schists thus experienced similar peak-stage upper amphibolite-facies met were buried to lower-crustal levels during orogenesis. These conditions are consistent with Barrovian-type metamorphism, peaking at sillimanite-g characteristic of collisional orogeny (e *et al*, 2020); especially when followed by decompression along a cooling path associated with tectonic exhumation (England & Richardson, 1977; England & Thompson Thompson & England, 1984; Harley, 1989). Slight differences in th exhumation path can be attributed to local thermal gradients, such a magmatic intrusions in the Chayu region that allow the metamorphic rocks to remain hotter during retrograde exhumation than those in the Bomi area. Var exhumation along strike is not uncommon in collisional orogens at this length scal importantly has been well-documented in the Andes (Lease *et al.* 2016), which is a modern-day accretionary orogen with many tectonic parallels with the south Asian margin du closure of the Neo-Tethys ocean.

The metamorphic zircon rims from the gneisses and concentrations and fractionated REE patterns (Fig. 10b), indicating the metamorphic zircon grew coevally with garnet and plagi during medium- to high-grade metamorphism (Rubatto, 2002; Rubatto & Hermann, 2007; Rubatto *et al*, 2013). Therefore, the ages of ~198 Ma obtained from these grains are taken to represent the timing of peak metamorphism, w *P–T* conditions just above the fluid-saturated solidus for metapelitic rocks (Palin & Dyck, 2020). These thermobarometric results are consistent with outcrop observations of incipient partial melt development and the generation of zircon at or soo after the onset of cooling and melt crystallization (Bea & Montero, 1999; Kunz *et al.*, 2018).

Late Triassic magmatism in the east Lhasa terrane

Four samples of granite collected from the Motuo–Bomi–Chayu region of the east Lhasa terrane yielded similar zircon U–Pb crystallization ages of 216–206 Ma, which correlate with U–Pb ages of magmatic zircons in biotite-hornblende schist (c. 217 Ma) from the same area (Fig. 1; Dong *et al.*, 2011c). The granitic rocks stu
$\varepsilon_{Hf}(t)$ values of –8.6 to –16.2 and old crustal model ages (T_{DM}C) of ca. 1.51 to 1.99 Ga (Fig. 12), indicating that they were derived from partial melting of Paleopr
materials. Diorites in the same area with a slightly younger age (c. 194 Ma) have negative $\varepsilon_{Hf}(t)$ values of –0.1 to –6.5 (Dong *et al.*, 2015), and so also likely formed from these older precursor rocks. Therefore, the east Lhasa terrane must have experienced widespread crustal-derived magmatism during the Late Triassic.

The Late Triassic granites studied here from the Chayu region plot in the S-type granite field on an A–C–F diagram (Fig. 13a) and have relatively high Al_2O_3 contents (12.33–14.58 wt. %), high A/CNK values (1.04–1.21), negative $\varepsilon_{Hf}(t)$ values (–8.6 to –16.2) and are mixed magmas sourced from greywacke- and pelite-derived melts (Fig. 13b). This par
supported by most zircons analysed from these granites containing inherited detrital co
(Fig. 9a–d) with metasedimentary protolith characteristics. These features suggest that th
studied S-type granites likely formed by crustal anatexis of the me
collisional orogeny (e.g. Zhang *et al.*, 2013; Chappell & White, 1992; Barbarin, 19
Liegeois, 1998), as S-type granites are uncommon in non-convergent plate
intraplate environments.

Tectonic implications

The Lhasa terrane represents the southern margin of Tibet and so is a key tectonic unit for documenting the spatio-temporal evolution of the India-Asia collision during the Cenozoic. The terrane is bordered by the Bangong-Nujiang suture zone to the north and by the Indus-Yarlung Tsangpo suture zone to the south, was initially divided into the northern, central, and southern sub-terranes, separated by the Shiquan River-
Luobadui-Milashan fault, respectively (e.g., Pan *et al.*, 2004, 2006; Zhu *et al.*, 2011, 2013). The southern part of Lhasa terrane preserves a semi-continuous record of th
northward subduction of the Neo-Tethyan ocean and the Cenozoic collision between India
and Asia (Allègre *et al.*, 1984; Acharyya, 2000; Yin & Ha
et al., 2001; Kapp *et al.*, 2003, 2007; Hou *et al.*, 2004, 2006; Chung *et al.*, 2005; Mo *et al.*, 2005; Zhang *et al*, 2010; Xia *et al*, 2011; Pan, *et al*, 2012; Zhang & Santosh, 2012; Zhu *et al.*, 2013; Dong *et al.*, 2018). However, the recent discovery of Sumdo high-pressure (HP)

metamorphic belt argued that Lhasa terrane also records the subduction and closure of Paleo-Tethys ocean from the Late Pale *et al*., 2006, 2007, 2009; Li *et al*., 2009b, 2012; Zeng *et al*., 2009; Cheng *et al*., 2015; Weller *et al*., 2015, 2016a; Chen *et al*., 2017). Together with the contemporaneous island volcanic rocks to the north, dismembered ophiolite units and the regional angul between the Middle and the Upper Permian, the belt is considered as a suture zone, which represents the relics of the northward su *et al*., 2009; Zeng *et al*., 2009; Li *et al*., 2009a, b; Cheng *et al*., 2012, 2015; Weller *et al*., 2015, 2016a). Separated by this suture zone, the Lhasa terrane is now considered to consist of two discrete crustal fragments: the North and South Lhasa terranes, with no central block (Fig. 15; Yang *et al*., 2006, 2007, 2009; Li *et al*., 2009a, b, 2012; Zeng *et al*., 2009; Zhang *et al*., 2014a; Cheng *et al*., 2015; Weller *et al*., 2015, 2016a; Chen *et al*., 2017).

The Sumdo Belt, central-east Lhasa terrane, contains high-pressure eclogite with a Late Permian metamorphic age of 270–240 Ma (Yang *et al*., 2006, 2007, 2009; Xu *et al*., 2007; Chen *et al*., 2008; Li *et al*., 2009b; Zeng *et al*., 2009; Cheng *et al*., 2012, 2015; Weller *et al*., 2015, 2016a). These rocks must have formed prior to the onset of collisional orogeny. Studies conducted on these rocks indicate that they experienced an amphibolite-epidote-amphibolite-facies retrograde metamorphism at ~200–230 Ma, which matches the evolution of many other metamorphic rocks with the similar *P–T* conditions and clockwise *P–T* path (MP amphibolite-facies, typical of the Barrovian-type metamorphism) and (Late Triassic to Early Jurassic; 225–192 Ma) along the central Lhasa terrane (Figs. 14 and 15), although they have slight variation in the character of the *P–T* paths due to different local thermal gradients in this length scale. As such, all of these lithologies constitute a large-scale Late Triassic to Early Jurassic metamorphic belt striking east–west for at least 500 km, from the Nyainqentanglha in the west, through the Sumdo in the central, to the Dongjiu region adjacent to Namche Barwa in the east (Fig. 15). This linear belt is now considered as the primary record of the collisional orogeny between North and South Lhasa terranes during the Early Mesozoic, and resulted from closure (Li *et al*., 2008, 2009a, 2011, 2012; Dong *et al*., 2011b; Lin *et al*., 2013b; Cheng *et al*., 2015; Weller *et al*., 2015, 2016a; Chen *et al*., 2017). Additionally, the Ear metamorphism along the central Lhasa terrane is associated with widespread coeval granitic magmatism, which is also interpreted to be the products of the collision between North and South terranes (Fig. 15; Kapp *et al*., 2005; Liu *et al*., 2006; Zhang *et al*., 2007; Li *et al*., 2008, 2009a; Zhu *et al*., 2011; Dong *et al*., 2015; Weller *et al*., 2016b). Therefore, we suggest that the Late Triassic magmat Motuo–Bomi–Chayu region of the eastern Lhasa terrane formed in a same tectonic setting of collisional orogeny between North and South Lhasa terranes, resulted from the closure of the PTO (Fig. 16). These data firstly indicate that the east Lhasa terrane east of the EHS, like the central-east Lhasa terrane to the west of the syntaxis, also witnessed closure of the Paleo-Tethys oceanic basin, and that the Sumdo metamorphic/orogenic belt documented in th east-central Lhasa terrane as recording the demise of the PTO should be extended eastward past the EHS into the east Lhasa terrane (Fig. 15).

There are key implications for this proposed extension of the Sumdo orogenic belt east of the EHS, where no HP or UHP eclogite-facies rocks have yet been disco absence of canonical indicators of paleo-subduction in this region of the Lhasa terrane east of Namche Barwa, such as lithofacies that form only at convergent plate boundaries (e mélange, blueschist, MORB-type eclogite, jadeitite; Stern *et al.*, 2013; Palin & White, 2016), has historically hindered tracing the paleo-closure of the North and blocks. Our new data provide evidence that regional scale metamo thickening were occurring in this region simultaneously with units in Sumdo, central Tibet (Weller *et al.*, 2015, 2016a), where HP mafic eclogite is well exposed. Further, Carboniferous-Permian volcanic rocks are documented on the southern margin o the North Lhasa plate in both the central Lhasa block and in the Motuo–Bomi–Chayu region (Fig. 15), indicating coeval alo *et al*, 2008; Yang *et al*, 2009). Why, then, are there not equivalent HP eclogite exposures east of the EHS? The exhumation potential of subducted oc depending on a wide range of petrophysical factors (e.g. Guillot et al., 2001; Warren, 2013). Further, a wide range of mechanisms has been proposed for allowing exposure at the Earth's surface following an initial period of rapid exhumation based on positive buoyancy (e.g. St-Onge et al., 2013).

Firstly, it may be considered that the subducted PTO lithosphere experienced a strike variation in dip angle, as noted today in the *et al*, 2001) and proposed for the lack of Cenozoic (U)HP eclogite in the central and east Himalaya (O'Brien *et al.*, 2001; Leech *et al.*, 2005). Eclogite from the Sumdo complex near to Basong Tso (Fig. 15) reached peak *P*–*T* conditions of 27 kbar and 670 °C, equivalent to transport to a depth of ~95 km before exhumation (Weller *et al.*, 2016a). If slab subduction beneath the eastern Lhasa terrane during the Mesozoic occurred at a much steeper angle, it is possible that the subducted oceanic root achieved negative buoyancy at an equivalent time to the Basong Tso eclogites (Agard *et al*, 2009), and so upon slab fragmentation descended terminally into the lower mantle. Alternatively, if the slab angle in this region was shallower than that interpreted for Basong Tso, relatively low-pressure eclogite may have formed (e.g. Hernandez-Uribe & Palin, 2019), although such low-angle subduction is often ass with formation of slab-derived magmas (adakites; Drummond *et al*., 1996), which are absent from the Motuo–Bomi–Chayu region. Thus, this latter hypothesis appears unlikely based on the current understanding of the geology of this part of the Lhasa terrane.

If (U)HP eclogite formed during closure of the PTO east of the EHS, and was exhumed and incorporated into the overlying crust, it may thus be pres subsurface, as the metamorphic pressures calculated from the rocks in this region are slightly lower than the eclogitic host gneisses in the Sumdo and Basong Tso region (cf. 9 kbar Basong Tso; Weller *et al*., 2015). Thus, we interpret that the level of exposure of the Lhasa terrane in Motuo–Bomi–Chayu region is slightly shallower than the temporal along-strike to the west. Such an assessment of orogen-parallel variation in exhumation rate should be considered in large-scale reconstructions of the evolution of the Tibetan r prior to the onset of uplift during Cenozoic collision with India.

CONCLUSIONS

The east Lhasa terrane wi (216–206 Ma) and regional metamorphism (209–198 Ma). Metasedimentary gneisses and schists studied from the Motuo–Bomi–Chayu region, eastern experienced medium-pressure amphibolite-facies m followed by a decompressional cooling retrograde process. The Late Triassic granites are peraluminous S-type granites and derived from the partial melting of nearby metasediments, indicating localized melt transport. The coeval Late Triassic magmatism and metamorphism in the east Lhasa terrane are related to the collision between North and South Lhasa, which resulted from closure of the Paleo-Tethys Ocean. Finally, these new data s recently discovered Sumdo metamorphic/orogenic belt that formed during closure of the PTO should be extended eastward to at least the east Lhasa terrane.

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REFERENCES

Acharyya, S.K., 2000. Break up of Australia-India-Madagascar block, opening of the Indian ocean and continental accretion in southeast Asia with s characteristics of the Peri-Indian collision zones. *Gondwana Research* **4**, 425–443.

Agard, P., Yamato, P., Jolivet, L., Burov, E., 2009. Exhumation of oceanic blueschists and eclogites in subduction zones: timing and mechanisms. *Earth-Science Reviews*, **92**, 53–79.

Allègre, C.J., Courtillot, V., Tapponnier, P., Hirn, A., Mattauer, M., Coulon, C., Jaeger, J.J., Achache, J., Schärer, U., Marcoux, J., Burg, J.P., Girardeau, J., Armijo, R., Gariépy, C., Göpel, C., Li, T.D., Xiao, X.C., Chang, C.F., Li, G.Q., Lin, B.Y., Teng, J.W., W 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., Xu, R.H., 1984. Structure and evolution of the Himalaya–Tibet orogenic belt. *Nature* **307**, 17–22.

Ashworth, J.R., 1975. The sillimanite zone of the Huntly-Portsoy area in th Dalradian, Scotland. *Geological Magazine* **112**, 113–136.

Ashworth, J.R., 1979. Textural and *Geological Society of London, Special Publications* **8**, 357–361.

Barbarin, B., 1998. A review of the relationships between granitoid types, their origins and their geodynamic environments. *Lithos* **46**, 605–626.

Bea, F., Montero, P., 1999. Behavior of accessory phases and redistribution of Zr, REE, Y, Th, and U during metamorphism and partial melting of metapelites in the lower crust: an example from the Kinzigite Forma *Geochimica et Cosmochimica Acta* **63**, 1133–1153.

Blichert, T.J., 2008. The Hf isotopic composition of zircon refer *Chemical Geology* **253**, 252-257.

Bouvier, A., Vervoort, J.D., Patchett, P.J., 2008. The Lu–Hf and Sm–Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications f composition of terrestrial planets. *Earth and Planetary Science Letters* **273**, 48–57.

Burg, J.P., Chen, G.M., 1984. Tectonics and structural *Nature* **311**, 219–223.

Caddick, M.J., Konopasek, J., Thompson, A.B., 2010. Preservation of garnet growth zoning and the duration of prograde metamorphism. *Journal of Petrology* **51**, 2327–2347.

Chappell, B.W., White, A.J.R., 1992. I- and S-type granites in the La *Transactions of the Royal* **83**, 1–26.

Chen, P.F., Bina, C.R., Okal, E.A., 2001. Variations in slab dip along the subducting Nazca Plate, as related to stress patterns and moment release of intermediate-depth seismicity and to surface volcanism. *Geochemistry, Geophysics, Geosystems*, **2**.

Chen, S.Y., Yang, J.S., Xu, X.Z., Li, H.Q., Yang, Y.H., 2008. Study of Lu–Hf geochemical tracing and LA-ICP-MS U–Pb isotopic dating of the Sumdo eclogite from the Lhasa block, Tibet. *Acta Petrologica Sinica* **24**, 1528–1538 (in Chinese with English abstract).

Chen, Z.J., Tian, Z.L., Zhang, Z.M., Dong, X., 2017. Early Jurassic metamorphism of th eastern segment of the Lhasa terrane in south Tibet and its tecto *International Geology Review* **59**, 1–17.

Cheng, H., Zhang, C., Vervoort, J.D., Lu, H.H., Wang, C., Cao, D.D., 2012. Zircon U–Pb and garnet Lu–Hf geochronology of eclogi *Lithos* **155**, 341–359.

Cheng, H., Liu, Y., Vervoort, J.D., Lu, H., 2015. Combined U–Pb, Lu–Hf, Sm–Nd and Ar–Ar multichronometric dating on the Bailang eclogite constrains the closure timing of the Paleo-Tethys Ocean in the Lhasa terrane, Tibet. *Gondwana Research* **28**, 1482–1499.

Chiu, H.Y., Chung, S.L., Wu, F.Y., Liu, D.Y., Liang, Y.H., Lin, Y.J., Iizuka, Y., Xie, L.W. Wang, Y. B., Chu, M.F., 2009. Zircon U–Pb and Hf isotope constraints from easte Transhimalayan batholiths on the precollisional magmatic and tectonic e southern Tibet. *Tectonophysics* **477**, 3–19.

Chung, S.L., Chu, M.F., Zhang, Y.Q., Xie, Y.W., Lo, C.H., Lee, T.Y., Lan, C.Y., Li, X.H Zhang, Q., Wang, Y.Z., 2005. Tibetan tectonic evolution inferred fr temporal variations in post-collisional magmatism. *Earth-Science Reviews* **68**, 173–196.

Connolly, J.A.D., 2005. Computation of phase equilibria by linear programming: a tool for geodynamic modeling and its application to *Earth and Planetary Science Letters* **236**, 524–541.

Dewey, J.F., Shackleton, R.M., Chengfa, C., Yiyin, S., 1988. The tectonic evolution of the Tibetan Plateau. *Philosophical Transactions of the Royal Society* **A 327**, 379–413.

Ding, L., Zhong, D., Yin, A., Kapp, P., Harrison, T.M., 2001. Cenozoi metamorphic evolution of the eastern Himal *Earth and Planetary Science Letters* **192**, 423–438.

Ding, L., Kapp, P., Zhong, D.L., Deng, W.M., 2003. Cenozoic Volcanism in Tibet: evidence for a Transition from Oceanic to Continental Subduction. *Journal of Petrology* **44**, 1833–1865.

Ding, H., Zhang, Z., Dong, X., Tian, Z., Xiang, H., Mu, H., Gou, Z., Shui, X., Li, W., Mao, L., 2016. Early Eocene (c. 50 Ma) collision of the Indian and A

Constraints from the North Himalayan metamorphi *Earth and Planetary Science Letters* **435**, 64–73.

Ding, H., Zhang, Z., Dong, X., Yan, R., Lin, Y., Jiang, H., 2015. Cambrian ultrap rhyolites from the Lhasa terrane, south Tibet: Evidence for Andean-type magma along the northern active margin of Gondwana. *Gondwana Research* **27**, 1616–1629.

Dong H.W., Xu, Z.Q., Li, Y., Liu, Z., Li, Z.H., 2013. Petrogenesis of high Sr/Y granite in Motuo area of Namche geochemistry, zircon U–Pb geochronology and Hf is *Acta Petrologica Sinica* **29**, 2013–2023 (in Chinese with English Abstract).

Dong, H.W., Xu, Z.Q., Yuan, L., Zhao, L., Li, H.Q., 2015. The mesozoic metamo magmatic events in the medog area, the eastern himalayan syntaxis: constraints from zircon U–Pb geochronology, trace elements and Hf isotope compositions in granitoids. *International Journal of Earth Sciences* **104**, 61–74.

Dong, X., Zhang, Z.M., Wang, J.L., Zhao, G.C., Liu, F., Wang, W., Yu, F., 2009. Provenance and formation age of Nyingchi Group in the southern Lhasa terrane, Tibetan Platean: petrology and zircon U–Pb geochronology. *Acta Petrologica Sinica* **25**, 1678–1694 (in Chinese with English Abstract).

Dong, X., Zhang, Z.M., Santosh, M., Wang, W., Yu, F., Liu, F., 2011a. Late Neoproterozoic thermal events in the northern Lhasa terrane, south Tibet: Zircon tectonic implications. *Journal of Geodynamics* **52**, 389–405.

Dong, X., Zhang, Z.M., Liu, F., Wang, W., Yu, F., Shen, K. geochronology of the Nyainqêntanglha Group from the Lhasa terrane: new constraints on the Triassic orogeny of the south Tibet. *Journal of Asian Earth Sciences* **42**, 723–739.

Dong, X., Zhang, Z.M., Klemd, R., He, Z.Y., Tian, Z tectonothermal evolution of the southern lhasa terrane, south tibet: consequence mesozoic andean-type orogeny. *Tectonophysics* **730**, 100–113.

Dong, X., Zhang, Z.M., Niu, Y.L., Tian, Z.L., Zhang, L.L., 2020. Reworked Precambr metamorphic basement of the Lhasa terrane, southern Tibet: Zi geochronology, Hf isotope and geochemistry. *Precambrian Research* **52**, 389–405.

Dong, Y.S., Li, C., Chen, H., Zhang, Y., 2011c. Study on geochronology and its geological significance of the Demala Group complex in Chayu area, Southeast Tibetan Plateau. *Acta Petrologica Sinica* **27**, 1198–1208 (in Chinese with English Abstract).

Drummond, M.S., Defant, M.J. & Kepezhinskas, P.K., 1996. Petrogenesis of slab-deri trondhjemite–tonalite–dacite/adakite magmas. *Earth and Environmental* *Transactions of the Royal Society of Edinburgh*, **87**, 205–215.

Ehlers, K., Powell, R., Stuwe, K., 1994. Cooling rate histories f equilibrium. *American Mineralogist* **79**, 737–744.

Elhlou, S., Belousova, E., Griffin, W.L., Pearson, N.J., O'Reilly, S.Y., 2006. Trace element and isotopic composition of GJ-red *Geochimica Et Cosmochimica Acta* **70**, 18-supp-S.

England, P.C., Richardson, S.W., 1977. The influence of erosion upon the mineral facies of rocks from different metamorphic environments. *Journal of the Geological Society of London* **134**, 201–213.

England, P.C., Thompson, A.B., 1984. Pressure–temp metamorphism. I. Heat transfer during the evolution of regions of thickened continental crust. *Journal of Petrology* **25**, 894–928.

Feisel, Y., White, R.W., Palin, R.M., Johnson, T.E., 2018. New constraints on granulite facies metamorphism and melt production in the Lewisian Complex, northw *Journal of Metamorphic Geology* **36**, 799–819.

Florence, F., Spear, F., 1991. Effects of diffusional modification of garnet growth zoning on P-T path calculations. *Contributions to Mineralogy and Petrology* **107**, 487–500.

Green, E.C.R., White, R.W., Diener, J.F.A., Powell, R., Holland, T.J.B., Palin, R.M., 2016. Activity–composition relations for the calculation of partia metabasic rocks. *Journal of Metamorphic Geology* **34**, 845–869.

Griffin, W.L., Pearson, N.J., Belousova, E., Jackson, S.E., van Achterbergh, E., S.Y., Shee, S.R., 2000. The Hf isotope composition of cratonic mantle: ICPMS analysis of zircon megacrysts in kimberlites. *Geochimica et Cosmochimica Acta* **64**, 133–147.

Griffin, W.L., Wang, X., Jackson, S.E., Pearson, N.J., O'Reilly, S.Y., Xu, X., Zhou, X., 2002. Zircon chemistry and magma mixing, SE China: in-situ analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. *Lithos* **61**, 237–269.

Guan, Q., Zhu, D.C., Zhao, Z.D., Dong, G.C., Zhang, L.L., Li, X.W., Liu, M., Mo, X.X Liu, Y.S., Yuan, H.L., 2012. Crustal thickening prior to 38 Ma in s evidence from lower crust-derived adakitic magmatism in the Gangd *Gondwana Research* **21**, 88–99.

Guillot, S., Hattori, K.H., de Sigoyer, J., Nägler, T., Auzende, A.L., 200 hydration of the mantle wedge and its role in the *Earth and Planetary Science Letters*, **193**, 115–127.

Harley, S.L., 1989. The origins of *Geological Magazine* **126**, 215–247.

He, S., Kapp, P., DeCelles, P.G., Gehrels, G.E., Heizler, M., 2007. Cre

geology of the Gangdese Arc in t
Tectonophysics **433**, 15–37.

Hernández-Uribe, D., Mattinson, C.G., Zhang, J.X., 2018. Phase equilibrium modelling and implications for P–T determinations of medium-temperature UHP
Qaidam terrane, China. *Journal of Metamorphic Geology*, 1–25.

Hernández-Uribe, D., Palin, R.M., 2019. A revised petrological model for subducted oceanic crust: insights from phase equilibrium modelling. *Journal of Metamorphic Geology* **37**, 745–768.

Holdaway, M.J., 2000. Application of new experimental and garnet Margules data
garnet–biotite geothermometer. *American Mineralogist* **85**, 881–892.

Holland, T.J.B., Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology* **16**, 309–343.

Holland, T., Powell, R., 2003. Activity–composition relations for phases
calculations: an asymmetric multicomponent formulation. *Contributions to Mineralogy and Petrology* **145**, 492–501.

Holness, M.B., Clemens, J.D., 1999. Partial melting of the Appin Qu
fracture-controlled H_2O infiltration in the aureole of the Ballachulish Igneous Complex, Scottish Highlands. *Contributions to Mineralogy and Petrology* **136**, 154–168.

Holness, M.B., Sawyer, E.W., 2008. On the pseudomorphing of melt-filled pores during the crystallization of migmatites. *Journal of Petrology* **49**, 1343–1363.

Hou, Z.Q., Gao, Y.F., Qu, X.M., Rui, Z.Y., Mo, X.X., 2004. Origin of adakitic intrus
generated during mid-Miocene
Earth and Planetary Science Letters **220**, 139–155.

Hou, Z.Q., Mo, X.X., Gao, Y.F., Yang, Z.M., Dong, G.C., Ding, L., 2006. Early processes and tectonic model for the Indian–Asian continental collision:
Cenozoic Gangdese igneous rocks in Tibet. *Acta Geologica Sinica* **80**, 1233–1248 (in Chinese with English abstract).

Hoskin, P.W.O., Schaltegger, U., 2003. The composition of
metamorphic petrogenesis. *Reviews in Mineralogy and Geochemistry* **53**, 27–62.

Hu, P.Y., Li, C., Wang, M., Xie, C.M., Wu, Y.W., 2013. Cambrian volcanism in the Lhasa terrane, southern Tibet: record of an early Paleozoic Andean-type magmatic arc along the Gondwana proto-Tethyan margin. *Journal of Asian Earth Sciences* **77**, 91–107.

Hu, P.Y., Zhai, Q.G., Zhao, G.C., Tang, Y., Wang, H.T., Zhu, D.C., Wang, W., Wu, H., 2019. Middle Neoproterozoic magmatic event in the western Nam Tso area, Tibetan Plateau: Constraint on the origin of the North Lhasa terrane. *Acta Petrologica Sinica* **35**, 3115–3129 (in Chinese with English abstract).

Ji, W.H., Chen, S.J., Zhao, Z.M., Li, R.S., He, S.P., Wang, C., 2009. Dis
Cambrian volcanic rocks in the Xainza area, Gangdese orogenic belt, Tibet, China and its significance. *Geological Bulletin of China* **28**, 1350–1354 (in Chinese with English abstract).

Kapp, P., DeCelles, P.G., Gehrels, G.E., Heizler, M., Ding, L., 2007. Geological records of the Lhasa-Qiangtang and Indo-Asian collisions in the Nima area o
Geological Society of America Bulletin **119**, 917–933.

Kapp, J., 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 th
block, southern Tibet. *Journal of Geophysical Research* **110**, 1–23.

Kapp, P., Murphy, M.A., Yin, A., Harrison, T.M., Ding, L., Guo, J., 2003. Mesozoi
Cenozoic tectonic evolution of th
Tectonics **22**, 1029.

Kohn, M.J. & Spear, F., 2000. Retrograde net transfer reaction insuran
temperature estimates. *Geology* **12**, 1127–1130.

Kriegsman, L.M., Alvarez-Valero, A.M., 2010. Melt-producing
reactions in pelitic xenoliths and migmatites. *Lithos* **116**, 310–320.

Kunz, B.E., Regis, D., Engi, M., 2018. Zircon ages in granulite facies rocks: decoupling from geochemistry above 850 °C? *Contributions to Mineral*
173, 26–41.

Lease, R.O., Ehlers, T.A., Enkelmann, E., 2016. Large along-strike variations in the onset of Subandean exhumation: Implications f
Earth and Planetary Science Letters, **451**, 62–76.

Leech, M.L., Singh, S., Jain, A.K., Klemperer, S.L., Manickavasagam, R.M.,
onset of India–Asia continental collision: early, steep subduction required by the timing of UHP metamorphism in the western Himalaya. *Earth and Planetary Scie*
Letters, **234**, 83–97.

Li, H.Q., Cai, Z.H., Chen, S.Y., Tang, Z.M., Yang, M., 2008. The Indosinian or
occurred in Lhasa terrain and the evidence from muscovite ^{40}Ar–^{39}Ar geochronology. *Acta Petrologica Sinica* **24**, 1595–1604 (in Chinese with English abstract).

Li, H.Q., Xu, Z.Q., Yang, J.S., Cai, Z.H., Chen, S.Y., Tang, Z.M., 2(
Indosinian orogenesis in Lhasa Terrane, Tibet. *Journal of Earth Science* **20**, 348–363.

Li, H.Q., Xu, Z.Q., Yang, J.S., Tang, Z.M., Yang, M., 2011. Syn-collisional exhumation of Sumdo eclogite in the Lhasa Terrane, Tibet: evidences from structural deformation and ^{40}Ar–^{39}Ar geochronology. *Earth Science Frontiers* **18**, 66–78 (in Chinese with English abstract).

Li, H.Q., Xu, Z.Q., Yang, J.S., Tang, Z.M., 2012. Indosinian orogenesis in the Lhasa Terrane, Tibet: new $^{40}Ar/^{39}Ar$ muscovite geochronology and ev Acta Geological Sinica **86**, 116–1127.

Li, H.Q., Xu, Z.Q., Wang, R.R., Dong, H.W., Sun, Z.B., Huang, X.M., 2013a. Petrogenesis and tectonic significance of the Late Jurassic granite discovered in the Bomi- region, eastern Tibet. *Acta Petrologica Sinica* **29**, 2024–2032 (in Chinese with English abstract).

Li, Z.L., Yang, J.S., Xu, X.Z., Li, T.F., Xu, X.Z., Ren, Y.F., R Geochemistry and Sm–Nd and Rb–Sr isotopic compositions of eclogite in the Lha terrane, Tibet, and its geological significance. *Lithos* **109**, 240–247.

Li, W.K., Xie, J.C., Dong, G.C., Mo. X.X., Zhao, Z.D., geochronology and geochemistry of Bomi granitoi significance. *Acta Petrologica Sinica* **29**, 3745–3754 (in Chinese with English abstract).

Li, S.S., Santosh, M., Palin, R.M., 2018. M Paleoproterozoic transition associated with microblock amalgamation in the Dharw Craton, India. *Journal of Petrology* **59**, 2435–2462.

Liang, Q., Jing, H., Gregoire, D.C., 2000. Determination of trace elements in granit inductively coupled plasma mass spectrometry. *Talanta* **51**, 507–513.

Liegeois, J.P., 1998. Preface—Some word *Lithos* **45**, 15–17.

Lin, Y.H., Zhang, Z.M., Dong, X., Shen, K., Lu, X., 2013a. Precambrian evolution of th lhasa terrane, tibet: constraint from the zircon U–Pb geochronology of the gr *Precambrian Research* **237**, 64–77.

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, *Journal of Asian Earth Sciences* **78**, 160–183.

Liu, Q.S., Jiang, W., Jian, P., Ye, P.S., Wu, Z.H., Hu, D.G., 2006. Zircon SHRIMP U–Pb age and petrochemical and geochemical features of Mesozoic muscovite monzonitic granite at Ningzhong, Tibet. *Acta Petrologica Sinica* **22**, 643–652 (in Chinese with English abstract).

Liu, Y.S., Hu, Z.C., Zong, K.Q., Gao, C.G., Gao, S., X Reappraisement and refinement of zircon U-Pb isotope and trace element analyses by LA-ICP-MS. *Chinese Science Bulletin* **55**, 1535–1546.

Ludwig, K.R., 2003. Isoplot/Ex Version 3.00: A Geochronological Toolkit fo Excel. *Special Publication, No.* 1–73.

Metcalfe, I., 2006. Palaeozoic and Mesozoic tectonic evolution and palaeogeography of East Asian crustal fragments: the Korean Peninsula in context. *Gondwana Research* **9**, 24–46.

Mo, X.X., Dong, G.C., Zhao, Z.D., Zhou, S., Wang, L.L., Qiu, R.Z., Zhang, F.Q., Spatial and temporal distribution and characteristics of granitoids in t Tibet and implication for crustal growth and evolution. *Geological Journal of China Universities* **11**, 281–290.

Mo, X.X., Hou, Z.Q., Niu, Y., Dong, G., Qu, X., Zhao, Z.D., Yang, Z., contributions to crustal thickening during continental collision: evidence from Cenozoic igneous rocks in southern Tibet. *Lithos* **96**, 225–242.

Mo, X.X., Niu, Y.L., Dong, G.C., Zhao, Z.D., Hou, Z.Q., Zh Contribution of syncollisional felsic magmatism to continental crust grow study of the Paleocene Linzizong volca *Chemical Geology* **250**, 49–67.

Mo, X.X., Zhao, Z.D., Deng, J.F., Dong, G.C., Zhou, S., Guo, T.Y., Zhang, S.Q., Wang, L.L., 2003. Response of volcanism to the India-Asia collision. *Earth Science Frontiers* **10**, 135–148 (in Chinese with English abstract).

Mo, X.X., Zhao, Z.D., DePaolo, D.J., Zhou, S., Dong, G.C., 2006. Three types of collisional and post-collisional magmatism in the Lhasa block, Tibet and implications for intracontinental subduction and mineralizatio *Acta Petrologica Sinica* **22**, 795–803 (in Chinese with English abstract).

Murphy, M.A., Yin, A., Harrison, T.M., Dürr, S.B., Chen, Z., Ryerson, F.J., Kidd, W.S Wang, X., Zhou, X., 1997. Did the Indo-Asian collision alone cre plateau? *Geology* **25**, 719–722.

Najman, Y., Appel, E., Boudagher-Fadel, M., Bown, P., Carter, A., Garzanti, E., Godin, L., Han, J., Liebke, U., Oliver, G. and Parrish, R., 2010. Timing of India–Asia collision: Geological, bi *Journal of Geophysical Research: Solid Earth*, **115,** B12.

O'Brien, P.J., Zotov, N., Law, R., Khan, M.A., Jan, M.Q., 2001. Coesite eclogite and implicati *Geology* **29**, 435–438.

Palin, R.M., White, R.W., 2016. Emergence of blueschists on Earth linked to secular changes in oceanic crust composition. *Nature Geoscience*, **9**, 60–64.

Palin, R.M., Dyck, B.J., 2020. Met *Encyclopedia of Geology, 2nd Edition: Reference Module i Environmental Sciences*, Elsevier, doi: 10.1016/B978-0-08-102908-4.00081-3

Palin, R.M., Searle, M.P., Waters, D.J., Parrish, R.R., Roberts, N.M.W., Horstwood, M.S.A., Yeh, M.W., Chung, S.L. Anh, T.T., 2013. A geochronological and petrological study of anatectic paragneiss and associated granite dykes fr metamorphic core complex, North Vietnam: constraints on the timing of metamorphism within the Red River shear zone. *Journal of Metamorphic Geology* **31**, 359–387.

Palin, R.M., Searle, M.P., St-Onge, M.R., Waters, D.J., Roberts, M.S.A., Parrish, R.R., Weller, O.M., Chen, S., Yang, J., 2014. Monazite geochronology and petrology of kyanite- and sillimanite-grade migmatites from the northwestern flank of the eastern Himalayan syntaxis. *Gondwana Research* **26**, 323–347.

Palin, R.M., Searle, M.P., St-Onge, M.R., Waters, D.J., Roberts, M.S.A., Parrish, R.R. Weller, O.M., 2015. Two-stage cooling history of semi-pelitic mylonite (sensu lato) from the Dongjiu–Milin shear zone, northwest flank of the eastern Himalayan syntaxis. *Gondwana Research* **28**, 509–530.

Palin, R.M., Weller, O.M., Waters, D.J., Dyck, B., 2016. Quantifying geological uncertainty in metamorphic phase equilibria modelling; a Monte Carlo assessment and implications for tectonic interpretations. *Geoscience Frontiers* **7**, 591–607.

Palin, R.M., Sayed, A.B., White, R.W., Mertz-Kraus, R., 2018. Origin, age, and significance of deep-seated granulite-facies migmatites in the Barrow zones of S Leuchan, Glen Muick area. *Journal of Metamorphic Geology* **36**, 1071–1096.

Palin, R.M., Santosh, M., Cao, W., Li, S., Hernandez-Uribe, D., Parsons, A.J., 2020. Secular change and the onset of plate tectonics on Earth. *Earth-Science Reviews*, **207**, 103172

Pan, G., Ding, J., Yao, D., Wang, L., 2004. Geological Map of Qinghai-Xi Plateau and Adjacent Areas (1:1500000). *Chengdu Cartographic Publishing House,* Chengdu, China (in Chinese).

Pan, G.T., Mo, X.X., Hou, Z.Q., Zhu, D.C., Wang, L.Q., Li, G.M., Zhao, Z.D., Geng, Q.R., Liao, Z.L., 2006. Spatial–temporal framework of the Gangdese orogenic belt and evolution. *Acta Petrologica Sinica* **22**, 521–533 (in Chinese with English abstract).

Pan, G.T., Wang, L.Q., Li, R.S., Yuan, S.H., Ji, W.H., Yin, F.G., Zhang, W.P., Wang, B.D., 2012. Tectonic evolution of the Qinghai-Tibet Plateau. *Journal of Asian Earth Sciences* **53**, 3–14.

Pattison, D.R.M., 1992. Stability of andalusite and sillimanite and the Al2SiO5 triple point: constraints from the Ballachulish Aureole, Scotland. *The Journal of Geology* **100**, 423–446.

Peng X.J., Chen Y.M., Zhang S.Q., 1999. Paleoproterozoic Demala Group-complex in the Zayu area, Tibet. *Regional Geology of China* **18**, 148–154 (in Chinese with English Abstract).

Powell, R., Holland, T.J.B., 2008. On thermobar *Journal of Metamorphic Geology*, **26**, 155–179.

Rubatto, D., 2002. Zircon trace element geochemistry: partitioning with garnet and the link between U–Pb ages and metamorphism. *Chemical Geology* **184**, 123–138.

Rubatto, D., Hermann, J., 2007. Zircon beh *Elements* **3**, 31–35.

Rubatto, D., Chakraborty, S., Dasgupta, S., 2013. Timescale of crustal melting in the Higher Himalayan Crystallines (Sikkim, elementconstrained monazite and zircon chronology. *Contributions to Mineralogy and Petrology* **165**, 349–372.

Searle, M.P., Windley, B.F., Coward, M.P., Cooper, D.J.W., Rex, A.J., Rex, D., Xiao, X.C., Jan, M.Q., Thakur, V.C., Kumar, S., 1987. The closing of Tethys and the tectonics of the Himalaya. *Geological Society of America Bulletin* **98**, 678–701.

Shui, X.F., He, Z.Y., Klemd, R., Zhang, Z.M., Lu, T.Y., Yan, L.L., 2018. Earl adakitic rocks in the southern Lhasa sub-terrane, southern Tibet: geodynamic implications. *Geological Magazine* **155**, 1–17.

Soderlund, U., Patchett, P.J., V ^{176}Lu decay constant determined by Lu-Hf and U-Pb isotope systematics of Precambrian mafic intrusions. *Earth and Planetary Science Letters* **219**, 311–324.

Spear, F.S., 1991. On the interpretation of peak metamorphic temperatures in light of garnet diffusion during cooling. *Journal of Metamorphic Geology* **9**, 379–388.

Spear, F.S., 1993. Metamorphic Phase Equilibria and Pressure–Temperature– *Mineralogical Society of America*, Washington, DC.

Stern, R.J., Tsujimori, T., Harlow, G., Groat, L.A., 2013. *Geology*, **41**, 723–726.

St-Onge, M.R., Rayner, N., Palin, R.M., Searle, M.P., Waters, pressure-temperature-time constraints for the Tso Morari dome implications for the burial and exhumation path of UHP units in the western Himalaya. *Journal of Metamorphic Geology* **31**, 469–504.

Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts implications for mantle compos *Geological Society, Lond* *Special Publications* **42**, 313–345.

Sylvester, P.J., 1998. *Lithos* **45**, 29–44.

Tajčmanová, L., Connolly, J.A.D., Cesare, B., 2009. A thermodynamic model for titanium and ferric iron solution in biotite. *Journal of Metamorphic Geology* **27**, 153–165.

Tapponnier, P., Peltzer, G., Armijo, R., 1986. On the mechanics of the collision

India and Asia. *Geological Society, London, Special Publications* **19**, 113–157.

Thompson, A.B., England, P.C., 1984. Pressure–temp metamorphism. II. Their inference and interpretation using mineral a metamorphic rocks. *Journal of Petrology* **25**, 929–955.

Tyler, I.M., Ashworth, J.R., 1982. Sillimanite-potash feldspar ass pelites, Strontian, Scotland. *Contributions to Mineralogy* **81**, 18–29.

Wang, L.Q., Pan, G.T., Zhu, D.C., Zhou, C.Y., Yu Carboniferous-Permian island arc orogenesis in the Gang evidence from volcanic rocks and geochemistry. *Geological Bulletin of C* **27**, 1509–1534 (in Chinese with English abstract).

Waters, D.J., 2001. The significance of prograde and retrograde quartz-bearing intergrowth microstructures in partially melted granulite facies rocks. *Lithos* **56**, 97–110.

Waters, D.J., 2019. Metamorphic constraints on the tectonic evolution of the High Himalaya in Nepal: the art of the possible. *Geological Society of London Special Publications* **483**, SP483–2018.

Warren, C.J., 2013. Exhumation of (ultra)-high-pressure terranes: concepts and mechanisms. *Solid Earth*, **4**, 75–92.

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 P–T–t conditions of north–south accretion: New insight into the pre-Himalayan architecture of the *Journal of Metamorphic Geology* **33**, 91–113.

Weller, O.M., St-Onge, M.R., Rayner, N., Waters, D.J., Searle, M.P., Palin, R.M., 2016a. U–Pb zircon geochronology and phase equilibria modelling of a mafic eclogite from the Sumdo complex of south-east Tibet: insights into prograde zircon assembly of the Tibetan plateau. *Lithos* **262**, 729–741.

Weller, O.M., St-Onge, M.R., Rayner, N., Searle, M.P., Waters, D. magmatism in the Western Nyainqentanglha mountains of southern Tibet: An exhumed bright spot? *Lithos* **245**, 147–160.

White, R.W., Powell, R., Holland, T.J.B., Johnson, T.E., Green, E.C.R., 2014. New mineral activity–composition relations for thermodynamic calculations in metapelitic systems. *Journal of Metamorphic Geology* **32**, 261–286.

Whitney, D.L., Evans, B.W., 2010. Abbreviations for names of rock-f *American Mineralogist* **95**, 185–187.

Worley, B., Powell, R., 2000. High-precision relative thermobarometry: theory and a worked example. *Journal of Metamorphic Geology* **18**, 91–102.

Wortel, M.J.R., 1984. Spatial and temporal variations in the Andea
Journal of the Geological Society, 141, 783–791.

Wu, C.M., Zhang, J., Ren, L.D., 2004. Empirical garnet–biotite–plagioclase–quartz (GBPQ) geobarometry in medium- to high-grade metapelites. *Journal of Petrology* **45**, 1907–1921.

Xia, L.Q., Li, X.M., Ma, Z.P., Xu, X.Y., Xia, Z.C., 2011. Cenozoic volcanism and tectonic evolution of the Tibetan Plateau. *Gondwana Research* **19**, 850–866.

Xie, Y.W., Peng, X.J., Qiangba, Z.X., Xiluo, L.J., Ciren, Y.J., 2007. Recent progress in the study of the Neoproterozoic-Cambrian Bomi Group in the Bomi-Zayü area, Tibet, China. *Geological Bulletin of China* **26**, 81–87 (in Chinese with Engl
abstract).

Xu, R.H., Schärer, U., Allègre, C.J., 1985. Magmatism and metamorphism in the Lhasa block (Tibet): a geochronological study. *Journal of Geology* **93**, 41–57.

Xu, Z.Q., Li, H.B., Yang, J.S., 2006. An orogenic plateau: the orogenic collage and orogenic types of the Qinghai-Tibet plateau. *Earth Science Frontiers* **13**, 1–17 (in Chinese with English abstract).

Xu, X.Z., Yang, J.S., Li, T.F., Chen, S.Y., Ren, Y.F., Li, Z.L., Shi, Y.R., 2007, SHRIMP U–Pb ages and inclusions of zircons from the Sumdo eclogite in the Lhasa blo
China. *Geological Bulletin of China* **26**, 1340–1355 (in Chinese with English abstract).

Xu, Z.Q., Dilek, Y., Cao, H., Yang, J.S., Robinson, P., Ma, C.Q., Li, H.Q., Jolivet, M., Roger, F., Chen, X.J., 2015. Paleo-Tethyan evolution of Tibet a
Cimmerides and West Cathaysides. *Journal of Asian Earth Sciences* **105**, 20–337.

Yang, J.S., Xu, Z.Q., Geng, Q.R., Li, Z.L., Xu, X.Z., Li, T.F., Ren, Y.F., 2006, A possible new HP/UHP (?) metamorphic belt in China: Discovery of eclogite in the Lhasa Terra
Tibet. *Acta Geologica Sinica* **80**, 1787–1792 (in Chinese with English abstract).

Yang, J.S., Xu, Z.Q., Li, T.F., Li, H.Q., Li, Z.L., Ren, Y.F., Xu, X.Z., Chen, S.
Oceanic subduction-type eclogite in the Lhasa block, Tibet, China: Rem
Paleo-Tethys ocean basin? *Geological Bulletin of China* **26**, 1277–1287 (in Chinese with English abstract).

Yang, J.S., Xu, Z.Q., Li, Z.L., Xu, 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 fo
PaleoTethys? *Journal of Asian Earth Sciences* **34**, 76–89.

Yin, A., Harrison, T.M., 2000. Geologic evolution of the Him
Annual Review of Earth and Planetary Sciences **28**, 211–280.

Zeng, L.S., Liu, J., Gao, L.E., Chen, F.Y., Xie, K.J., 2009. Early Mesozoic high-pre
metamorphism within the Lhasa block, Tibet and implications for regional tecton

Earth Science Frontiers **16**, 140–151.

Zhang, J., Santosh, M., Wang, X., Guo, L., Yang, X., Zhang, B., 2012a. Tectonics o northern Himalaya since the India–Asia collision. *Gondwana Research*, **21**, 939–960.

Zhang, K.J., Xia, B., Zhang, Y.X., Liu, W.L., Zeng, L., Li, J.F., Xu, L.F., 2014c. C Tibetan Meso-Tethyan oceanic plateau. *Lithos* **210-211**, 278–288

Zhang, X.R., Shi, R.D., Huang, Q.S., Liu, D.L., Gong, X.H., Chen, S.S., Wu, K., Yi, G.D., Sun, Y.L., Ding, L., 2014b. Early Jurassic high-pressure metamorphism of the Amd terrane, Tibet: Constraints from zircon U–Pb geochronolog *Gondwana Research* **26**, 975–985.

Zhang, H.F., Xu, W.C., Guo, J.Q., Zong, K.Q., Cai, H.M., Yuan, H.L., 2007. In orogenesis of the Gangdise terrane: evidences fr petrogenesis of granitoids. *Earth Science–Journal of China University of Geosciences* **32**, 155–166 (in Chinese with English abstract).

Zhang, Z.M., Zhao, G.C., Santosh, M., Wang, J.L., Dong, X., S Cretaceous charnockite with adakitic affini southeastern Tibet: Evidence for Neo-T *Gondwana Research* **17**, 615–631.

Zhang, Z.M., Santosh, M., 2012. Tectonic evolution of Tibet and surr *Gondwana Research* **21**, 1–3.

Zhang, Z.M., Dong, X., Liu, F., Lin, Y.H., Yan, R., He, Z.Y., Santosh, M., 2012b. The making of Gondwana: Discovery of 650 Ma HP granulites from the Nort *Precambrian Research* **212**, 107–116.

Zhang, Z.M., Dong, X., Liu, F., Lin, Y.H., Yan, R., Santosh, M., 2012c. Tectonic Evolution of the Amdo Terrane, Central Tibet: Petrochemistry and Zircon U-Pb Geochronology. *Journal of Geology* **120**, 431–451.

Zhang, Z.M., Dong, X., Xiang, H., Liou, J.G., Santosh, M., 2013. Building of th Gangdese Arc, South Tibet: Paleocene Plutonism and Granulite-Facies Metamorphism. *Journal of Petrology* **54**, 2547–2580.

Zhang, Z.M., Dong, X., Santosh, M., Zhao, G.C., 2014a. Metamorp evolution of the Lhasa terrane, Central Tibet. *Gondwana Research* **25**, 170–189.

Zhang, Z.M., Xiang, H., Dong, X., Li, W.C., Ding, H.X., Gou, Z.B., Tia Oligocene HP metamorphism and anatexis of the Higher H Sequence in Yadong region, east-central Himalaya. *Gondwana Research* **41**, 173–187.

Zhu, D.C., Mo, X.X., Niu, Y., Zhao, Z.D., Wang, L.Q., Liu, Geochemical investigation of Early Cretaceous igneous rock traverse throughout the central Lhasa Terrane, Tibet. *Chemical Geology* **268**, 98–312.

Zhu, D.C., Zhao, Z.D., Niu, Y., Mo, X.X., Chung, S.L., Hou, Z.Q., Wang, L.Q., Wu, F.Y., 2011. The Lhasa Terrane: Record of a microcontinent and its histories of growth. *Earth and Planetary Science Letters* **301**, 241–255.

Zhu, D.C., Zhao, Z.D., Niu, Y.L., Dilek, Y., Wang, Q., Ji, W.H., Dong, G.C., Sui, Q.L., Liu, Y.S., Yuan, H.L., Mo, X.X., 2012. Cambrian bimodal volcanism in the Lhasa Terrane, southern Tibet: record of an early Paleozoic Andean-type magmatic arc in the Australian protoTethyan margin. *Chemical Geology* **328**, 290–308.

Zhu, D.C., Zhao, Z.D., Niu, Y., Dilek, Y., Hou, Z.Q., Mo, X.X., 2013. The origin and pre-Cenozoic evolution of the Tibetan Plateau. *Gondwana Research* **23**, 1429–1454.

Zhu, D.C., Wang, Q., Zhao, Z.D., Chung, S.L., Cawood, P.A., Niu, Y., Liu, S.A., Wu, F.Y., Mo, X.X., 2015. Magmatic record of India-Asia collision. *Sci Rep-Uk* **5**, 17236.

Zhu, D.C., Li, S.M., Cawood, P.A., Wang, Q., Zhao, Z.D., Liu, S.A., Wang, L.Q., Assembly of the Lhasa and Qiangtang terranes in central Tibet by divergent subduction. *Lithos* **245**, 7–17.

FIGURE CAPTIONS

Fig. 1. (a) Simplified geological map of the Lhasa terrane, showing the main suture zones and terranes. JSSZ, Jinsha suture zone; LSSZ, Longmu Tso-Shuanghu suture zone; BNSZ, Bangong-Nujiang suture zone; SDSZ, Sumdo Paleo-Tethys suture zone; ITSZ, Indus-Yarlung Tsangpo suture zone; ATF, Altyn Tagh Fault; KJF, Karakurum-Jiali Fault; RRK, Red River Fault; EHS, eastern Himalayan syntaxis; NQ, North Qiangtang terrane; SQ, South Qiangtang terrane; NL, North Lhasa terrane; SL, South Lhasa terrane. (b) Geological map of the east Lhasa terrane, showing the sample locations and magmatic and metamorphic ages reported in this work. The literature data are after Dong *et al*., (2011c, 2015).

Fig. 2. Field photographs and photomicrographs of the magmatic rocks from the east Lhasa terrane, showing the texture and mineral components of granite. Ms, muscovite; Bt, biotite; Pl, plagioclase; Kfs, K-feldspar; Q, quartz.

Fig. 3. Outcrops of metapelitic gneiss (a) and schist (b) in the east Lhasa terrane.

Fig. 4. Photomicrographs of mineral assemblages and microstructures of the gneisses. (a) and (b) Sample T15–32–3 with large garnet porphyroblasts surrounded by an aligned m defined by biotite, muscovite, plagioclase, quartz and minor sillimanite. Garnet and biotite are partly replaced by chlorites. (c) and (d) Sample T15–33–7 showing a gneiss to pe sillimanite–biotite–plagioclase–quartz matrix with garnet and K-feldspar porphyroblasts, and

large lath-like or randomly orientated fine-grained muscovite. (e) A very small cuspate quartz dihedral angle against plagioclase in sample T15–33–7. (f) K-feldspar grains surrounded by plagioclase rim in sample T15–33–7. Ms, muscovite; Bt, biotite; Pl, plagioclase; Kfs, feldspar; Q, quartz; Sil, sillimanite; Grt, garnet; Chl, Chlorite; Ilm, ilmenite.

Fig. 5. Photomicrographs of mineral assemblages and microstructures of the schists. (a) and (b) Sample T15–43–1 exhibiting large garnet porphyroblasts, rims replaced by biotite-muscovite-plagioclase aggregates, wrapped by matrix folia biotite, muscovite, plagioclase, quartz and minor ilmenite. Muscovite occurs both as aligned flakes within foliation and as larger, subhedral to euhedral, unfoliated grains against garnet rims. (c) and (d) Sample T15–43–3 containing garnet porphyroblasts surrounded by a matrix foliation defined by bio quartz. Garnet rims are part cordierite. (e) Micro-exsolved lamellae of plagioclase hosted by K-feldspar in sample T15–43–3. (f) Garnet grains have inclusion-rich cores and inclusion-absen textural equilibration with matrix phases. Ms, muscovite; Bt, biotite; Pl, plagioclase; Kfs, K-feldspar; Q, quartz; Sil, sillimanite; Grt, garnet; Crd, Cordierite; Ilm, ilmenite.

Fig. 6. Compositional profiles of garnet por sample T15–43–1; b, sample T15–43–3) and X_{Mg} vs. Ti (cpfu) diagram for biotite (c).

Fig. 7. (a) Primitive mantle normalized trace element diagrams and (b) chondrite normalized rare earth element (REE) diagrams of granites. The trace element data for primitive mantle and REE data for chondrites are after Sun and McDonough (1989).

Fig. 8. Pressure–temperature (*P*–*T*) pseudosections for samples (a) T15–32–3, (b) T15–33–7, (c) T15–43–1 and (d) T15–43–3, calculated using the bulk-rock compositions give Supplementary Table 6. (e) and (f) Summary plots *P*–*T* evolution of studied gneisses and schists respectively. The red bold fonts refer to th observed mineral assemblage. The bold brown lines mark the positions of the solidus, bold yellow lines mark the stability of muscovite. The blue, purple, green represent plagioclase (X_{Ca}), biotite (Ti) and garnet (X_{Mg}) and (X_{Ca}) isopleths, respectively. The pink- and blue-filled polygons represent the peak a conditions. The yellow-filled circles represent the thermobarometry. The bold black lines and dashed lines with arrow refer to the prograde and retrograde *P*–*T* paths. Peak apparent thermal gradients wer

assuming a crustal density of 3000 kg/m^3 and a linear gradient.

Fig. 9. Representative cathodoluminescence (CL) images of zircon grains from studied rocks showing the analysed spot locations and related ages (in Ma).

Fig. 10. Chondrite-normalized REE patterns of zircons from granites (a) and metamorphic rocks (b). Chondrite values are after Sun and McDonough (1989).

Fig. 11. Zircon U–Pb concordia diagrams for studied rocks.

Fig. 12. Zircon $\varepsilon_{Hf}(t)$ values vs. U–Pb ages diagram of the Late Triassic granites.

Fig. 13. (a) A–C–F discrimination diagram for I-type and S-type magmas (after Chappell and White, 1992) and (b) Rb/Sr vs. Rb/Ba discrimination diagram for source of the (after Sylvester, 1998).

Fig. 14. Summary of the inferred *P–T–t* paths for the studied east Lhasa terrane gneisses and schists, and comparison with those reconstructed fo metamorphic rocks from central-east Lhasa terrane. *P–T* paths. The geothermal gradients of 20, 27 and 45°C/km are shown. Aluminos phase relations are after Pattison (1992). *et al*. (2011b), Lin *et al*. (2013b), Weller *et al*. (2015) and Chen *et al*. (2017).

Fig. 15. The distribution characteristics of the Paleo-Tethys Ocean orogenic belt related magmatic and metamorphic rocks. The abbreviations are the same as in Fig. 1.

Fig. 16. Schematic plate tectonic evolution model of the east Lhasa terrane during the Early Mesozoic. The abbreviations are the same as in Fig. 1.

TABLE CAPTIONS

Table 1. The major features of the studied rocks from the east Lhasa terrane.

Supplementary table 1. The compositions of representative garnet from the east L terrane metamorphic rocks.

Supplementary table 2. The compositions of representative biotite from the east L terrane metamorphic rocks.

Supplementary table 3. The compositions of representative plagioclase from the east Lhasa terrane metamorphic rocks.

Supplementary table 4. The compositions of representative K-feldspar from the east Lhasa terrane metamorphic rocks.

Supplementary table 5. The compositions of representative cordierite from the east Lhasa terrane metamorphic rocks.

Supplementary table 6. Major (wt. %) and trace (ppm) element data of the studied rocks from the east Lhasa terrane.

Supplementary table 7. LA–ICP–MS U–Pb dating and rare earth element results of the magmatic and metamorphic zircons.

Supplementary table 8. Hf isotopic data of zircons for the granites from the east Lhasa terrane.