Discovery of Meso- to Neoproterozoic magmatism and metamorphism in the eastern Himalaya: Implications for assembly of the Rodinia supercontinent

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Abstract

The Himalayan orogen formed following the Cenozoic India-Asia collision, and contains many exposures of Precambrian rocks that reveal the pre-collisional geological evolution of India and its behavior during the assembly and breakup of the Rodinia supercontinent. Here we present new geochronological and geochemical data for amphibolites and orthogneisses from the eastern Himalayan orogen, which record the first identification of Late Mesoproterozoic arc-related magmatism and Early Neoproterozoic metamorphism in the region. Magmatic zircon cores from amphibolites and orthogneisses yield mean $^{207}Pb/^{206}Pb$ ages of 1200–1140 Ma, whereas metamorphic zircon rims give mean $^{206}Pb/^{238}U$ ages of 940–920 Ma. These rocks have fractionated REE patterns, LILE enrichments, and negative Nb, Ta, and Ti anomalies. The amphibolites have high zircon $\varepsilon_{Hf}(t)$ values of +2.6 to +11.5 and whole-rock $\varepsilon_{Nd}(t)$ values of -0.80 to +4.06, and low whole-rock $^{87}Sr/^{86}Sr_{(i)}$ ratios, while the orthogneisses have low zircon $\varepsilon_{Hf}(t)$ values of -15.1 to -0.4 and whole-rock $\varepsilon_{Nd}(t)$ values of -7.66 to -3.88, and high whole-rock $^{87}Sr/^{86}Sr_{(i)}$ ratios. These compostions suggest that the amphibolite protoliths were derived from partial melting of depleted mantle, and the orthogneiss protoliths were derived from remelting of more ancient crustal rocks during Mesoproterozoic accretionary orogeny. These records are consistent with Grenvillian tectonothermal events of the Rayner-Eastern Ghats orogen, implying that a huge Meso- to Neoproterozoic accretionary to collisional system operated along the eastern Indian margin during the assembly of Rodinia. These findings also suggest that the Lhasa terrane was situated along the northern Indian margin during the Neoproterozoic, supporting hypotheses that the Lhasa terrane previously drifted away from the Indian continent before they were combined again during the Cenozoic. These new data thus constrain

Neoproterozoic plate tectonic reconstructions and paleogeographic models of Rodinia supercontinent formation.

Keywords: Himalayan orogen; Mesoproterozoic arc magmatism; Neoproterozoic metamorphism; Rodinia supercontinent; Precambrian evolution

1. Introduction

The Himalayan orogen resulted from the Cenozoic collision between the Indian and Asian continents, which was characterized by intensive metamorphism, anatexis, magmatism and deformation (e.g., Yin and Harrison, 2000). However, there are several occurrences of Precambrian sedimentary, magmatic, and metamorphic units preserved within the Himalayan orogen (Fig. 1a), which shed important light on its pre-collisional history. Such events include Late Paleoproterozoic magmatism (~1900–1700 Ma; e.g., Pandey, 2022 and references therein), Early Mesoproterozoic (~1650–1550 Ma) magmatism and metamorphism (Zhang et al., 2012a; Guo et al., 2017), Late Mesoproterozoic (~1150 Ma) metamorphism (Wang et al., 2014), and the Early Neoproterozoic magmatism (~880–800 Ma; Ding and Zhang, 2016; Zhang et al., 2021).

Late Mesoproterozoic to Early Neoproterozoic magmatic and metamorphic rocks occur in the Shillong Plateau and the Eastern Ghats Belt in the southeastern part of Indian continent (e.g., Yin et al., 2010; Dasgupta et al., 2017). Coeval tectonothermal events have been reported in other terranes thought to have been joined against India at some point during the past c. 2000 Myr, including Australia (e.g., Kirkland et al, 2013), East Antarctica (e.g., Liu et al., 2021), and the Lhasa terrane (e.g., Chen et al., 2019; Dong et al., 2022). However, only rare examples of Mesoproterozoic and Neoproterozoic rocks are exposed within the central and western Himalayas (Fig. 1a; e.g., granulitized eclogites and orthogneisses with Early Neoproterozoic protolith ages of ~986 Ma and ~930 Ma; Cottle et al., 2009; Singh et al., 2022), which limits our understanding of the geological makeup, formation and evolution of the northernmost part of the Indian continent through time, and hinders effective paleogeographic plate reconstructions between India and adjacent continental blocks during the Proterozoic.

Here, we report new petrological, geochronological, and geochemical information from amphibolites and orthogneisses from the eastern Himalaya (Fig. 1). We show that these metamorphic rocks were derived from Late Mesoproterozoic arc-type magmatic rocks, and subsequently underwent Early Neoproterozoic metamorphism, marking the first discovery of Meso- to Neoproterozoic lithologies in this part of the Himalayan Range. These findings provide key constraints on the lithological makeup, formation, and evolution of India, and for paleogeographic linkages between the Indian continent and Lhasa terrane during the Proterozoic assembly of the Rodinia supercontinent.

2. Geological setting and samples

The Himalayan orogen in the southern Tibetan Plateau is commonly divided into four near-parallel tectonostratigraphic units that are laterally continuous for more than 2400 km. From north to south, these are the Tethyan Himalayan Sequence (THS), the Greater Himalayan Sequence (GHS), the Lesser Himalayan Sequence (LHS), and the Sub-Himalayan Sequence (SHS), which are separated by the South Tibetan Detachment System (STDS), Main Boundary Thrust (MBT), Main Central Thrust (MCT) and Main Frontal Thrust (MFT), respectively (Fig. 1a; e.g., Yin and Harrison, 2000).

Our study area is located within the Eastern Himalayan Syntaxis (EHS) in the eastern segment of the Himalayan orogen, which exposes (1) the Lhasa terrane (or Gangdese magmatic arc), representing the southern margin of the Asian continent, (2)the Indus-Yarlung Tsangpo suture zone (IYSZ), containing remnants of the Neo-Tethyan Ocean crust that once separated the Asian and Indian plates, and (3) Himalayan sequences, representing the northeastern margin of the Indian continent (Fig. 1b). The Lhasa terrane records Late Paleoproterozoic (1870–1780 Ma) and Early Mesoproterozoic (1560–1510 Ma) magmatic events, and Late Mesoproterozoic (1200–1120 Ma) and Late Neoproterozoic (625–600 Ma) metamorphic events (Lin et al., 2013; Chen et al., 2019; Chen et al., 2022; Dong et al., 2022). The Himalayan sequences preserve records of Late Paleoproterozoic (1760 Ma), Early Mesoproterozoic (1645–1560 Ma), and Early Paleozoic (510–490 Ma) magmatism, with Early Mesoproterozoic (1645–1590 Ma) metamorphism (Guo et al., 2008, 2017; Zhang et al., 2012a). Inherited detrital zircons from paragneisses in the Himalayan sequences have ages ranging from the Neoarchean to early Paleozoic, and major age populations at 2490 Ma, 1640 Ma, 990 Ma and 480 Ma (Wang et al., 2014; Zhang et al., 2012a).

Here, we collected samples of amphibolite and orthogneiss from the Tethyan Himalayan Sequence in the Lulang area of the EHS (Fig. 1b and c). The studied rocks occur as layer-like bodies within amphibolite, augen gneiss, schist, marble and quartzite (Fig. 1c). These rocks show strong foliations that formed during Cenozoic deformation and metamorphism, and these units are cross-cut by ductile shear zones and brittle faults. Previous study has revealed Jurassic, Cretaceous and Cambrian protolith ages for some of the amphibolites, gneisses and augen gneisses (Shi, 2024). Associated schists have an amphibolite-facies mineral assemblage of garnet, sillimanite, biotite, muscovite, and plagioclase and quartz, and formed during the Miocene (Shi, 2024).

The studied amphibolite samples (T21-89-5/-6 and T22-7-2) were collected from a thin layer present within the gneiss and schist country-rocks (Fig. 1c). The dioritic gneiss sample (T22-16-1) was collected from a thick layer of folded gneiss situated between schists and augen gneisses, and is bounded by steeply dipping faults on both sides (Fig. 1c and Fig. 2a). The granitic gneisses (T22-4-1/-2/-3) were sampled from a unit of thick-layered gneiss (Fig. 1c). The amphibolites contain amphibole, plagioclase, garnet, quartz, ilmenite and zircon (Fig. 2b and c), the dioritic gneiss contains plagioclase, quartz, epidote, biotite, K-feldspar, and minor ilmenite and zircon (Fig. 2d), and the granitic gneisses contain quartz, plagioclase, K-feldspar, biotite, and minor epidote, ilmenite and zircon (Fig. 2e). These mineral assemblages indicate that both the amphibolites and orthogneisses experienced amphibolite-facies metamorphism, which is consistent with the metamorphic grade of the adjacent schistose country rock (Shi, 2024).

3. Analytical methods.

3.1. Zircon U–Pb dating and trace element analysis

We selected seven samples from the eastern Himalaya orogen for zircon U–Pb dating and trace element analysis. Cathodoluminescence (CL) images of zircon grains were taken at Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China. Zircon U–Pb dating and trace element analysis were conducted using LA-ICP-MS in the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. Detailed operating conditions and data reduction procedures are given in Hu et al. (2015) and Zong et al. (2017). In this study, the spot size and frequency of the laser were set to 24 μm and 4 Hz, respectively. Off-line selection and integration of background and analytic signals, time-drift correction and quantitative calibration for trace element analysis and U–Pb dating were performed by the

Excel-based software ICPMSDataCal (Liu et al., 2008, 2010). Concordia diagrams and weighted mean calculations were made using Isoplot/Ex_ver4 (Ludwig, 2012) and data-point errors are shown at ± 1σ. We report $^{207}Pb/^{206}Pb$ ages for zircons with ages >1000 Ma and $^{206}Pb/^{238}U$ ages for younger zircons. Results described in this study exclude analyses with >10% discordance.

3.2. Zircon Hf isotopic analysis

We conducted Hf isotope analysis on zircon grains from seven samples previously characterized by zircon U-Pb dating. Zircon Hf isotope compositions were acquired using a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Germany) in combination with a Geolas HD excimer ArF laser ablation system (Coherent, Göttingen, Germany) at the Milma Lab, China University of Geosciences, Beijing, China. The Hf isotope analytical spots were conducted in the same or adjacent locations as the U-Pb dating spots. All data were acquired on zircons in single spot ablation mode with 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 described 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 initial $^{176}Hf/^{177}Hf$ ratios and $\varepsilon_{Hf}(t)$ values were calculated with reference to the chondritic reservoir at the time of zircon growth from the magmas. The measured $^{176}Lu/^{177}Hf$ ratios and the ^{176}Lu decay constant of 1.865×10^{-11} yr^{-1} (Scherer et al., 2001) were used to calculate the initial $^{176}Hf/^{177}Hf$ ratios. Chondritic values of $^{176}Lu/^{177}Hf = 0.0336$ and $^{176}Hf/^{177}Hf = 0.282785$ (Bouvier et al., 2008) were used for the calculation of εHf values. The two-stage model ages (T_{DM2}) for each zircon were calculated by assuming that the parental magma originated from average continental crust ($^{176}Lu/^{177}Hf = 0.015$) that was originally derived from depleted mantle (Griffin et al., 2002).

3.3. Whole-rock geochemical analysis

All amphibolite and orthogneiss samples were selected for whole-rock geochemical analyses, with each sample analyzed in duplicate for major and trace elements. Whole-rock major and trace element compositions were analyzed at the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. The oxides of major elements including loss on ignition (LOI) were determined by X-ray fluorescence spectrometer (XRF, ZSX Primus II). Trace elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700e) following Li (1997).

3.4. Whole-rock Sr-Nd isotopic analysis

Five samples were selected for whole-rock Sr and Nd isotope analysis using a Thermo Fisher Scientific Neptune MC-ICP-MS at Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. Detailed operating conditions for the Neptune MC-ICP-MS are the same as described by Yang et al. (2010, 2012). All Sr and Nd isotope ratios were corrected for mass discrimination via internal normalization to the ^{86}Sr/^{88}Sr ratio of 8.375209 and ^{146}Nd/^{144}Nd ratio of 0.7219 (Lin et al. 2016). The ^{87}Sr/^{86}Sr ratio of the NBS SRM 987 Sr standard solution was 0.710244 ± 10 (two standard deviations, n = 32), and the ^{143}Nd/^{144}Nd ratio of the JNDI-1 Nd standard solution was 0.512118 ± 5 (two standard deviations, n = 31), respectively.

4. Results

4.1. Zircon U–Pb ages and trace elements

Zircons from three amphibolite samples have anhedral to subhedral, spherical or short prismatic shapes with lengths of 80–150 μm. Most zircon grains in the amphibolites display a core-rim structure (Fig. 3a-c). The core domains exhibit weak oscillatory zoning, and thin rim domains show no zoning. Fourteen, twelve, and twelve analytical spots of zircon core domains from samples T21-89-5, T21-89-6, and T22-7-2 yielded ^{206}Pb/^{238}U ages of 1116–1156 Ma, 1112–1176 Ma, and 1031–1085 Ma, with upper intercept ages of 1179 ± 97 Ma (MSWD = 0.36), 1165 ± 48 Ma (MSWD = 0.47), and 1212 ± 190 Ma (MSWD = 0.19), respectively (Fig. 4a, c and e; Supplementary table 1), and ^{207}Pb/^{206}Pb ages of 1085–1176 Ma, 1092–1193 Ma, and 1169–1236 Ma, and weighted-mean ^{207}Pb/^{206}Pb ages of 1141 ± 21 Ma (MSWD = 0.54), 1144 ± 25 Ma (MSWD = 0.45), and 1199 ± 33 Ma (MSWD = 0.15), respectively (Fig. 4a, c and e; Supplementary table 1). These dated core domains have variable but high Th/U ratios (0.15–0.88), fractionated rare earth element (REE) patterns of heavy rare earth element (HREE) enrichment and light rare earth element (LREE) depletion, and negative Eu anomalies (δEu = 0.31–0.70; Fig. 4b, d and f; Supplementary table 1).

Zircon grains from dioritic gneiss sample T22-16-1 exhibit subhedral prismatic shapes with lengths of 150–200 μm, and a core-rim structure, with oscillatory-zoned cores and extremely thin rims (Fig. 3d). Twelve analytical spots for the zircon cores yielded ^{206}Pb/^{238}U ages of 1100–1159 Ma, with an upper intercept age of 1174 ± 65 Ma (MSWD = 0.28; Fig. 5a; Supplementary table 1), and ^{207}Pb/^{206}Pb ages of 1043–1206 Ma, with a weighted-mean ^{207}Pb/^{206}Pb age of 1173 ± 27 Ma (MSWD = 0.20; Fig. 5a; Supplementary table 1). The dated core domains have high Th/U ratios (0.57–1.52), fractionated REE patterns of HREE enrichment and LREE depletion, and significant negative Eu anomalies (δEu = 0.14–0.34; Fig. 5b; Supplementary table 1).

Zircons from three granitic gneiss samples have subhedral-euhedral prismatic shapes with lengths of 150–200 μm. These zircons show well-preserved core-rim structures: the cores show oscillatory zoning, whereas the rims have weak patchy zoning or are unzoned (Fig. 3e-g). Ten, ten, and eleven analytical spots of zircon cores for granitic gneiss samples T22-4-1, T22-4-3, and T22-4-4 yielded ^{206}Pb/^{238}U ages of 1034–1147 Ma, 1026–1156 Ma, and 1062–1099 Ma with upper intercept ages of 1154 ± 88 Ma (MSWD = 1.9), 1205 ± 99 Ma (MSWD = 0.86), and 1232 ± 120 Ma (MSWD = 0.93), respectively (Fig. 5c, e and g; Supplementary table 1). The zircon core domains produced ^{207}Pb/^{206}Pb ages of 1035–1267 Ma, 1080–1294 Ma, and 1054–1252 Ma with weighted-mean ^{207}Pb/^{206}Pb ages of 1149 ± 45 Ma (MSWD = 1.19), 1155 ± 44 Ma (MSWD = 0.98), and 1155 ± 43 Ma (MSWD = 0.66), respectively (Fig. 5c, e and g; Supplementary table 1). Nine, twelve, and ten analytical spots of zircon rims for the three samples yielded ^{206}Pb/^{238}U ages of 945–900 Ma, 969–921 Ma, and 952–908 Ma (Fig. 5c, e and g; Supplementary table 1). The zircon rims have weighted-mean ^{206}Pb/^{238}U age of 924 ± 11 Ma (MSWD = 2.1) for sample T22-4-1 (exluding two analytical spots with maximum and minimum ages), and 936 ± 7.2 Ma (MSWD = 1.2) for sample T22-4-3 (excluding two spots with older ages, and one spot with the youngest age), and 944 ± 8.4 Ma (MSWD = 1.8) for all analytical spots from sample T22-4-4 (Fig.5c, e and g; Supplementary table 1). The dated zircon core domains have relatively high relatively Th/U ratios (0.83–1.60), fractionated REE patterns of HREE enrichment and LREE depletion, and significant negative Eu anomalies (δEu = 0.06–0.19; Fig. 5d, f and h; Supplementary table 1). The zircon rims have relatively low Th/U ratios (0.006–0.134), low LREE contents, and fractionated REE patterns of HREE enrichment and LREE depletion, with weak negative Eu anomalies (δEu = 0.14–0.85; Fig. 5d, f and h; Supplementary table 1).

4.2. Zircon Hf isotopes

Thirty Hf isotopic analyses on zircon core domains from the amphibolites yielded initial $^{176}Hf/^{177}Hf$ isotopic ratios of 0.282155–0.282397, and $^{176}Lu/^{177}Hf$ isotopic ratios of 0.000330–0.000778, and have relatively high $\varepsilon_{Hf}(t)$ values ranging from +2.6 to +11.5, and corresponding two-stage Hf model ages (T_{DM2}) of 1790–1236 Ma (Fig. 6; Supplementary table 2). Ten Hf isotopic analyses on zircon core domains from the dioritic gneiss yielded initial $^{176}Hf/^{177}Hf$ isotopic ratios of 0.281991–0.282051, and $^{176}Lu/^{177}Hf$ isotopic ratios of 0.000546–0.001134, and have relatively low $\varepsilon_{Hf}(t)$ values ranging from -2.7 to -0.4, and corresponding two-stage Hf model ages (T_{DM2}) of 2149–2003 Ma (Fig. 6; Supplementary table 2). Thirty analyses on zircon core domains from the granitic gneisses yielded initial $^{176}Hf/^{177}Hf$ isotopic ratios of 0.281649–0.281911, and $^{176}Lu/^{177}Hf$ isotopic ratios of 0.000362–0.001078, and have low $\varepsilon_{Hf}(t)$ values ranging from -15.1 to -5.8, with two-stage Hf model ages (T_{DM2}) of 2900–2325 Ma (Fig. 6; Supplementary table 2).

4.3. Whole-rock major element, trace element

The studied amphibolites have SiO_2 of 42.91–48.90 wt.%, Al_2O_3 of 11.49–12.01 wt.%, MgO of 5.03–6.57 wt.%, CaO of 8.15–9.99 wt.%, Na_2O of 1.29–1.87 wt.%, and K_2O of 0.43–0.79 wt.% (Supplementary table 3), and thus resemble medium-K calc-alkaline mafic rocks (Fig. 7a). Theese rocks display fractionated REE patterns that are enriched in LREE and depleted in HREE, with slightly negative Eu anomalies (δEu = 0.72–0.85; Fig. 7b). They are enriched in large ion lithophile elements (LILE), and have pronounced negative anomalies in Nb, Ta, and Zr, and weak negative anomalies in Ti (Fig. 7c). The dioritic gneisses have SiO_2 of 59.30 and 59.31 wt.%, Al_2O_3 of 14.63–14.75 wt.%, MgO of 2.02–2.14

wt.%, CaO of 2.23–2.27 wt.%, Na_2O of 3.08–3.19 wt.%, K_2O of 2.61–2.75 wt.%, and A/CNK of 0.835–0.836 (Supplementary table 3), which are typical of metaluminous, and high-K calc-alkalic diorites (Fig. 7a). The granitic gneisses have have SiO_2 of 67.42–67.84 wt.%, Al_2O_3 of 14.01–14.39 wt.%, MgO of 0.61–1.05 wt.%, CaO of 1.82–2.57 wt.%, Na_2O of 1.92–2.57 wt.%, K_2O of 5.55–7.23 wt.%, and A/CNK of 0.965–1.006 (Supplementary table 3), and so resemble metaluminous to weakly peraluminous and shoshonitic granites (Fig. 7a). All orthogneisses show fractionated REE patterns with significant negative Eu anomalies (δEu = 0.48–0.62; Fig. 7b), and LILE enrichment and negative Nb, Ta, Zr, and Ti anomalies (Fig. 7c).

4.4. Whole-rock Sr-Nd isotopic compositions

Three amphibolite samples have $^{87}Sr/^{86}Sr$ ratios of 0.713685, 0.713735, and 0.711914, and $^{143}Nd/^{144}Nd$ ratios of 0.512344, 0.512351, and 0.512359, respectively. They therefore have moderate $^{87}Sr/^{86}Sr_{(i)}$ of 0.7098, 0.7013, and 0.7096, variable but relatively high $\varepsilon_{Nd}(t)$ values of -0.80, +0.05, and +4.06, and two-stage Nd model ages of 1714, 1658, and 1429 Ma [$^{87}Sr/^{86}Sr_{(i)}$ ratios and $\varepsilon_{Nd}(t)$ values are calculated based on $^{207}Pb/^{206}Pb$ weighted mean ages of each sample; Supplementary table 4]. The dioritic gneiss sample has a $^{87}Sr/^{86}Sr$ ratio of 0.720634, $^{143}Nd/^{144}Nd$ ratio of 0.511765, $^{87}Sr/^{86}Sr_{(i)}$ of 0.7092, $\varepsilon_{Nd}(t)$ value of -3.88, and two-stage Nd model age of 1952 Ma (Supplementary table 4). The granitic gneiss has a $^{87}Sr/^{86}Sr$ ratio of 0.785100, $^{143}Nd/^{144}Nd$ ratio of 0.511526, high $^{87}Sr/^{86}Sr_{(i)}$ of 0.7135, negative $\varepsilon_{Nd}(t)$ value of -7.55, and two-stage Nd model age of 2189 Ma (Supplementary table 4).

5. Discussion

5.1. Late Mesoproterozoic magmatic rocks of the eastern Himalaya

Although the studied amphibolites and orthogneisses underwent amphibolite-facies metamorphism, zircons extracted from these rocks all contain cores with variably sized overgrowth rims. These zircon cores exhibit oscillatory zoning, high Th/U ratios (mostly > 0.149), and fractionated REE patterns, indicating a magmatic origin (e.g., Möller et al., 2003). Therefore, the weighted-mean $^{207}Pb/^{206}Pb$ ages of 1199–1141 Ma obtained from these core domains are interpreted as the crystallization ages of the igneous protoliths of the amphibolites and orthogneisses. This indicates that the rocks now exposed in the eastern Himalaya, representing the former northeastern part of the Indian continent, are metamorphic products of the Late Mesoproterozoic mafic and felsic magmatic rocks.

The amphibolites have geochemical affinity to arc-type magmatic rocks, with key features being fractionated REE patterns, LILE enrichments, and Nb, Ta, and Ti negative anomalies (Fig. 7b and c). In various whole-rock and zircon trace element discrimination diagrams, the amphibolite data fall within the fields of continental arc magmatic rocks (Fig. 8 and 9). Moreover, these amphibolites have depleted mantle-like Sr-Nd-Hf isotopic compositions, including relatively low whole rock $^{87}Sr/^{86}Sr_{(i)}$ ratios (0.7013–0.7098), and relatively high $\varepsilon_{Nd}(t)$ values (-0.80 to +4.06) and zircon $\varepsilon_{Hf}(t)$ values (+2.6 to +11.5) (Fig. 6; Supplementary table 2 and 4). These trace element and isotopic features indicate that the protoliths of amphibolites were depleted mantle-derived mafic magmatic rocks that formed in a continental arc setting akin to the Andes today.

The orthogneisses also show geochemical affinities to arc-like magmatic rocks, with fractionated REE patterns, LILE enrichments, and Nb, Ta, and Ti negative anomalies; however, the orthogneiss has high whole-rock $^{87}Sr/^{86}Sr_{(i)}$ ratios of 0.7092 to 0.7135, low whole-rock $\varepsilon_{Nd}(t)$ values of -7.55 to -3.88, and low zircon $\varepsilon_{Hf}(t)$ values of -15.1 to -0.4, and Paleoproterozoic two-stage Hf model ages (Fig. 6; Supplementary table 2 and 4). These indicate that the orthogneisses were probably derived from remelting of older arc crust. The dioritic gneiss has zircon Hf model ages comparable to Early Mesoproterozoic (1594–1583 Ma) orthogneisses in the Namche Barwa region (Fig. 6; Guo et al., 2008, 2017). These more ancient orthogneisses are associated with 1645–1590 Ma mafic magmatic rocks that show arc-related geochemical signatures (Zhang et al., 2012a), which suggests that the studied dioritic gneiss formed via remelting of Early Mesoproterozoic arc-related intrusions. The zircon Hf model ages of the granitic gneisses resemble those of orthogneisses with Late Paleoproterozoic (1790–1760 Ma) protolith ages situated in the Namche Barwa and Tawang areas of the eastern Himalaya (Fig. 6). The Late Paleoproterozoic Tawang orthogneisses, located ~350 km southeast of the EHS, show arc-related geochemical characteristics, including fractionated REE patterns, LILE enrichments, and significant Nb and Ti negative anomalies (Bikramaditya et al., 2021). Therefore, Paleo- to Mesoproterozoic rocks in the eastern Himalaya thus may represent source rocks (protoliths) of the studied Late Mesoproterozoic orthogneisses, although it is also possible that both the Late Paleoproterozoic and Late Mesoproterozoic orthogneisses were derived from remelting of more ancient arc-type magmatic rocks.

5.2. Early Neoproterozoic metamorphism of the eastern Himalaya

Wide rim domains of zircon from the granitic gneisses have low Th/U ratios (0.006–0.134), low REE contents, and fractionated REE patterns (Fig. 5d, f and h), typical of zircons found in medium- to low-grade metamorphic rocks (e.g., Mojzsis and Harrison, 2002). Therefore, the mean $^{206}Pb/^{238}U$ ages of 940–920 Ma obtained from these rims indicate that the orthogneisses underwent the Early Neoproterozoic metamorphism. Application of the Ti-in-zircon thermometer (log (Ti-in-zircon) = 5.711 - 4800/(T+ 273) - $\log\alpha_{SiO2}$ + $\log\alpha_{TiO2}$, with α_{SiO2} = 1 and α_{TiO2} = 0.5; Ferry and Watson, 2007) using measured Ti contents of the zircon rims obtained temperatures of 591–744 ℃ (av. 673 ℃) (Supplementary table 1), which are within the temperature range of amphibolite-facies metamorphism. Because the minerals observed in the studied rocks likely recrystallized during Cenozoic metamorphism related to India-Asian collision, it is difficult to estimate the actual *P*–*T* conditions of Early Neoproterozoic metamorphism. Nevertheless, this work shows for the first time that the eastern Himalaya preserves rocks recording Early Neoproterozoic metamorphism.

5.3. Meso- to Neoproterozoic orogeny within the eastern Indian continental margin

The Grenvillian orogeny, associated with the convergence and final amalgamation of the Rodinia supercontinent, triggered widespread magmatism and metamorphism between 1300 Ma and 900 Ma that is preserved in nearly all Meso- and Neoproterozoic terranes (e.g., Rivers, 2015; Spencer et al., 2015). In many plate reconstructions for this period of time, India, East Antarctica, and Australia are thought to have been joined together, and comprised the northwestern part of Rodinia (Fig. 10; e.g., Li et al., 2023; Johanson, 2014; Merdith et al., 2021). This is supported by evidence for a composite Rayner-Eastern Ghats orogenic system, which records Late Mesoproterozoic accretionary and Early Neoproterozoic collisional orogenesis during convergence between the India and East Antarctic continental plates (Fig. 10 and Fig. 11; e.g., Upadhyay, 2008; Yin et al., 2010; Bose et al, 2011). The Rayner and Eastern Ghats orogens are currently preserved within the northern part of East Antarctica and the southeastern part of India, respectively.

The Rayner orogen preserves 1210–900 Ma mafic to felsic magmatism, and coeval high-grade metamorphism (e.g., Alekseev et al., 2021; Liu et al., 2021; Giri et al., 2023). Magmatism during the period 1210–1020 Ma developed in a continental arc setting (the

Rayner arc) situated above a southward-subducting oceanic slab, and this Rayner Arc was separated by an oceanic or back-arc basin (Eastern Ghats belt) from the Indian craton (Fig. 10a and 11a; Liu et al., 2014, 2017; Mondal et al., 2023). Metamorphism and magmatism in the Rayner orogen dated at 1020–960 Ma is attributed to collision of the Rayner and Fisher arcs with the East Antarctic continent (Mikhalsky et al., 2006; Halpin et al., 2012; Liu et al., 2013, 2017), and metamorphic and magmatic events recorded between 940 Ma and 900 Ma are related to back-arc basin closure leading to the final collision of East Antarctica and magmatic arcs with the Indian continent (Fig. 10b and 11c; Mikhalsky et al., 2015; Morrissey et al., 2015).

The Eastern Ghats orogen experienced 1130–900 Ma mafic to felsic magmatism and coeval high-grade metamorphism that has been linked to the development and closure of a back-arc basin between the India continent and Rayner arc (Fig. 11a and 11c; e.g., Dasgupta et al., 2013, 2017; Axelsson et al., 2020; Ganguly et al., 2021; Mondal et al., 2023). Mantle-derived magmatism and associated ultrahigh-temperature granulite-facies metamorphism at 1130–990 Ma resulted from asthenospheric heat input due to back-arc extension and crustal thinning (Fig. 11a; Korhonen et al., 2013; Dasgupta et al., 2017; Bose et al., 2022; Karmakar et al., 2025), whereas asthenospheric upwelling induced by the subduction rollback and slab breakoff at 980–960 Ma triggered charnockite and anorthosite magmatism in the Eastern Ghats orogen (Ganguly et al., 2018; Saikia and Nasipuri, 2024). The subsequent period from 950 to 900 Ma was marked by mafic to felsic magmatism and high-temperature granulite-facies metamorphism, which occurred during the India-Antarctic collision following closure of the back-arc basin (Fig. 11c; Nasipuri et al., 2018; Das et al., 2021; Ganguly et al., 2021).

This study reveals for the first time that Late Mesoproterozoic arc-related magmatism and Early Neoproterozoic metamorphism occurred in the northeastern segment of the Indian continent (Fig. 1a). The timing and duration, and tectonic environments in which these magmatic and metamorphic events occurred are comparable to Meso- to Neoproterozoic tectonothermal events recorded within the Rayner-Eastern Ghats orogen. Furthermore, Grenvillian-age orogenesis in the Shillong Plateau of northeast India recorded 1300–950 Ma magmatism and metamorphism related to arc development and subsequent continental collision (Fig. 11b and d; Yin et al. 2010; Neogi et al., 2022). In addition, 1265–1120 Ma arc-related magmatism and metamorphism in the eastern Lhasa terrane has been linked to Grenvillian accretionary orogenesis (Lin et al., 2013; Chen et al., 2019). When considered together, we suggest that the Meso- to Neoproterozoic Eastern Ghats-Rayner orogen itself extended into northeastern India and the eastern Lhasa terrane (Fig. 10 and 11). This implies the existence of a huge Grenvillian orogenic belt over 2500 km long that developed along the entire eastern Indian continental margin (Fig. 1a), which witnessed a long-lived orogenic process from the Late Mesoproterozoic subduction to Early Neoproterozoic collision.

Unlike the Eastern Ghats orogenic belt that evolved from the arc-back basin between the ancient Indian craton and the Rayner continental arc (Fig. 11a), the Late Mesoproterozoic orogeny in the eastern segments of Himalaya and Lhasa terrane occurred during subduction of oceanic plate beneath the northeastern margin of the Indian continent (Fig. 10a and 11b), and the Early Neoproterozoic metamorphism occurred during the collision of the India and Fisher intraoceanic arc with East Antarctica following the closure of the ocean basin (Fig. 10b and 11d). Specifically, our newly identified 1200 Ma mafic magmatic rocks are products of the subduction-related mantle-derived magmatism, while coeval felsic magmatism resulted from the remelting of more ancient arc-type magmatic rocks transported into the lower arc crust during the accretionary orogeny. These mantle- and crust-derived magmatic rocks underwent subsequent amphibolite-facies metamorphism during Early Neoproterozoic collisional orogeny.

5.4. Significance for reconstruction of the Rodinia supercontinent

The present study probably provides new constraints on the paleogeographic reconstruction of the Indian continent and neighboring terranes along the northwestern margin of the Rodinia supercontinent, specifically regarding whether India collided with West Australia during the Neoproterozoic (e.g., Karlstrom et al, 1999; Ameen et al., 2022; Li et al., 2023). Collision-related Early Neoproterozoic tectonothermal events were widespread in eastern India and East Antarctica, but absent in West Australia (Fig. 10b; e.g., Ksienzyk and Jacobs, 2015; Tucker et al., 2015). This tectonothermal disparity probably indicates that the Indian continent was juxtaposed exclusively against the northwestern part of East Antarctica, whereas Australia was connected to the northeastern part of East Antarctica during the Early Neoproterozoic (Fig. 10b).

The paleogeographic location of the Lhasa terrane within the Rodinia and Gondwana supercontinents has been greatly disputed. Some previous studies argued that the Lhasa terrane was situated at the northern margin of the Indian continent, based on inherited detrital zircons in metasedimentary rocks from the Lhasa terrane and Himalaya having similar age spectra and populations at ~2500 Ma, 1800–1600 Ma, 1200–900 Ma, and 500 Ma (e.g., Gehrels et al., 2011; Guo et al., 2017; Spencer et al., 2019; Jiang et al., 2021). However, others proposed that the Lhasa terrane has a West Australia origin, and drifted away from the northern margin of West Australia during the Early Mesozoic (Zhu et al., 2013; Wang et al., 2021; Zhang et al., 2023). The main basis for this proposal has been that Paleozoic to Mesozoic sedimentary rocks in the Lhasa terrane have a pronounced detrital zircon U-Pb age peak at 1200–1100 Ma, and that Late Mesoproterozoic magmatic rocks of this age occur widely within West Australia, but are absent in the Indian continent.

In fact, previous studies suggested that the abundant 1200–1100 Ma detrital zircons in the Phanerozoic sedimentary rocks of the Lhasa terrane were likely derived from the Eastern

Ghats Belt and Shillong Plateau in the Indian continent (Yin et al., 2010; Guo et al., 2017; Chen et al., 2019), the Albany-Fraser Orogen in West Australia (Yoshida and Upreti, 2006; Zhu et al, 2013; Wang et al., 2021), or the eastern part of the Lhasa terrane (Dong et al., 2020; 2022). The present study further reveals that the Grenvillian-aged magmatic and metamorphic rocks occurred widely in Eastern Lhasa, Eastern Himalaya, Shillong Plateau and Eastern Ghats belt of the eastern margin of the Indian continent, and Rayner Province of East Antarctica, which formed a huge Late Mesoproterozoic to Early Neoproterozoic orogenic belt that developed between Indian and East Antarctic continents (Fig. 10 and 11). Thus, this orogen may represent the potential source for the widespread 1200–1100 Ma detrital zircons found in sedimentary rocks in the northern margin of Indian continent and Lhasa terrane located to its north.

This study and previous works show that the Lhasa terrane and the northern Indian continent have a similar Precambrian evolution, with major magmatic and metamorphic events at 1900–1700 Ma, 1650–1500 Ma, and 1250–900 Ma. Specifically, the north Indian margin documents magmatism at 1880–1760 Ma interpreted as reflecting subduction or continental collision (Kohn et al., 2010; Pandey, 2022; Zhang et al., 2022), subsequent 1650–1560 Ma magmatism and metamorphism can be linked to Andean-type orogeny (Zhang et al., 2012a; Wang et al., 2014), and the newly discovered 1200–900 Ma magmatism and metamorphism documented here can be linked to a distinct subduction to continental collision cycle. The Lhasa terrane preserves subduction-related magmatism and metamorphsim at 1870–1780 Ma, and 1560–1520 Ma, and 1260–1120 Ma (Lin et al., 2013; Chen et al., 2019; Dong et al., 2020, 2022). Collectively, we argue that the Lhasa terrane originated from India, and was very likely connected to the northern margin of the Indian continent until the Late Neoproterozoic (Fig. 10 and 11).

6. Conclusions

This study shows that the eastern Himalayan orogen recorded Late Mesoproterozoic (1200–1140 Ma) arc-related magmatism and Early Neoproterozoic (940–920 Ma) metamorphism, which addresses missing information about the Precambrian tectonic evolution of the northern margin of the Indian continent. In combination with previous results, we suggest that the northeastern margin of the Indian continent formed part of the Proterozoic Rayner-Eastern Ghats orogen. This huge composite orogenic system witnessed a long-lived accretionary to collisional orogenic process that operated between India and East Antarctica during the Meso- and Neoproterozoic assembly of Rodinia supercontinent. The Lhasa terrane was likely located at the northern Indian margin during the Early Neoproterozoic within northwestern Rodinia. These new data have important implications for paleogeographic models describing the assembly and breakup of Rodinia.

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Figures Captions

Fig. 1. (a) Sketch geological map of the Tibetan Plateau and adjacent areas, showing key locations of Meso- to Neoproterozoic magmatic and metamorphic rocks. Data sources are as follows: Himalaya (Cottle et al., 2009; Guo et al., 2017; Singh et al., 2022; Wang et al., 2014; Zhang et al., 2012a), Shillong Plateau (Yin et al., 2010; Kumar et al., 2022), Eastern Ghats belt (Bose et al., 2022; Mondal et al., 2023), and Lhasa Terrane (Chen et al., 2019; Dong et al., 2022). (b) Geological map of the eastern Himalayan syntaxis (modified after Zhang et al., 2015), showing the locations of known Precambrian magmatic and metamorphic rocks and their ages. (c) Cross-section of the Tethyan Himalayan Sequence (THS) and Indus-Yarlung Tsangpo suture zone (IYSZ), showing the locations of the studied samples.

Fig. 2. Field photographs (a) and photomicrographs (b–e) of the studied metamorphic rocks. (a) The dioritic gneisses are strongly foliated and show tight folds. The hammer for scale is 33 cm long; (b, c) The amphibolites (samples T21-89-6 and T22-7-2) contain similar mineral assemblages, consisting of garnet poikiloblasts and matrix amphibole, plagioclase, quartz,

ilmenite and zircon; (d) The dioritic gneiss (T22-16-1) contains plagioclase, quartz, epidote, biotite, K-feldspar, and minor ilmenite and zircon; (e) The granitic gneiss (T22-4-1) contains quartz, plagioclase, K-feldspar, biotite, and minor epidote, ilmenite and zircon. Mineral abbreviations: Amp = amphibole, Bt = biotite, Ep = epidote, Grt = garnet, Ilm = ilmenite, Pl = plagioclase, K-feldspar, and Qtz = quartz.

Fig. 3. Representative cathodoluminescence (CL) images of zircons from the amphibolites (a–c), diorite gneiss (d), and granitic gneisses (e–f). The white solid circles and the green dotted circles denote the analytical spot locations for U-Pb ages and Hf isotopes, respectively, and relevant ages (in Ma) and $\varepsilon_{Hf}(t)$ values are marked near the corresponding analytical spots.

Fig. 4. U–Pb concordia diagrams (a, c, and e) and chondrite-normalized REE patterns (b, d, and f) of zircon in the amphibolites.

Fig. 5. U–Pb concordia diagrams (a for the dioritic gneiss, c, e, and g for the granitic gneisses) and chondrite-normalized REE patterns (b for the dioritic gneiss, d, f, and h for the granitic gneisses) of zircon in the orthogneisses.

Fig. 6. Zircon U–Pb age (Ma) versus $\varepsilon_{Hf}(t)$ value diagram of the studied rocks and related magmatic rocks. Data sources: Namche Barwa orthogneisses (Guo et al., 2017), and Tawang orthogneisses (Bikramaditya et al., 2021; Pathak and Kumar, 2019).

Fig. 7. Whole-rock major and trace element diagrams of the studied amphibolites and orthogneisses. (a) SiO_2 versus K_2O diagram (bounderies after Frost et al., 2001). (b) Chondrite-normalized REE patterns. (c) Primitive mantle-normalized trace element patterns.

Fig. 8. Whole-rock trace element diagrams of the amphibolites. (a) La-Y-Nb ternary diagram (bounderies after Cabanis and Lecolle, 1989). (b) Ta/Yb versus Th/Yb diagram (bounderies after Gorton and Schandl, 2000). (c) La/Yb versus Nb/La, and (d) La/Yb versus Th/Nb diagrams (bounderies after Hollocher et al., 2012).

Fig. 9. Trace element diagrams of magmatic zircons from the amphibolites (boundaries after Carley et al., 2014).

Fig. 10. Late Mesoproterozoic (a) and Early Neoproterozoic (b) reconstruction of the Rodinia supercontinent (modified after Li et al., 2023; Venkateshwarlu and Chalapathi Rao, 2013).

Fig. 11. Tectonic models of the subduction and collisional orogenesis between the India and East Antarctica continents during the building of Rodinia supercontinent (modified after Liu et al., 2014; Mondal et al., 2023). Locations of sections (a and b) and (c and d) are shown in Fig. 10 a and b, respectively.

Table Captions

Supplementary Table 1. Zircon U–Pb ages and trace element compositions of the amphibolites and orthogneisses.

Supplementary Table 2. Zircon Lu-Hf isotopic compositions of the amphibolites and orthogneisses.

Supplementary Table 3. Whole-rock major element and trace element compositions of the amphibolites and orthogneisses.

Supplementary Table 4. Whole-rock Sr and Nd isotopic compositions of the amphibolites and orthogneisses.