On the origin of high-pressure mafic granulite in the Eastern Himalayan Syntaxis: implications for the tectonic evolution of the Himalayan orogen

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Abstract

The Himalayan orogen, resulting from the Early Cenozoic collision of the Indian and Asian plates, exposes a spectacular assemblage of high-grade metamorphic rocks and leucogranites in its core, and is an ideal vehicle to study active orogenic processes and test geodynamic models of how the crust responds to collisional orogeny. This paper focused on migmatitic high-pressure (HP) mafic granulite and associated leucosome from the Greater Himalayan Crystallines (GHC) in the Eastern Himalayan Syntaxis (EHS), and conducted a systematic petrological and petrochronological study in order to understand the conditions and timescales over which high-grade rocks and partial melts were produced during the Himalayan orogeny. Combining with previous study results from the Western and Central Himalayas and Trans-Himalayan magmatic arc, we obtained the following conclusions: (1) The mafic granulite from the EHS has a mineral assemblage of garnet, clinopyroxene, plagioclase, quartz, rutile and sphene, and underwent HP and high-temperature (HT) granulite facies metamorphism and associated partial melting, with peak metamorphic conditions of 15–17 kbar and 820–880 °C. The GHC, at least its western part, of the EHS underwent coherent HP granulite-facies metamorphism. (2) The HP mafic granulites experienced long-lived dehydration melting of amphibole from ~40 Ma to ~20 Ma during prograde metamorphism and generated up to ~16 vol.% partial melt. The variable degrees of dehydration melting of the HP mafic, pelitic and felsic granulites in the EHS formed voluminous granitic melts with distinct compositions, and provided the source for the Himalayan granites. (3) The GHC in the EHS contains Proterozoic (~1760–1560 Ma) and Early Paleozoic (~500–490 Ma) granitoids, Proterozoic (1645–1590 Ma), and Early Cretaceous (~130 Ma) and Late Cretaceous (~90–80 Ma) gabbroic rocks. (4) Peak metamorphic pressure of the GHC gradually decreases, whereas the metamorphic temperature progressively increases from the Western to Eastern Himalayas. This indicates that the Indian continental crust deeply subducted into the mantle in the Western Himalaya after the Indo-Asia collision, whereas the Indian crust underthrusted or relaminated beneath the Asian continental crust, and formed the thickened lower crust in the Central and Eastern Himalayas. (5) The melts derived from the relaminated Indian crust probably resulted in isotopic compositional enrichment of the Early Cenozoic mantle- and juvenile crust-derived magmatic rocks of the Gangdese arc, and in turn the mantle-derived plutonic rocks might provide an additional heat source for the partial melting of the thickened lower crust of the Eastern and Central Himalayan orogen.

Keywords: HP granulite; Partial melting; Timescales; Thickened lower crust; Tectonic evolution; Himalayan orogen

1. Introduction

The Himalayan orogen, resulting from the Cenozoic collision of the Indian and Asian plates after the closure of the Neo-Tethyan ocean, exposes a spectacular assemblage of high-grade metamorphic rocks and leucogranites in its core (Yin and Harrison, 2000; Kohn, 2014). These rocks, representing the buried and subsequently exhumed Indian continental crust, are an ideal vehicle to study active orogenic processes and test geodynamic models of how the crust responds to collisional orogeny (e.g., Guillot et al., 2008, 2013; Searle et al., 2011; Kohn, 2014).

In the Eastern Himalayan Syntaxis (EHS), migmatitic high-grade metamorphic rocks are well exposed due to Late Cenozoic rapid exhumation and erosion (e.g., Burg et al., 1998; Zeitler et al., 2001; Booth et al., 2004, 2009; Enkelmann et al., 2011). Despite intense study of these rocks, markedly different metamorphic conditions and ages have been obtained, which has in turn led to different interpretations and models for the overall tectonic evolution and leucogranite formation of the Eastern Himalayan orogen. These distinct viewpoints dominantly arose from previous studies mostly focusing on felsic and pelitic migmatites, especially the residuum of the migmatites; however, these rocks commonly experienced varying degrees of retrograde metamorphism, and therefore did not record the complete metamorphic and anatectic history of the Eastern Himalayan orogen. In contrast, mafic rocks, including high-pressure (HP) eclogite, granulite and blueschist, are often preferentially studied because these rocks typically experience much less deformation and recrystallization during exhumation to the present-day surface than their host rocks and thus provide crucial preserved evidence for these processes in the form of their metamorphic pressure–temperature histories (O'Brien, 2018).

In this paper, we focus on migmatitic HP mafic granulite and hosting leucosome from the Namche Barwa region of the EHS, and report systematic petrological and petrochronological data that advance our understanding of the conditions and timescales over which high-grade rocks and partial melts are produced during the Himalayan orogeny. The present results show that the mafic granulite underwent prolonged HP and HT metamorphism and associated intensive partial melting over 20 Myr. When combined with previous results, we conclude that the Eastern Himalayan orogen only experienced HP granulite facies metamorphism due to the shallow subduction (underthrusting) or relamination of the Indian continental crust beneath the Asian crust, and large volume of melts generated by dehydration melting during the burial and exhumation of the crustal rocks contributed to the formation of Himalayan granites. Combining with the presence of UHP eclogites in the Western Himalaya, and HP eclogites and granulites in the Central Himalaya, we propose that the whole Himalayan orogen has a gradual decreasing metamorphic pressure but increasing metamorphic temperature from west to east, implying the Indian plate has a subduction angle that flattens from west to east after the Indo-Asian collision at the Early Cenozoic. In addition, we related the partial melting of the thickened lower crust consisting of the underthrusted Indian crust to the formation of Himalayan granites and the syn-collisional magmatism of Trans-Himalayan arc. Therefore, the present study provides new insights into tectonic evolution of the Eastern Himalayan Syntaxis and Himalayan orogen in general.

2. Geological setting and samples

The Himalayan orogen, located at the southern part of Tibetan Plateau, extends for more than 2400 km from the Western Himalayan Syntaxis (WHS; Nanga Parbat Syntaxis) in Pakistan to the Eastern Himalayan Syntaxis (EHS; Namche Barwa Syntaxis) in China, and exhibits a distinct arcuate form, with sharp bends of major drainages and tectonic lines at both syntaxes (Fig. 1a). The Himalayan orogen consists mainly of four roughly parallel and laterally continuous tectonostratigraphic units (e.g., Yin and Harrison, 2000; Yin, 2006; Guillot et al., 2008; Kohn, 2014). From south to north, they are the Sub-Himalayan Sequence (Neogene Siwalik Formation), the Lesser Himalayan Sequence (LHS), the Greater Himalayan Crystallines (GHC), and the Tethyan Himalayan Sequence (THS) (Fig. 1a). These units are separated by the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT), the Main Central Thrust (MCT), the South Tibetan Detachment system (STD) and the Indus-Yarlung Tsangpo suture zone (IYS) from south to north, respectively (Fig. 1a). The southern margin of the Asian continent to north of IYS contains large volumes of Mesozoic to early Cenozoic batholiths and volcanic rocks that formed during the subduction of Neo-Tethyan oceanic lithosphere and the Indo-Asian collision. These igneous rocks form the Trans-Himalayan magmatic arc with the Gangdese arc as its eastern part and Kohistan-Karakorum arc as its western part (Fig. 1a).

The EHS consists of three major tectonic units (Fig. 1b): the Lhasa terrane (or Gangdese magmatic arc), representing the southern segment of the Asian continent; the IYS, forming the residual of the Neo-Tethyan ocean between the Asian and Indian plates; and the Himalayan sequences, representing the northern margin of the Indian continent (Yin and Harrison, 2000; Booth et al., 2004; Geng et al., 2006; Zhang et al., 2010a; Xu et al., 2012). The Lhasa terrane consists mainly of Cambrian to Eocene sedimentary rocks, Mesozoic to Cenozoic metamorphic rocks and Gangdese batholiths (Fig. 1b). The Himalayan sequences include the THS and GHC (Fig. 1b). The former consists of Paleozoic and Mesozoic sedimentary strata metamorphosed under greenschist to epidote-amphibolite facies conditions. The GHC, also referred to as the Namche Barwa Complex (NBC) by Zhang et al. (2012), consists of migmatitic orthogneiss, paragneiss, mafic granulite, amphibolite, schist, marble and calc-silicate rock. All the rocks of the GHC underwent high-grade metamorphism and partial melting during the Cenozoic (Zhong and Ding, 1996; Liu and Zhong, 1997; Burg et al., 1998; Ding et al., 2001; Booth et al., 2004, 2009; Liu et al., 2007; Xu et al., 2010, 2012; Zhang et al., 2010a, 2012, 2015, 2018; Guilmette et al., 2011; Su et al., 2012; Liu and Zhang, 2014; Tian et al., 2016, 2019, 2020; Peng et al., 2018; Kang et al., 2020).

In the EHS, migmatitic mafic granulites occur frequently as layers or lenses within gneisses and schists in the GHC, but mostly are transformed into garnet-bearing amphibolite or amphibolite due to the late retrograde overprint of amphibolite facies. The mafic granulite (samples 45-1 and 45-5) and hosting leucosome (sample 97-12) studied in this work were collected from the core of a thick (~30 m wide) layer of garnet amphibolite within migmatitic pelitic granulite (garnet-kyanite schist) in the Jiala area near the Namche Barwa peak (Fig. 1b). The fresh granulite and garnet amphibolite outcrop is a very steep roadcut along the great canyon of Yarlung Tsangpo River at coordinates N29°40'58.10" and E94°54'44.16". Field observations show that the granulite gradually transformed into the garnet-baring or garnet-free amphibolites with increasing amphibole and plagioclase modes, and decreasing garnet and clinopyroxene modes from the core to margin of the rock layer. Therefore, the weakly retrograded granulite consists mainly of garnet, clinopyroxene, plagioclase and quartz with minor amphibole, whereas the markedly retrograde granulite (amphibolite) is composed of amphibole, plagioclase and quartz, with or without garnet. Both the granulite and amphibolite contain abundant felsic leucosomes that occur as concordant and discordant bands, veins or networks (Fig. 2). The garnets in both the granulite and amphibolite commonly show a white-eye socket structure (Fig. 2b), indicating the garnets were partly replaced by very fine-grained amphibole and plagioclase along their margins. The leucosomes within both the granulite and amphibolite contain similar minerals of plagioclase, quartz and minor amphibole and garnet (Fig. 2).

3. Analytical methods

Whole-rock bulk compositions of mafic rocks and hosting leucosome were obtained by X-ray fluorescence (XRF) (Rigaku-3080) with an analytical uncertainty of <0.5% at the National Geological Analysis Center of China, Beijing. Approximately 2 kg of each sample was crushed to form a powder. Mineral compositions were analyzed using a JEOL JXA 8900 electron microprobe (EPM) with a 15 kV accelerating voltage, 20 nA beam current, 5 μm spot diameter, and count time of 10 s for peak and background, at the Institute of Geology, Chinese Academy of Geological Sciences. Natural or synthetic almandine garnet, biotite, kaersutite, diopside, plagioclase, magnetite and rutile were used as standards. ZAF corrections were carried out.

In situ zircon U–Pb dating and trace element analyses were conducted using the LA-ICP-MS housed in the Mineral and Fluid Inclusion Microanalysis Lab, Institute of

Geology, Chinese Academy Geological Sciences. The NWR 193^{UC} laser ablation system (Elemental Scientific Lasers, USA) was equipped with Coherent Excistar 200 excimer laser and a Two Volume 2 ablation cell. The laser ablation system was coupled to an Agilent 7900 ICPMS (Agilent, USA). The detailed analytical methods are described by Yu et al. (2019). LA-ICP-MS tuning was performed using a 50 μm diameter line scan at 3 μm/s on NIST 612 at ~3.5 J/cm^2 with repetition rate 10 Hz. Adjusting the gas flow to get the highest sensitivity (^{238}U~5 × 10^5 cps) and the lowest oxide ratio (ThO/Th < 0.2%). P/A calibration was conducted on the NIST 610 using a 100 μm diameter line scan. Other laser parameters are the same as that of tuning. Mass analyzed were ^{31}P, ^{49}Ti, ^{56}Fe, ^{89}Y, ^{91}Zr, ^{93}Nb, ^{139}La, ^{140}Ce, ^{141}Pr, ^{146}Nd, ^{147}Sm, ^{151}Eu, ^{157}Gd, ^{159}Tb, ^{163}Dy, ^{165}Ho, ^{166}Er, ^{169}Tm, ^{173}Yb, ^{175}Lu, ^{178}Hf, ^{181}Ta, ^{202}Hg, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, ^{235}U and ^{238}U, with a total sweep time of ~0.23 seconds. Zircon were mounted in epoxy discs, polished to expose the grains, cleaned ultrasonically in ultrapure water, then cleaned again prior to the analysis using AR grade methanol. Pre-ablation was conducted for each spot analysis using 5 laser shots (~0.3 μm in depth) to remove potential surface contamination. Zircon 91500 and GJ-1 were used as primary and secondary reference materials respectively. The 91500 was analyzed twice and GJ-1 analyzed once every 10-12 analysis of the sample. Multiple groups of 10 to 12 sample unknowns were bracketed by triplets of primary and secondary zircon standards. Typically, 35-40 seconds of the sample signals were acquired after 20 seconds gas background measurement. Using the exponential function to calibrate the downhole fractionation (Paton et al., 2010). NIST610 and ^{91}Zr were used to calibrate the trace element concentrations as external reference material and internal standard element respectively. The spot size of the laser was set to 25 μm or 30 μm for this zircon dating. The Iolite software package was used for data reduction (Paton et al., 2010). Concordia diagrams and weighted mean calculations were made using Isoplot/ Ex_ver3 (Ludwig, 2003).

4. Petrology

The studied mafic granulite contains garnet, clinopyroxene, plagioclase, quartz, amphibole, orthopyroxene, rutile, ilmenite and sphene (Fig. 3). The coarse-grained garnets occur as porphyroblasts (Figs. 2b and 3) and mostly have a mineral inclusion-rich core, and a nearly inclusion-free rim (Figs. 3a and 4). The mineral inclusions in the garnet core are fine-grained plagioclase, quartz, amphibole and sphene. The garnets are commonly replaced by symplectitic coronas of amphibole + plagioclase ± clinopyroxene ± orthopyroxene along their rims (Fig. 3), as shown by the white-eye socket structure in Fig. 2b. Most clinopyroxenes occur in the matrix and are commonly replaced by amphiboles along their rims (Fig. 3a, b). Some clinopyroxenes occur as relics within late-stage amphibole grains (Fig. 3d) and very fine-grained clinopyroxenes occur in the symplectitic corona rimmed the garnet. Relatively coarse-grained plagioclases occur as the matrix, while fine-grained plagioclase occurs in the symplectitic corona around the garnet. Amphibole occurs as a prograde mineral within the garnet core, as a late corona mineral around matrix clinopyroxene, and as a symplectitic mineral around the garnet (Fig. 3). Orthopyroxenes only occur in the corona around the garnet and clinopyroxene (Fig. 3d). Fine-grained sphene, rutile and ilmenite occur as matrix minerals or as inclusions within garnet and clinopyroxene.

The textural features described above show that the mafic granulite records three stages of mineral assemblage. The prograde assemblage (M1) is represented by the core of garnet and hosting inclusion minerals of amphibole, plagioclase, quartz, and sphene. The peak metamorphic assemblage (M2) is characterized by coexistence of the porphyroblastic garnet (rim), the matrix plagioclase, clinopyroxene, quartz, sphene and rutile. The retrograde assemblage (M3) is amphibole + plagioclase + clinopyroxene + quartz + ilmenite + orthopyroxene. These late minerals occur as the symplectite around the garnet, or as corona around the matrix clinopyroxene. Because the mafic granulite have locally transformed into garnet- and clinopyroxene-free amphibolite, the latest stage of retrograde assemblage (M4) is amphibole + plagioclase + quartz + biotite + ilmenite.

Garnet from the two mafic granulite samples has similar compositions, characterized by relatively high almandine and grossular, and low pyrope and spessartine components (Appendix Table 1). X-ray mapping and profile analysis show that the garnet has compositional zoning, with increasing pyrope and grossular components, and decreasing almandine and spessartine components from core to rim except for the outmost rim with decreasing grossular and increasing almandine components (Appendix Table 1; Figs. 4 and 5). The gradual increase of pyrope and gradual decrease of spessartine are typical of growth zoning, indicating that the garnet grew during prograde metamorphism (Spear, 1991; Spear et al., 1990).

Clinopyroxenes in the matrix from the sample 45-5 contain CaO of 21.29–23.21 wt.% and Na_2O of 0.35–0.61 wt.%, with low jadeite components (<0.94; Appendix Table 2). The matrix clinopyroxenes from sample 45-5 have similar compositions to those of sample 45-5, but contain slightly higher MgO and CaO, and lower FeO contents (Appendix Table 2). The clinopyroxenes in the symplectite of the sample 45-1 have higher FeO, and lower CaO, MgO and Na_2O (0.09–0.19 wt.%) contents than those of the matrix (Appendix Table 2). All clinopyroxenes are thus diopside due to relatively high CaO and low Na_2O contents. Orthopyroxenes in the symplectite contain FeO of 34.32–36.06 wt.% and MgO of 12.28–12.81 wt.% (Appendix Table 2).

The matrix plagioclases from the two samples contain Na_2O of 5.91–7.65 wt.% and CaO of 6.02–9.01 wt.%, with anorthite component of 0.30–0.45 and albite of 0.54–0.67 (Appendix Table 3). By contrast, the plagioclases in the symplectite have relatively low Na_2O of 0.24–4.30 wt.% and high CaO of 11.87–19.53 wt.%, with anorthite component of 0.60–0.98 and albite of 0.02–0.39 (Appendix Table 3). The matrix and symplectitic plagioclases from the sample 45-5 have lower CaO and higher Na_2O contents than those from the sample 45-1. Amphiboles from the two samples have similar chemical compositions, characterized by relatively high CaO and low Na_2O contents (Appendix Table 4), and are therefore calcic amphibole. In addition, the amphiboles in the different textural domains show no systematic compositional difference.

5. Thermobarometry

5.1 Phase Equilibrium Modeling

Metamorphic *P*–*T* conditions of the mafic granulite sample 45-5 are constrained by phase equilibrium modeling using THERMOCALC 3.45 (Powell and Holland, 1988), the internally consistent dataset (ds62) of Holland and Powell (2011), and a new set of thermodynamic models of Green et al. (2016) for meta-mafic rocks in the system Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-O_2 (NCKFMASHTO). The activity-composition relations used are the same as Green et al. (2016). Uncertainty on the position of mineral stability fields is thought to be less than 50 °C and 1 kbar at 2 S.D. (Palin et al., 2016).

The *P*–*T* pseudosection constructed using the measured bulk composition in the range of 3–20 kbar and 500–900 °C is shown in Fig. 6. The bulk compositions (in mole %) are SiO_2 = 52.63, TiO_2 = 2.43, Al_2O_3 = 8.53, CaO = 12.55, MgO = 6.40, FeO = 9.88, K_2O = 0.34, Na_2O = 2.48, H_2O = 3.84 and O_2 = 0.92. In the calculated *P*–*T* range, garnet appears above 6.5–10 kbar, rutile appears above ~10.5 kbar, muscovite appears in upper left corner under the conditions of 10.4–20 kbar and 500–840 °C, orthopyroxene appears in the lower right corner at ~3–8.7 kbar and 785–900 °C; amphibole can stable to 885 °C in the calculated pressure range, plagioclase is unstable in the upper left corner above ~11.7 kbar, and biotite breaks down above 740 °C and 14 kbar (Fig. 6). The system solidus is water-saturated and has a negative *P*–*T* slope between ~710 ˚C at ~3 kbar and ~645 ˚C at ~8.7 kbar, and becomes water-undersaturated and varying slopes between ~8.7 kbar and 20 kbar (Fig. 6).

The most basic constraints on the metamorphic *P*–*T* conditions are provided by the calculated stability fields of each observed mineral assemblage on the pseudosection. The observed peak metamorphic M2 assemblage Grt + Cpx + Pl + Qz + Rt + Sph is stable at *P*–*T* conditions of 12–19 kbar and 780–900 °C in the presence of melt (Fig. 6). The retrograde M3 assemblage Opx + Cpx + Pl + Amp + Qz + Ilm is stable at 785–800 °C at 3–8 kbar. The metamorphic conditions are further constrained by mineral compositional isopleths. As described above, the garnet of the mafic granulite has growth compositional zoning, characterized by X_{Mg} (=Mg/(Mg+Fe+Ca)) increasing from 0.114 at the core to 0.175 at the rim. The modeling result shows that isopleths of X_{Mg} have a steep slope and are basically independent of pressure, indicating that the granulite underwent heating process from ca. 720 °C at 13 kbar (X_{Mg}=0.114) to ~830 °C at 15 kbar (X_{Mg}=0.175; Fig. 6b). The maximum X_{Mg} of 0.175 of the rim of garnet and the minimum X_{Ca} (=Ca/(Ca+Na+K)) of 0.301 of the matrix plagioclase intersect at 820 °C and 13.7 kbar, which is at the stability field of the peak mineral assemblage, and provides a rough lower limit of metamorphic pressure of the granulite because the matrix plagioclase with the lowest CaO content was probably not detected. The generated melt volume is between 14% and 20% at the stability field of peak mineral assemblage (Fig. 6b).

5.2 Conventional Geothermobarometry

Peak metamorphic conditions of the two granulite samples were independently verified by performing conventional thermobarometry. Using compositions of clinopyroxene (average value of all analytical spots), garnet with the highest MgO content, and plagioclase with the highest Na_2O content, the combination of Gt-Cpx-Pl-Qz barometer of Newton and Perkins (1982) with Gt-Cpx thermometers of Powell et al. (1985) and Krogh (1988) yielded *P–T* conditions of ~17 kbar and 870–880 °C for the sample 45-5, and ~15 kbar and 840–850 °C for the sample 45-1. Using the same mineral compositions, the combination of Gt-Cpx-Pl-Qz barometer of Eckert et al. (1991) with the Gt-Cpx thermometers described above, the two samples yielded similar *P–T* conditions of ~1.8 GPa and 840–870 °C. These conditions are at the stability field of the peak mineral assemblage documented by *P–T* pseudosection modeling (Fig. 6).

6. Zircon U–Pb dating and trace elements

Because the retrograde mafic granulite from the same outcrop as the present studied mafic granulites has been dated using zircon U-Pb method by Zhang et al. (2018), this paper focused on U–Pb ages and trace elements of zircon from the garnet-bearing leucosome of the HP mafic granulites. As shown in Fig. 2c, the leucosome (sample 97-12) occurs as concordant band within the migmatitic granulite. The separated zircon grains are colorless, euhedral to subhedral and prismatic shape with length of 200–300 μm, and commonly show a well-preserved core-mantle-rim structure on cathodoluminescence (CL) images (Fig. 7). Some zircon grains have incomplete core-mantle-rim structure due to the absence of the inherited core domains. The core domains of zircon are euhedral to subhedral and prismatic form, and show light luminescence and weak oscillatory zoning. The zircon mantle domains are subhedral and prismatic, show relatively slight luminescence and weak oscillatory or patchy zoning. The rim domains show dark luminescence, and weak oscillatory zoning or unzoned.

All 81 analytical spots on the different domains of zircon yielded concordant or near concordant but varying ^{206}Pb/^{238}U ages ranging from 137.7 to 15.3 Ma (Appendix Table 5; Fig. 8a). The core, mantle and rim domains have ^{206}Pb/^{238}U ages ranging from 137.7 to 124.3 Ma (with a weighted mean age of 130 ± 3.5 Ma), 41.5 to 35.6 Ma, and 34.6 to 15.3 Ma, respectively (Fig. 8a,b). The core domains have relatively high REE concentrations, fractionated REE patterns with distinct negative Eu anomalies (Fig. 9; Appendix Table 5). The cores also have relatively high HREE, MREE (Gd+Tb) and Y concentrations, and distinct high Th/U ratios (Fig. 10). The mantle domains have relatively high but variable HREE and Y, relatively low LREE and MREE contents, very low Th/U ratios, and distinct fractionated HREE patterns (Figs. 9 and 10). The rim domains have low HREE and Y concentrations, relatively high MREE (Gd+Tb) and Th/U ratios, and therefore show weak fractionated, flat and even depleted HREE patterns (Figs. 9 and 10). Moreover, it is noted that HREE and Y contents of the mantle and rim domains of zircon show distinct decreasing trend with decreasing ages (Fig. 10a,b), while MREE (Gd+Tb) contents and Th/U ratios show distinct increasing with decreasing ages (Fig. 10c,d).

7. Discussions

7.1 HP metamorphism and *P*–*T* paths of the EHS

The typical HP granulites occur widely in the western part of GHC of the EHS (Fig. 1b). Due to the very poor accessibility of the eastern and southeastern parts of the EHS, whether there are the HP granulites in these areas remains unknown. The pelitic and felsic HP granulites in the GHC are characterized by having peak metamorphic mineral assemblage of garnet + kyanite + plagioclase + K-feldspar + biotite + quartz + rutile, commonly with antiperthite (or ternary feldspar) (Liu and Zhong, 1997; Ding et al., 2001; Liu et al., 2007; Zhang et al., 2010a, 2015; Guilmette et al., 2011; Su et al., 2012; Xiang et al., 2013; Tian et al., 2016, 2019, 2020). Although migmatitic mafic rocks, including garnet-bearing amphibolite and garnet-free amphibolite, occur widely in the EHS, typical HP mafic granulites, containing garnet, clinopyroxene, plagioclase, quartz and rutile, are rarely reported (Zhong and Ding, 1996; Liu and Zhang et al., 2014; Zhang et al., 2018; Kang et al., 2020). Field observation shows that the HP mafic granulites occur as small bodies within thickly layered amphibolite, and show transitional contacts with the hosting amphibolite, characterized by gradual decreasing of garnet and clinopyroxene contents, and increasing of amphibole and plagioclase contents. This indicates that the most mafic granulite were retrograded into the amphibolite with or without garnet. Similarly, the pelitic and felsic HP granulites in the EHS commonly were transformed into low-pressure (LP) granulite or amphibolite-facies rocks during the exhumation, characterized by sillimanite replacing kyanite, cordierite + plagioclase + biotite replacing garnet (Liu and Zhong, 1997; Ding and Zhong, 1999; Ding et al., 2001; Zhang et al., 2010, 2015; Guilmette et al., 2011; Xiang et al., 2013; Tian et al., 2016). In this case, we consider that the GHC, at least the western part of GHC, probably underwent early and coherent HP granulite-facies metamorphism and late LP granulite- and amphibolite-facies retrograde metamorphism, and the widely distributed migmatitic garnet-bearing amphibolites, garnet- and sillimanite-bearing gneisses and schists are actually the retrograde products of early HP mafic, felsic and pelitic granulites.

The metamorphic conditions of the pelitic and felsic rocks in the EHS have been well constrained by recent petrological and phase equilibrium modeling studies (e.g., Guilmette et al., 2011; Xiang et al., 2013; Zhang et al., 2015; Tian et al., 2016, 2019, 2020). For example, Guilmette et al. (2011) shown that the felsic granulite records peak metamorphic *P*–*T* conditions of >14 kbar and 825 °C, possibly up to 15–16 kbar and 850 °C, which was followed by decompression and cooling to 9 kbar and 810 °C (Fig. 11). Zhang et al. (2015) indicated that the pelitic granulites underwent HP and HT metamorphism with a peak condition of ~16 kbar and ~900 °C, and post-peak near-isothermal decompression to ~5–6 kbar and ~850 °C. Tian et al. (2016, 2019) argued that the felsic granulite recorded a peak-metamorphic condition of 15–16 kbar and 825–835 °C. For the metabasic rocks, using conventional geothermobarometry, peak metamorphic conditions of ~17–18 kbar and ~890 °C and retrograde conditions of ~5 kbar and ~850 °C were estimated by Liu and Zhong (1997), and peak metamorphic conditions of 14–15 kbar and ~800 °C and retrograde conditions of 8–10 kbar and 800 °C by Ding et al. (2001), and 14 kbar and ~904 °C by Liu and Zhang (2014). Recently, considering amphibole as one of peak metamorphic minerals, *P*–*T* conditions of 14–15.5 kbar and 780–790 °C and 15−17 kbar and 805−840 °C were estimated for the HP mafic granulites from the EHS by Zhang et al. (2018) and Kang et al. (2020). The present phase equilibria modelling shows that the observed peak metamorphic mineral assemblage of the studied typical HP mafic granulite is stable at *P*–*T* conditions of 12–19 kbar and 780–900 °C (Fig. 6), with a possible limited metamorphic conditions of ~820 °C and ~14 kbar. The present geothermobarometry calculations yielded *P*–*T* conditions of 15–18 kbar and 840–880 °C. Therefore, considering the potential errors of phase equilibria modelling and geothermobarometry, a variety of HP granulites from the EHS have similar HP and HT metamorphic conditions of 15–17 kbar and 820–880 °C. This indicates that the Indian continental lower crustal rocks were buried to at least 50–55 km-depth during the collisional orogeny.

Previous studies have all demonstrated that the HP granulites in the EHS recorded clockwise metamorphic *P*–*T* paths. Moreover, these *P*–*T* paths are mostly characterized by an early prograde metamorphism with both increasing *P* and *T*, and a subsequent retrogression of isothermal decompression (e.g., Guilmette et al., 2011; Xiang et al., 2013; Liu and Zhang, 2014; Zhang et al., 2015, 2018; Tian et al., 2016; Kong et al., 2020), and a late isobaric cooling process (Zhang et al., 2018). Thus metamorphic *P*–*T* paths are typical of HP and UHP metamorphic rocks in collisional orogens.

The present study also indicates that the mafic granulite experienced heating prograde process due to the porphyroblastic garnets of the granulite displays clear growth zoning, characterized by increasing MgO and decreasing MnO from the core to rim of the garnet grains (Figs. 4 and 5). A petrological study (Zhang et al. 2018) showed that coarse-grained (up to 1.5 cm in diameter) porphyroblastic garnet in a garnet amphibolite, collected from the same location as the present studied mafic granulite and formed as the retrograde product of the present studied granulite, displays distinct growth compositional zoning, which has a more MgO-rich and MnO-poor core in comparison with the present analyzed garnet cores, providing more favorable evidence for the prograde metamorphism of both increasing *T* and *P*. Moreover, the core of coarse-grained garnet in the retrograde granulite contains the early prograde mineral inclusions of amphibole, plagioclase, biotite, quart and titanite, which constrained a prograde metamorphic condition of ~650 °C and ~10 kbar (Zhang et al., 2018). In addition, a similar prograde metamorphic condition of 9.5–12.8 kbar and 550–710 °C was estimated to the pelitic granulite from the adjacent area (Zhang et al., 2015). The late retrograde mineral assemblage of amphibole, plagioclase, biotite, quartz, ilmenite and titanite of the retrograde mafic granulite yielded a retrograde metamorphic condition of ~600–700 °C and < 6 kbar (Zhang et al., 2018). Because the present granulite and the retrograde granulite occur in the same location, we consider that they have the same prograde and late retrograde conditions. In addition, the present study shows that the early retrograde mineral assemblage (M3) of Opx + Cpx + Pl + Amp + Qz + Ilm is stable in a *P*–*T* field of 785–870 °C at 3–8 kbar, which indicates the granulite underwent an early isothermal decompression process (Fig. 6). Based on these considerations described above, we suggest that the HP mafic granulite has a clockwise *P*–*T* path, characterized by an early prograde metamorphism of heating and burial, and subsequent isothermal decompression, and late isobaric cooling process (Figs. 6 and 11).

7.2 Partial melting of the GHC and origin of the Himalayan granites

Field observation shows that the GHC in the EHS underwent intense migmatization, and a variety of rocks of the GHC contain abundant leucosomes that occur as concordant and discordant bands, thin layers, networks and veins. These in-situ or in-source leucosomes clearly indicate the host rocks underwent distinct partial melting. Moreover, the kyanite- and garnet-bearing leucosomes are common in the migmatitic pelitic and felsic granulites. This provides a solid petrological evidence for the partial melting in conditions of HP granulite-facies. The previous and present petrological studies all shown that the peak metamorphic conditions of various types of HP granulites have markedly exceeded their solidus, indicating that these granulites have underwent the partial melting during the prograde metamorphism. For the pelitic and felsic granulites, prograde partial melting was driven by dehydration melting of muscovite and biotite (Guilmette et al., 2011; Xiang et al., 2013; Zhang et al., 2015; Tian et al., 2016, 2019; Liu et al., 2019), and for the mafic granulites, the prograde partial melting was dominated by dehydration melting of amphibole (Zhang et al., 2018; Kang et al., 2020). The present phase equilibria modelling clearly shows that the mafic granulite has a distinct decreasing amphibole mode, and increasing garnet and melt modes during the prograde metamorphism and partial melting (Fig. 12). This indicates that the partial melting of the mafic granulite is dominated by dehydration melting of amphibole, in addition to minor contribution of dehydration melting of epidote and biotite during the early stage of partial melting, and decomposition melting of plagioclase during the late stage of partial melting (Fig. 12). This modelling also shows that the partial melting of the mafic granulite can product significant amount of melt (~16 vol.%) at the peak metamorphic condition of ~850 °C and ~16 kbar (Figs. 6b and 12). Similar or even more melts were estimated for the peak metamorphic stage of garnet amphibolites from the EHS (Zhang et al., 2018; Kang et al., 2020). Up to 20–30 vol.% partial melt can be produced during prograde to peak metamorphism of the pelitic and felsic HP granulites in the EHS (Guilmette et al., 2011; Xiang et al., 2013; Zhang et al., 2015; Tian et al., 2016, 2019). These indicate that the partial melts derived from the dehydration melting of variety rocks of the GHC have significantly contributed to the formation of the Himalayan granites.

Most studies considered extensive partial melting of high-grade metamorphic pelitic rocks from the GHC to produce the Himalayan leucogranites (e.g., Le Fort et al., 1987; Harris and Massey, 1994; Guillot and Le Fort, 1995; Harris et al., 1995; Patiño-Douce and Harris, 1998; Knesel and Davidson, 2002; Aoya et al., 2005; Guo and Wilson, 2012; Zeng et al., 2012; Weinberg, 2016). Three distinct melting processes have been proposed: prograde heating with an increase in pressure (Visonà and Lombardo, 2002; Zhang et al., 2004; Groppo et al., 2010; Guilmette et al., 2011), decompression melting during exhumation (Harris and Massey, 1994; Harrison et al., 1997; Patiño-Douce and Harris, 1998; Harris et al., 2004; Viskupic et al., 2005; Guo and Wilson, 2012), and water-fluxed melting (Knesel and Davidson, 2002; Gao et al., 2014, 2017; Weinberg, 2016). In fact, the Himalayan granites have highly varying chemical compositions (e.g., Gou and Wilson, 2012; Wu et al., 2015), indicating that different geological processes may have formed them. Gao et al. (2014, 2017) argued that the dehydration melting and water-fluxed melting of pelitic schists resulted in the changes of trace element and isotopic compositions of the Himalayan leucogranites. But, we consider that, in addition to the different melting mechanisms and crystallization fractionation of melts, the distinct protolith types, different degrees of partial melting and possible melt mixing were more important control effects on the chemical compositions of Himalayan granites. The present and previous studies have demonstrated that the pelitic, felsic and mafic rocks from the EHS all underwent intensive partial melting. In this case, the melts derived from the different protoliths must have different chemical compositions. For example, the Eocene high Sr/Y granites were considered to be derived from the partial melting of amphibolites in the thickened lower crust of the Himalayan orogen based on geochemical evidence (Zeng et al., 2011; Hou et al., 2012; Liu et al., 2014). In fact, Guillot and Le Fort (1995) demonstrated that the Himalayan leucogranites with distinct $^{87}Sr/^{86}Sr$ initial isotopic ratios were derived from two different sources: two-mica leucogranites formed from metagreywacke (with Sr_i <0.752 and εNd <-15) and tourmaline leucogranites formed from metapelite (Sr_i> 0.752; εNd>-15). In addition, Gou et al. (2016) argued that the tourmaline-muscovite leucogranites formed via muscovite-dehydration melting, whereas the muscovite-biotite leucogranites dominantly resulted from biotite-dehydration melting during the prograde metamorphism of the pelitic and felsic granulites of the GHC.

7.3 Timescale of metamorphism and anatexis of the GHC in the EHS

Zircon of the high-grade metamorphic rocks in the EHS have been dated using U–Pb in-situ dating methods by many studies (e.g., Ding et al., 2001; Booth et al., 2004, 2009; Liu et al., 2007; Xu et al., 2010; Zhang et al., 2012; Tian et al., 2020), moreover, some of the studies also simultaneously obtained trace element compositions of the dated zircon domains, which allows us to link the dating results to the general age of metamorphism (Zhang et al., 2010, 2015, 2018; Su et al., 2012; Tian et al., 2020). Zhang et al. (2010, 2015) showed that the overgrowth domains, including the mantle and rim, of zircon of the four typical pelitic HP granulites in the Danniang and Pai areas of the EHS have concordant and varying U–Pb ages of 39.5–23.8 Ma, 35.6–16.3 Ma, 43.9–19.4 Ma and 24.8–7.2 Ma, respectively. Moreover, the zircon overgrowth domains have low HREE concentrations, flat HREE patterns, low Th/U ratios, and negative Eu anomalies, typical of metamorphic zircon that grew coevally with garnet and plagioclase during HP granulite-facies metamorphism and associated partial melting (Corfu et al., 2003; Hoskin and Schaltegger, 2003; Rubatto, 2002; Rubatto and Hermann, 2007; Rubatto et al., 2013). Therefore, Zhang et al. (2015) concluded that the metamorphic zircon overgrowth rims with varying ages ranging from 43.9 to 7.2 Ma grew at different episodes of a single granulite-facies metamorphic process, and the HP pelitic granulites underwent a long-lived HT metamorphic process over 30 Myr. Recently, Tian et al. (2020) showed that metamorphic overgrowth domains of zircon from the HP pelitic granulites in Jiala area have variable U–Pb ages ranging from 50 to 13 Ma. In addition, the highly varying U–Pb ages have been obtained from the metamorphic zircon domains of migmatitic garnet amphibolites (retrograde HP mafic granulites) in the EHS, such as 39–10 Ma in Jiala area (Peng et al., 2018), 39–11 Ma in Jiala area (Zhang et al., 2018), and 40–10 Ma in Pai area (Kang et al., 2020). These data also show that the mafic granulites from the different areas of the EHS underwent prolonged metamorphic processes over 30 Myr. But, some different points of view for the peak-metamorphic and retrograde times of the EHS HP granulites have been suggested. For example, Ding et al. (2001) considered that the HP granulite-facies metamorphic and MP retrograde stages occurred at ~40 Ma and ~11 Ma, respectively. Liu et al. (2007) assigned ~33–30 Ma to HP metamorphism and ~23 Ma to LP retrogression, respectively. Zhang et al. (2010) argued that the HP peak-metamorphism and LP overprint occurred at 37–33 Ma and 28–16 Ma, respectively. Xu et al. (2010) assigned ~24 Ma to the peak-metamorphism and 19–17 Ma to subsequent retrograde metamorphism. Su et al. (2012) inferred that that the peak metamorphic age for the HP granulites is at ~24–25 Ma, and subsequent amphibolite-facies retrograde metamorphism occurred at ~18 Ma. Liu and Zhang (2014) suggested that the peak metamorphic age for the HP mafic granulites is at ~20 Ma (Fig. 11). Zhang et al. (2015) thought that the near-peak and peak-metamorphism of the EHS HP granulites occurred at ~40–30 Ma, and the early and late stages of retrograde metamorphism under granulite-facies conditions formed at ~25–15 Ma and ~11–7 Ma, respectively. Recently, the wide range of metamorphic ages have been approximately linked to the timescales of high T metamorphism and partial melting, and melting crystallization of the GHC in the EHS. Such as, Tian et al. (2019) shown that the age intervals of the prograde to peak-pressure, and exhumation and melt crystallization of the HP felsic granulite were from ~33 Ma to ~25 Ma, and from ~24 to ~8 Ma. Kang et al. (2020) indicated that the garnet amphibolite in Pai area experienced a HP prograde and anatectic process from ~40 Ma to ~20 Ma, and the retrograde metamorphism and melt crystallization from ~20 to 10 Ma.

The present study shows that the zircon mantle and rim domains mostly have lower REE and Y contents, Th/U ratios than those of the zircon cores (Figs. 9 and 10). These are typical of metamorphic zircon that grew coevally with garnet and plagioclase during granulite-facies metamorphism and partial melting (Corfu et al., 2003; Hoskin and Schaltegger, 2003; Rubatto, 2002; Rubatto and Hermann, 2007; Rubatto et al., 2013). It is noted that the zircon mantle and rim domains show a distinct decrease in HREE and Y contents, and a distinct increase in Gd+Tb contents with decreasing ages (Fig. 10a-c). These changes are consistent with the growth of garnet and breakdown of amphibole during the prograde metamorphism and associated partial melting (Fig. 12) due to the garnet being as the main host of HREE and Y, and amphibole as the main host of Gd+Tb in mafic granulites (Nehring et al., 2010). In this case, we consider that the prograde metamorphism and partial melting of the mafic granulite probably began at ~42 and lasted to ~20 Ma (Fig. 11). The distinct increasing Th/U ratios with decreasing ages (Fig. 10d) probably indicate a gradual increasing degree of partial melting of the mafic granulite.

In fact, the garnet amphibolites – which are retrograded granulites – collected from the same outcrop as the studied mafic granulite, similar age intervals of 39–10 Ma were obtained using zircon U–Pb dating by Peng et al. (2018) and Zhang et al. (2018). Peng et al. (2018) interpreted the old ages of ~39 Ma and ~35 Ma to be the Eocene magmatic event, and the age range of ~30–10 Ma to be the metamorphic time of the garnet amphibolite; but Zhang et al. (2018) thought that the garnet amphibolite underwent the prograde metamorphism and associated partial melting from ~39 Ma to

~22 Ma, and the isothermal decompression, cooling retrogression and melt crystallization between 22 and 11 Ma (Fig. 11). The new data presented here are generally consistent with the previous conclusions that the prograde metamorphism and partial melting of the garnet amphibolite from the EHS initiated at 39–40 Ma and lasted to 20–22 Ma (Zhang et al., 2018; Kang et al., 2020), and the peak metamorphic age of the mafic granulite in the EHS was at ~20 Ma (Liu and Zhang, 2014). In addition, available studies shown that the retrograde metamorphism and melt crystallization of the HP granulites probably have lasted to 10–5 Ma and even later in the EHS (Booth et al., 2004, 2009; Zhang et al., 2015). In this case, we have enough evidence to believe that the EHS HP granulites experienced a long-lived HT metamorphism, partial melting and melt crystallization process over 30 Myr. This is basically in accordance with the long-lasting HT metamorphic process of GHC from the Nepal to Sikkim and Bhutan, Central Himalaya, such as 32–17 Ma (Searle et al., 2003), 33–13 Ma (Cottle et al., 2009a; Kali et al., 2010) and 37–20 Ma (Kohn and Corrie, 2011), and a long-lived partial melting process, such as 40–14 Ma (Wang et al., 2013), 33–18 Ma (Imayama et al., 2012), 36–17 Ma (Rubatto et al., 2013). In addition, this is also generally consistent with the channel flow model that predicts the GHC with a prolonged granulite-facies metamorphism with the HP metamorphism (P max.) at ~30 Ma, peak metamorphism (T max.) at ~20Ma, and granulite-facies retrogression at ~10 Ma (Jamieson et al., 2004).

7.4 Pre-Cenozoic magmatism of the GHC

Traditionally, the GHC was considered as a Late Proterozoic to Paleozoic metasedimentary sequence (e.g., Kohn, 2014), although it contains abundant meta-magmatic rocks with different protolith ages. Early Paleozoic (~510–470 Ma) granitoids and granitic gneisses have been increasingly reported along the Himalaya orogenic belt (Miller et al., 2001; Gehrels et al., 2006; Cawood et al., 2007; Xu et al., 2005; Wang et al., 2012; Gao et al., 2015, 2019; Ding et al., 2017; Palin et al., 2018), and Neoproterozoic granitoids have recently been found in the GHC of the Eastern

Himalaya (Ding and Zhang, 2016a; Wang et al., 2017a). For the Eastern Himalayan Syntaxis, protoliths of the meta-magmatic rocks in the GHC includes the Proterozoic (~1760–1560 Ma), early Paleozoic (~500–490 Ma) granitoids, Proterozoic (1645–1590 Ma) gabbroic rocks (Guo et al., 2008; Zhang et al., 2008, 2012; Wang et al., 2014), and late Cretaceous (~90–80 Ma) gabbroic rocks (Peng et al., 2018). This paper for the first time reported the Early Cretaceous gabbroic rocks in the GHC. The Early and Late Cretaceous basic rocks were widely disturbed within the Tethyan Himalaya (Zhu et al., 2009; Liu et al., 2014; Wang et al., 2016), and probably related to the breakup of eastern Gondwana (Zhu et al., 2009; van Hinsbergen et al., 2011), and tectonic events on the northern Indian passive margin before its collision with the Eurasian Plate (Peng et al., 2018), respectively. The Early Paleozoic magmatism was commonly considered as the products of Andean-type orogeny along the northern margin of Gondwana supercontinent (Gao et al., 2019 and references therewith); the Neoproterozoic granitoids probably resulted from the Andean-type orogeny along the northwestern margin of Rodinia supercontinent (Ding and Zhang, 2016); the Proterozoic thermal events were probably induced by the Andean-type orogeny following the Columbia supercontinent assembly (Zhang et al., 2012).

7.5 Metamorphism and tectonic evolution of the Himalayan orogen

The Himalayan orogen formed due to India–Asia continental collision, which initiated at ~60–50 Ma (Yin & Harrison, 2000; Leech et al., 2005; Najman et al., 2010, 2017; Meng et al., 2012; Wu et al., 2014; Zhu et al., 2015; Ding et al., 2016b). As the collisional products, as shown in Fig. 1a, ultrahigh pressure (UHP) and near-UHP metamorphic rocks occur in the Western Himalaya (O'Brien et al., 2001; Kaneko et al., 2003; Ahmad et al., 2006; Guillot et al., 2008; Rehman et al., 2008; Wike et la., 2010, 2015; Lanari et al., 2013; Palin, 2014, 2017; Kouketsu et al., 2016), HP granulites (Groppo et al., 2010, 2012; Kali et al., 2010; Sorcar et al., 2014; Zhang et al., 2017a,b) and HP eclogites (Lombardo and Rolfo, 2000; Groppo et al., 2007; Cottle et al., 2009a; Chakunga et al., 2010; Corrie et al., 2010; Grujic et al., 2011;

Warren et al., 2011; Kellett et al., 2014; Kohn, 2014; Lombardo et al., 2016; Wang et al., 2017b; Li et al., 2019) occur throughout the Central Himalaya, whereas only HP granulites are exposed in the Eastern Himalayan Syntaxis (Liu & Zhong, 1997; Ding et al., 2001; Booth et al., 2009; Xu et al., 2010; Zhang et al., 2010, 2015, 2018; Guilmette et al., 2011; Su et al., 2012; Liu and Zhang, 2014; Tian et al., 2016, 2019, 2020; Kang et al., 2020; This study). The UHP or near UHP eclogites occur at Kaghan Valley and Stak (Pakistan), and Tso Morari massif (NW India), and close to the Indus-Yarlung Tsangpo suture zone in the Western Himalaya (Fig. 1a). The UHP metamorphic conditions were estimated at 600–770 °C and 3.0–3.5 GPa (Fig. 11; Wike et al., 2010; Rehman et al., 2013; Palin et al., 2017). This confirms that the northwestern margin of Indian continent was deeply subducted into the mantle depth of at least 100–120 km (Fig. 13a). Based on extensive zircon U–Pb dating, the coesite eclogite stage was determined at 50–45 Ma, and amphibolite facies retrograde stage at 45–40 Ma, and the prograde metamorphic stage at ~55–50 Ma (Kaneko et al., 2003; Parrish et al., 2006; Rehman et al., 2013; Donaldson et al., 2013; St-Onge et al., 2013). Therefore, the UHP rocks in the Western Himalaya underwent rapid subduction and rapid exhumation.

The HP eclogites (or granulitized eclogites) from the Central Himalaya were found in Khartz (Ama Drime), Dinggye and Thongmön areas, China (Lombardo and Rolfo, 2000; Groppo et al., 2007; Cottle et al., 2009; Wang et al., 2017b; Li et al., 2018), Arun valley, Nepal (Corrie et al., 2010), Mount Kangchendzonga, North Sikkim (Rolfo et al., 2008), and Jomolhari massif, NW Bhutan (Grujic et al., 2011; Warren et al., 2011; Regis et al., 2014) (Fig. 1a). These HP mafic rocks commonly occurred as the thin layers, lenses or boudins within felsic and pelitic rocks. The peak metamorphic *P*–*T* conditions were constrained at 22–25 kbar and 700–800 °C (Fig. 11; Groppo et al., 2007; Corrie et al., 2016; Wang et al., 2017b; Li et al., 2019), indicating that the continental crust of the Central Himalaya has been thickened to ~70 km (Fig. 13b). Zircon U–Pb ages of ~18–14 Ma were obtained from the retrograde eclogites (Li et al., 2003; Grujic et al., 2011; Lombardo et al., 2016; Wang et al., 2017b), and well preserved eclogites (Li et al., 2019). These ages were interpreted to date either eclogite-facies metamorphism (Grujic et al., 2011; Wang et al., 2017b; Li et al., 2019) or granulite-facies overprinting (Groppo et al., 2007; Lombardo et al., 2016). Corrie et al. (2010) reported a garnet Lu–Hf age of ~20 Ma for one relict eclogite from Arun valley. Based on garnet Lu–Hf ages of 38–34 Ma and zircon U–Pb ages of 15–13 Ma from the retrograde eclogites in Ama Drime, Kellet et al. (2014) considered that the eclogite facies metamorphism occurred at ~38 Ma, and granulite-facies overprinting followed at ~15–13 Ma. They argued that unlike UHP eclogites of the Northwest Himalaya, the Ama Drime eclogites are not characteristic of rapid burial and exhumation of a cold subducted slab, instead resulted from crustal thickening during the early stages of continental collision, and resided in the lower-middle crust for >20 Myr. before they were exhumed and reheated, and that the Indian crust have already reached at least ~60 km thickness by the late Eocene. In this case, the Central Himalayan eclogites were probably exhumed relatively slowly and were subjected to thermal relaxation in the thickened continental crust producing a strong granulite-facies overprint at intermediate crustal levels.

For felsic and pelitic rocks, forming as country rocks of the HP eclogites in the Central Himalaya, a wide range of metamorphic ages from the middle and late Eocene to middle Miocene has been increasingly reported (Fig. 1a; Cottle et al., 2009b; Kohn and Corrie, 2011; Rubatto et al., 2013; Carosi et al., 2015; Iaccarino et al., 2015; Wang et al., 2015a, b; Zhang et al., 2017a). This indicates that these felsic and pelitic rocks have similar long-lived metamorphic evolution to the hosting HP eclogites although their metamorphic conditions were commonly estimated at granulite facies or amphibolite facies due to the intensive HT retrograde metamorphism erasing the record of early HP eclogite facies. As argued by O’Brien (2018), there are no convincing evidence that the eclogites have been tectonically emplaced into the GHC para- and orthogneisses, and the eclogitization and granulitization of the metabasites was in situ: that is, that these particular nappe units of the Higher Himalaya also experienced eclogite-facies conditions as a whole. In addition, it is possible that the

GHC consists of different slices, with different histories, separated by ductile shear zones, as suggested by many studies (e.g. Goscombe et al., 2006, 2018; Groppo et al., 2009; Carosi et al., 2010; Chakungal et al., 2010; Grujic et al., 2011; Warren et al., 2011; Montomoli et al., 2013, 2015; Larson et al., 2015; Wang et al., 2015b, 2016), and the HP eclogitic slice probably forms as the upper structural unit of the GHC due to most HP eclogites occurring near the STD (Fig. 1a).

As described above, the previous works and present study all demonstrated that the Eastern Himalayan Syntaxis only experienced the HP granulite facies metamorphism under conditions of ~14–16 kbar and ~800–900 °C, indicating that the crust of the Eastern Himalaya has been thickened to ~50-km-depth (Fig. 13c). Moreover, the HP granulites underwent a long-lived metamorphic evolution that probably stared at ~50 Ma and lasted to 10–5 Ma, with a possible peak (P max.) metamorphic stage at ~20 Ma (Fig. 11), indicating that the HP granulites experienced a slow burial and slow exhumation. Unlike the Western Himalayan UHP rocks formed in the cool subduction zone (Fig. 13a), the HP eclogites and HP granulites from the Central and Eastern Himalayas underwent distinct HT metamorphism during the prograde and/or retrograde metamorphic stages in the hot and thickened lower crust (Fig. 13b,c), and therefore witnessed intensive partial melting. The generated voluminous melts provided the source for the Himalayan granites. It is noted that the Eastern Himalayan HP granulites underwent a prolonged partial melting process from ~40 to ~20 Ma during the prograde metamorphism (Fig. 11), which is generally consistent with the long-term duration of Himalayan granitic magmatism during the late Eocene to early Miocene (Aikman et al., 2008, 2012; Qi et al., 2008; Zeng et al., 2011; Guo and Wilson, 2012; Hou et al., 2012; Wu et al., 2015; Liu et al., 2016).

The above discussions show that the metamorphic pressure of GHC gradually decreases from west to east, from the UHP eclogite in the Western Himalaya, through HP eclogite in Central Himalaya, to HP granulite in the Western Himalaya (Figs. 1a and 11). In contrast, the metamorphic temperature of GHC progressively increases from west to east, from 600–770 °C in the Western Himalaya, through 700–800 °C in

Central Himalaya, to 750–900 °C in the Western Himalaya (Fig. 11). We consider that the northwestern margin of Indian continent has been deeply subducted into the mantle depth of at least 100–120 km followed the closure of the Neo-Tethyan Ocean (Fig. 13a), whereas in the Central and Eastern Himalayas, the Indian continental crust decupled from the deeply subducted lithospheric mantle shallowly subducted (underthrusted) or relaminated beneath the Asian continental crust, and formed the thickened lower crust of the Himalayan orogen and the Gangdese migmatitic arc after the Indo-Asia collision (Fig. 13b,c). Moreover, we suggest that the underthrusted Indian crustal materials formed one of sources for the syn-collisional and crust-derived granites of the Gangdese arc, representing the eastern part of Trans-Himalayan magmatic arc (Fig. 1a). Many studies demonstrated that the subduction-related magmatic rocks of the Gangdese arc consist mainly of mantle-derived gabbros, and show distinct geochemical features of depleted mantle, whereas the syn-collisional magmatic rocks of the arc include voluminous crust-derived granites, and display different degrees of enrichment of Hf and Nd isotopic compositions (e.g., Chung et al., 2005; Chu et al., 2006, 2011; Mo et al., 2007, 2008; Ji et al., 2009; Wu et al., 2010, 2014; Zhu et al., 2011, 2018; Zhang et al., 2010b, 2014, 2019, 2020). The distinct Hf isotopic change between the subduction- and collision-related magmatic rocks of the Gangdese arc was interpreted as tracking the evolving progress of Himalayan sediment subduction driven by the approaching Indian continent (Chu et al., 2011). We speculate that the syn-collisional granites are products of mixing of melts that were derived from partial melting of both the thickened juvenile arc crust and relaminated Indian crust (Fig. 13b,c). Recent studies shown that the early Cenozoic S-type granites occur in the Gangdese arc (Guo et al., 2012; Zhang et al., 2013; Ma et al., 2017), providing favorable evidence for the Gangdese thickened lower crust having the meta-sedimentary rocks of underthrusted Indian crust. By comparison, the syn-collisional granites in the Kohistan and Karakorum arc, representing the western part of the Trans-Himalayan arc, were dominantly derived from the partial melting of juvenile crust, and therefore basically do not show the geochemical characteristics of ancient crust (e.g., Ravikant et al., 2009). This is probably because the deeply subducted and UHP metamorphosed Indian crust has not involved in the syn-collisional arc magmatism (Fig. 13a). Recent studies shown that Eocene mantle-derived gabbros have intruded into the Tethyan Himalayan Sequences (Fig. 13b,c; Ji et al., 2016), therefore the mantle-derived heat probably provides an additional heat source for HT metamorphism and partial melting of the thickened lower crust of the Himalayan orogen to produce the Himalayan granites.

8. Conclusions

1. Mafic granulite from the GHC of the EHS contains garnet, clinopyroxene, plagioclase, quartz, rutile and sphene, and underwent HP and HT granulite facies metamorphism and associated partial melting, with peak metamorphic conditions of 15–17 kbar and 820–880 °C. Considering the abundance of typical pelitic, felsic and mafic HP granulites, we concluded that the GHC, at least the western part of GHC, the EHS, underwent early and coherent HP granulite-facies metamorphism and late LP granulite- and amphibolite-facies retrograde overprint.
2. The HP mafic granulites in the EHS underwent long-lived dehydration melting of amphibole from 40 Ma to 20 Ma during prograde metamorphic burial and heating, and generated up to ~16 vol.% partial melt at peak metamorphic conditions. The variable degrees of dehydration melting of the HP mafic, pelitic and felsic granulites formed voluminous granitic melts with distinct compositions, and provided the source for the Himalayan stage of granites.
3. The GHC in the EHS contains abundant Pre-Cenozoic magmatic rocks, including the Proterozoic (~1760–1560 Ma) and Early Paleozoic (~500–490 Ma) granitoids, Proterozoic (1645–1590 Ma), Early Cretaceous (~130 Ma) and Late Cretaceous (~90–80 Ma) gabbroic rocks. They recorded multistage of Andean-type orogenesis along the northern margin of Gondwana or Indian continent before the Cenozoic Himalayan orogeny.
4. The metamorphic pressure of GHC of the Himalayan orogen gradually decreases,

whereas the metamorphic temperature progressively increases from west to east. These indicate that the northwestern margin of Indian continent deeply subducted into the mantle after the Indo-Asia collision, whereas in the Central and Eastern Himalayas, the Indian continental crust underthrusted or relaminated beneath the Asian continental crust, and formed part of the thickened lower crust of the southern Tibetan Plateau.

5. Partial melting of relaminated Indian crust is likely to result in enrichment of isotopic compositions of the depleted mantle- and juvenile crust-derived magmatic rocks of the Gangdese arc during the Early Cenozoic. The mantle-derived magmatism probably provides an additional heat source for the partial melting of the thickened lower crust of the Eastern and Central Himalayan orogen.

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Supplementary data to this article:

Appendix Table 1. Chemical compositions (wt. %) of garnet in the HP mafic granulite

Appendix Table 2. Chemical compositions (wt. %) of pyroxene in the HP mafic granulite

Appendix Table 3. Chemical compositions (wt. %) of plagioclase in the HP mafic granulite

Appendix Table 4. Chemical compositions (wt. %) of amphibole in the HP mafic granulite

Appendix Table 5. Zircon U–Pb dating and trace element (ppm) data of the leucosome in the HP mafic granulite

Figure captions:

Fig. 1. (a) Sketch geological map of the Himalayan orogen (modified after Yin and Harrison, 2000; Guillot et al., 2008; Kohn, 2014; Ding et al., 2016b), showing locations and ages of representative ultra-high pressure (UHP) and high pressure (HP) metamorphic rocks, and some medium pressure (MP) rocks with Eocene metamorphic and anatectic ages. The data sources are as follows: Arun Valley (Corrie et al., 2010), Annapurna (Kohn and Corrie, 2011), Bhagirathi (Singh, 2019), Cona (Ding et al., unpublished data), Dolpa (Carosi et al., 2010), Everest (Cottle et al., 2009b), Gianbul (Horton et al., 2015), Jomolhari (Grujic et al., 2011), Jumla (Braden et al., 2017), Kaghan (Kaneko et al., 2003), Kali Gandaki (Iaccarino et al., 2015), Mabja dome (Lee Whitehouse, 2007), Manali (Stübner et al., 2014), Namche Barwa Syntaxis (Zhang et al., 2015), Nyalam (Wang et al., 2013, 2015a, b), Stak (Kouketsu et al., 2016), Sikkim (Rubatto et al., 2013), Thongmön (Li et al., 2019), Tso Morari (Donaldson et al., 2013), Yadong (Zhang et al., 2017a), and Yardoi dome (Ding et al., 2016b,c). UHP, MBT = Main Boundary Thrust, MCT = Main Central Thrust, MFT = Main Frontal Thrust, and STD = South Tibetan Detachment system. (b) Geological map of the Eastern Himalayan Syntaxis, showing the locations of known HP granulites and the studied HP mafic granulite sample (modified after Zhang et al., 2015).

Fig. 2. Outcrop photo of migmatitic mafic granulite and amphibolite. (a) Migmatitic mafic granulite and amphibolite contain abundant felsic leucosomes that occur as bands and networks. (b) Migmatitic mafic granulite with banded felsic leucosomes. The mafic granulite, consisting of garnet, clinopyroxene, plagioclase and minor amphibole and quartz, has been gradually retrograded to the garnet amphibolite, consisting of amphibole, garnet, plagioclase and quartz, from the right side to left side of the picture. Note that the red garnet grains in both the granulite and amphibolite have the white-eye socket structure, indicating the garnets were replaced by the kelyphitic rims of very fine-grained amphibole and plagioclase. The studied mafic granulite sample 45-5 was sampled from the right side of the picture. (c) Leucosome bands in the mafic granulite consist of plagioclase, quartz, garnet and minor amphibole. The dated leucosome sample 97-12 was collected from the Leucosome band in the middle of the photo. The hammer for scale is 35 cm long, and the coins are 1.5 cm across.

Fig. 3. Photomicrographs (a, b) and BSE images (c, d) of the mafic granulite. (a) Mafic granulite, consisting of garnet, clinopyroxene, plagioclase, quartz, amphibole and ilmenite. Garnets are partly replaced by symplectitic corona of amphibole and plagioclase, and clinopyroxenes by amphiboles along their margins. (b) Mafic granulite. Garnets are replaced by symplectitic corona of amphibole + plagioclase, or amphibole + plagioclase + clinopyroxene, and clinopyroxenes by amphiboles along their rims. (c) and (d) Garnets of the mafic granulite are partly replaced by symplectitic corona of amphibole, plagioclase and orthopyroxene, and clinopyroxenes by amphibole or orthopyroxene along their rims. Mineral abbreviations: Amp-amphibole, Cpx-clinopyroxene, Grt-garnet, Ilm-ilmenite, Opx-orthopyroxene, Pl-plagioclase, Qtz-quartz, and Sph-sphene.

Figure 4 X-ray mapping of garnet grains of the mafic granulite, showing that the garnet has compositional zoning, characterized by increasing Mg and Ca, decreasing Fe and Mn from core to rim. Warm colors indicate higher concentrations of each element. The dashed lines across the garnet grains are locations of the compositional files shown in Fig. 5.

Figure 5 Compositional profiles of the garnet grains. The compositional profiles represent rim to rim analyses through garnet grains. The profile locations are shown in the Fig. 4. Mineral abbreviations: Alm- almandine, Grs-grossular, Prp-pyrope, Spe-spessartine.

Figure 6. *P*–*T* pseudosections calculated with the measured bulk composition for the mafic granulite. Isopleths of X_{Mg}=Mg/(Mg+Fe+Ca) (shown as X_{Mg}, white lines) of garnet and X_{Ca} =Ca/(Ca+Na+K) (X_{Ca}, yellow dotted lines) of plagioclase, and isomodes of melt (thin and red lines) are shown in the right penal. The thick and red lines with narrow represent the speculated *P*–*T* path of the HP mafic granulite. Mineral abbreviations: Amp-amphibole, Bt-biotite, Cpx-clinopyroxene, Ep-epidote, Grt-garnet, Ilm-ilmenite, Ms-muscovite, Opx-orthopyroxene, Pl-plagioclase, Qtz-quartz, Rt-rutile, Sph-sphene and L-liquid.

Figure 7. Cathodoluminescence (CL) images of zircon form the leucosome of mafic granulite, showing the analyzed spot locations and relevant ages (in Ma).

Figure 8. (a) U–Pb concordia diagram of zircon of the granulite leucosome; (b) Relative probability diagram of U–Pb ages of the zircon mantle and rim domains.

Figure 9. Chondrite-normalized REE patterns of the core (a), mantle (b), rim (c) and core + mantle + rim of zircon of the granulite leucosome.

Figure 10. HREE (a), Y (b), Gd + Tb (c) and Th/U ratios (d) versus ages of zircon of

the granulite leucosome

Figure 11. Metamorphic *P*–*T*–t paths of the mafic granulite, HP eclogite and UHP eclogite from in the Eastern, Central and Western Himalayas, respectively. All numbers refer to metamorphic ages in Ma. AM: amphibolite-facies, BS: blueschist-facies, EA: epidote-amphibolite facies, G: granulite-facies, GS: greenschist-facies, HG: high-granulite facies, HP-Ec: high-pressure eclogite-facies, UHP-Ec: ultrahigh-pressure eclogite facies.

Figure 12. Modal proportions changes of phases calculated along the prograde *P*–*T* path of the HP mafic granulite.

Figure 13. Tectonic model of the Himalayan orogen (modified after Willett and Beaumont, 1994). (a) In the Western Himalaya, the Indian continental crust deeply subducted into the mantle and underwent UHP metamorphism, and the syn-collisional arc magmatic rocks were derived from the partial melting of the depleted mantle and thickened juvenile lower crust. (b, c) In the Central and Eastern Himalayas, the Indian crust underthrusted or relaminated beneath the Gangdese arc crust, and formed part of the thickened lower crust consisting of HP eclogite-facies or HP granulite-facies rocks. The Himalayan granites were derived from the thickened Indian crust, and the syn-collisional arc magmatic rocks were derived from the depleted mantle, the thickened juvenile and ancient (Indian) crusts. Note that the Eocene mantle-derived gabbro intruded into the Himalayas.