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Timing of granulite-facies metamorphism in the eastern Himalayan syntaxis and its tectonic implications

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Abstract

We present geochronological evidence in the eastern Himalayan syntaxis (Namche Barwa) for high-pressure (HP) granulite-facies metamorphism and explain its importance for understanding both the deep continental subduction of the Indian plate beneath Asia and its subsequent exhumation. The timing of peak and retrograde metamorphism in part constrains these processes but is debated. We present zircon U-Pb and trace element data on granulite-facies rocks. Zircon cores and rims from a weakly retrograded mafic granulite (P=14-18 kbar, T≈800 °C) yield U-Pb ages of 24.0±0.3 Ma and 18.8±0.3 Ma, respectively. Zircon cores and rims from an orthogneiss, the host of the mafic granulite, yield U-Pb ages of 490±3 Ma and 3024.2±0.4 Ma, respectively. An amphibolitized mafic granulite gives a U-Pb zircon age of 3117.0±0.4 Ma. Combined with petrography, zircon CL images, Th/U ratios and REE patterns, we suggest that the peak metamorphic age for the HP granulite is at ~24 Ma and subsequent moderate- and low-pressure retrograde metamorphism occurred at 19-17 Ma, indicating reasonably rapid exhumation for the HP granulite. The ages of detrital zircons from a metasedimentary rock, another host rock of the mafic granulite, range from ~0.6 to ~2.0 Ga with peak at 0.8-1.2 Ga. The protolith depositional ages for the metasedimentary rock are constrained to be between 490 and ~600 Ma. Our data suggest that the granulite terrane in the eastern Himalayan syntaxis has an affinity with the Greater Himalayan Series. The HP granulite-facies metamorphic events in the eastern Himalayan syntaxis are distinct from ultra-high pressure (UHP) metamorphic events in the western Himalayan syntaxis in both age and depth of burial. However, the metamorphic history of the eastern and western Himalayan syntaxises becomes similar after ~24 Ma. The Namche Barwa granulites appear to result from the underthrusting of the Indian plate lithologies beneath the Lhasa block during progressive collisional processes, followed by extrusion and/or exhumation that result from a slab breakoff of the Indian plate during the Miocene.
Keywords: U-Pb zircon dating, trace element, high-pressure granulite, Namche Barwa group, eastern Himalayan syntaxis

1. Introduction

The 2500 km long, east-west-trending Himalaya is the most promising orogen on the Earth to study continent-continent collision processes (e.g., Argand 1924; Gansser, 1964; Hodges, 2000; Yin, 2006). Exposures of high-pressure (HP) metamorphic rocks within the Himalayan orogen provide particular insights about the collisional and exhumation process (Tonarini et al., 1993; Guillot et al., 1997; Ding et al., 2001). In the western Himalayan syntaxis, the coesite-bearing ultrahigh-pressure (UHP) eclogites, occurring in the Tso Morari and Kaghan areas, have demonstrated that the continental crust of the entire northwestern part of the Indian plate was subducted beneath the Kohistan-Ladakh arc to a minimum depth of 90 km (O’Brien et al., 2001; Mukherjee and Sachan, 2003). Chronologic investigations show that the UHP metamorphism occurred in the Early Eocene (de Sigoyer et al., 2000; Kaneko et al., 2003; Leech et al., 2005; Parrish et al., 2006). In the eastern Himalayan syntaxis, the eastern termination of the Himalayan orogen, HP granulites are present but no eclogite has yet been recorded (Zhong and Ding 1996; Liu and Zhong, 1997). Chronological study of the granulite-facies metamorphism, however, has yielded contentious results (Ding and Zhong, 1999; Ding et al., 2001; Liu et al., 2007). Early zircon U-Pb and clinopyroxene Ar-Ar dating suggested granulite-facies peak metamorphism occurred between 69 Ma and 45 Ma, and retrograde metamorphism between 23 Ma and 18 Ma (Ding and Zhong, 1999). Recently, using the U-Pb zircon dating method, Ding et al. (2001) obtained two groups of metamorphic ages for mafic granulite samples: ~40 Ma and 11-25 Ma. They interpreted the ca.40 and ca.11 Ma ages to represent the timing of HP and moderate-pressure (MP) metamorphism, respectively. The ages between 11 and 25 Ma were interpreted as mixing with an older component though the
lack of analyses of crystal zoning renders this interpretation speculative. Liu et al. (2007) carried out U-Pb zircon dating of a garnet-sillimanite gneiss, the host rock of the mafic granulite. They obtained ages of ca.500 Ma for zircon cores while zircon rims yielded two groups of ages: 30-33 Ma and ~23 Ma. The first group was interpreted as HP peak metamorphic age and the second group was interpreted as HP retrograde metamorphic age. Together these data remain contradictory and with a lack of stronger supporting data, the age of both HP and retrogressive metamorphism remains unclear.

U-Pb zircon dating, combined with zircon trace element analyses can provide powerful constraints on zircon growth and zircon age interpretation (e.g., Hermann et al., 2001; Rubatto, 2002; Whitehouse and Platt, 2003; Bingen et al., 2004; Tomkins et al., 2005). In this paper, we present LA-ICP-MS microprobe U-Pb zircon data, coupled with zircon trace element analyses, from two mafic granulites, a host orthogneiss and a high-grade metasedimentary rock in the eastern Himalayan syntaxis. We use these data to discuss the timing of the peak and retrograde metamorphism for the granulites, the tectonic position of the HP granulite terrane and tectonic evolution in the eastern Himalayan syntaxis in an attempt to resolve this controversy.

2. Geologic setting

2.1 Regional geology

The eastern Himalayan syntaxis (EHS) (Fig.1) is the eastern termination of the Himalaya collisional orogen. The main structural features of the Himalaya and the primary geological unit subdivisions bend strongly around an uplifted area at Namche Barwa and coincide with the ‘U-turn’ of the Yalu-Tsangpo River (Burg et al., 1998; Zeitler et al., 2001). The EHS comprises three major tectono-stratigraphic units (Geng et al., 2006): (1) the Namche Barwa group of high grade metamorphic rocks; (2) the Indus-Yarlung suture (IYS);
96(3) the Gangdese magmatic belt. The northwestern and southeastern contacts between the
97Namche Barwa group and the Gangdese magmatic belt are the sinistral Dongjiu-Miling fault
98and dextral Aniqiao fault, respectively. The syntaxis is cut at its northeastern tip by the active

100 The Namche Barwa Group, the core of the EHS, is dominantly layered quartz-feldspar-
101biotite gneiss with a migmatitic character (Burg et al., 1998). According to recent geological
102mapping (Geng et al., 2006), it can be subdivided into three mappable lithological subunits:
103Zhibai formation, Duoxiongla migmatite and Paixiang formation (Fig.1). The Zhibai
104formation is the most highly metamorphosed and has undergone high-temperature ductile
105deformation. It comprises garnet-bearing gneiss with sporadic boudins of mafic granulite
106(garnet clinopyroxenite), kyanite granulite and garnet amphibolite (Fig.2; Liu and Zhong,
1071997; Geng et al., 2006). The Duoxiongla migmatite is composed of migmatitic gneiss and
108orthogneiss with protolith ages ranging from 1.6 Ga to 1.8 Ga by U-Pb zircon dating (Guo et
109al., 2008). The Paixiang formation is dominantly felsic gneiss with subordinate diopside and
110forsterite-bearing marble, clinopyroxenite and scapolite diopsidite (Geng et al., 2006). The
111Namche Barwa Group is intruded by young granitoids with ages of 3-13 Ma (Burg et al.,
1121998; Ding et al., 2001; Booth et al., 2004).

113 The IYS unit is the middle tectonic unit separating the Namche Barwa group in the
114Indian plate from the Gangdese magmatic belt in the Asian plate (Fig.1). It is a 2-10 km wide
115continuous zone, consisting of highly deformed metasedimentary and ultramafic-mafic rocks,
116the latter representing slices of the Neo-Tethyan oceanic slab (Geng et al., 2006). The
117geochemical data on the IYS dismembered mafic volcanic rocks show a back-arc basin
118affinity, which is comparable to those of the IYS suture zone at Xigatze and Zedang (Geng et
119al., 2006). Clinopyroxene $^{40}\text{Ar}/^{39}\text{Ar}$ dating study suggested the crystallization age at 200±4 Ma
120for the IYS ophiolite (Geng et al., 2004).
The Gangdese magmatic belt lies to the west, north and east of IYS (Fig. 1). It is mainly composed of the Nyingchi group and intrusive granites. The Nyingchi group has been divided into lower, middle, and upper parts (YIGS, 2005). The lower Nyingchi group comprises amphibolitic gneiss and leptynite intercalated with mafic granulite; the middle Nyingchi group consists of biotite paragneiss and granitic gneiss intercalated with kyanite-sillimanite biotite schist and marble; the upper Nyingchi group consists of kyanite-sillimanite-garnet two-mica schist and biotite schist intercalated with biotite gneiss, marble, and leptynite. Detrital zircon age data suggest that the maximum depositional age of the middle-upper Nyingchi group is less than 60 Ma, and the maximum depositional age of the lower Nyingchi group is no older than 490 Ma (Zhang et al., 2008). The Gangdese granites in the eastern Himalayan syntaxis were mostly emplaced during two episodes of ~133-110 Ma and ~66-57 Ma (Booth et al., 2004, 2009; Chiu et al., 2009). The Early Cretaceous granites were probably generated in a post-collisional regime in response to the Late Jurassic-Early Cretaceous collision between the Qiangtang and Lhasa terranes (Chiu et al., 2009). The Late Cretaceous-Paleocene granites resulted from northward Neotethyan subduction during late Mesozoic time (Chiu et al., 2009). They are intruded by the later muscovite granite, two-mica granite and garnet granite, ranging from 26 Ma to 21 Ma in age (Ding et al., 2001; Chung et al., 2003; Booth et al., 2004; Zhang et al., 2008). They could be related to the Gangdese thrust event (Booth et al., 2004) or the removal of the tectonically thickened lithospheric mantle in the late Oligocene time (Chung et al., 2003).

P-T conditions for the Zhibai formation

For the granulite-bearing complex (Zhibai formation), early work has shown that two metamorphically distinct mineral assemblages occur in the pelitic gneiss (Liu and Zhong, 1997). The peak metamorphic assemblage is garnet+kyanite+rutile+felspar+quartz. They...
were formed at $P\approx14-18$ kbar and $T\approx850$ °C (Liu and Zhong, 1997; Ding et al., 1999), estimated by a Grt-Ky-Qz-An (GASP) barometer (Newton and Haselton, 1981) and coupled with a two-feldspar thermometer (Kroll et al., 1993) as well as a Grt-Bi (GARB) thermometer (Berman, 1990). The P-T estimates are supported by Booth et al. (2009), using THERMOCALC. Exhumation of the gneisses produced low-pressure assemblages marked by cordierite+spinel at $P\approx5$ kbar and $T\approx850$ °C (Liu and Zhong., 1997; Ding et al., 1999), estimated by a Grt-Bi thermobarometer (New and Haselton, 1981; Hodges and Spear, 1982) and a Crd+Sil+Grt+Qz (CAGS) thermobarometer (Wells, 1979). Boudins of mafic granulite are common in these gneisses. These rocks are composed of nearly equal garnet and pyroxene. In field exposures, the retrograded garnet-amphibolite and amphibolite usually occur on the outer margins of the mafic granulite (Zhong and Ding, 1996; Zhang et al., 2007).

On the basis of microstructural observations and mineral relationships, three metamorphic stages and related mineral assemblages have been recognized by Zhong and Ding (1996): (1) M1-HP granulite-facies assemblages, consisting of garnet, clinopyroxene and minor quartz; (2) M2-MP granulite-facies assemblages, characterized by the symplectite of plagioclase+orthopyroxene+clinopyroxene after garnet; (3) M3, amphibolite-facies assemblages, including hornblende+plagioclase+biotite. According to thermometer by Ellis and Green (1979), the peak temperature is ~$800$ °C (Zhong and Ding, 1996). Referring to reaction Opx+An=Grt+Qz described by Zhai et al. (1992), Zhong and Ding (1996) argued that the peak pressure is 14-15 kbar corresponding to $800$ °C. This is consistent with the above pelitic gneisses (Liu and Zhong, 1997; Ding et al., 1999). The MP metamorphic conditions for the M2 assemblages were defined by Zhong and Ding (1996) at $P=8\sim10$ kbar and $T=800\sim900$ °C (Opx-Cpx thermobarometer, Wood and Banno, 1973; Harley, 1984). According to the Am-Pl thermobarometer by Perchuk (1966) and Plyusnina (1982), the amphibolite-facies assemblages (M3) formed at $P=4.5\sim6$ kbar and $T=650\sim700$ °C (Zhong and
Ding 1996), which is also consistent with that of the above pelitic gneisses. Together, the thermobarometric studies on both the pelitic gneisses and mafic granulites from Namche Barwa yield similar steep clockwise P-T paths (Fig.3).

2.3 Sample description

Four samples were selected for geochronological analysis (Fig. 1). These samples were collected from the granulites-bearing complex in the Zhibai formation (GPS: N 29°38′18.7″; E 94°56′57.9″). Two mafic granulite samples (T605 and T604) were collected in a boudin of mafic lithologies. While the sample T604 from the margin of the boudin, the sample T605 collected from the core of the boudin. Sample T605 is a weakly retrograded mafic granulite, consisting mainly of amphibole (~50%), clinopyroxene (17%), plagioclase (~18%), garnet (~10%), quartz (~3%), ilmenite (~1%) and titanite (~1%) (Fig.4a). Thin-section observation shows garnet breakdown to amphibole-plagioclase, locally to clinopyroxene-plagioclase symplectite. These retrograded minerals are preserved in the narrow coronas rimming garnet with grain size of 30-100 μm and vermiform and embayed outline (Fig.4a). The retrogression of sample T604 is much stronger than for the sample T605. It is a completely amphibolitized granulite containing the assemblage amphibole (~67%), plagioclase (~30%) and biotite (~3%) (Fig.4b). Besides, two gneiss samples (T602 and T609) were collected from the host rocks of the mafic granulites. Sample T609 is a garnet-bearing granitic gneiss. It consists of quartz (~25%), K-feldspar (~35%), plagioclase (~25%), biotite (~10%) and garnet (~5%) (Fig.4c). Sample T602 is a pelitic gneiss. It consists of quartz (~30%), plagioclase (~30%), K-feldspar (~10%), biotite (~20%) and garnet (~10%) (Fig.4d).

3. Analytical methods

Zircons were separated from rock samples using conventional techniques. The zircon...
crystals were mounted in an epoxy disc and then were polished to expose internal sections. Cathodoluminescence (CL) imaging for the zircons was carried out at the State Key Laboratory of Continental Dynamics, Northwest University, Xi’an, China. Using CL images to differentiate growth zoning and core-rim positions, the zircons were analyzed for U-Th-Pb isotopic compositions and U, Th, Pb and REE concentrations using LA-ICP-MS methods at the State Key Laboratory of Geological Process and Mineral Resources, China University of Geosciences, Wuhan, China. The laser spot was 32 μm in diameter with He as transport gas. Measurements were corrected using calibration to reference zircon standard 91500 and NIST SRM 610 glass. The detailed analytical procedures are similar to those reported in Yuan et al. (2004). The common Pb correction use the EXCEL program of ComPbCorr#3-151 (Andersen, 2002), assuming that the observed $^{206}\text{Pb}/^{238}\text{U}$, $^{207}\text{Pb}/^{235}\text{U}$ and $^{208}\text{Pb}/^{232}\text{Th}$ ratios for a discordant zircon can be accounted for by a combination of lead loss at a defined time. Data processing is carried out using Isoplot (Ludwig, 2003).

4. Results

4.1 Sample T605

Zircons in T605 are colourless and anhedral. They are oval to round crystals, and have grain sizes of 50-150 μm in length, with ratios of length to width ranging from 1:1 to 2:1. CL images reveal that most grains comprise a core, surrounded by a weakly luminescent rim (Fig.5a). The core and rim exhibit weak planar zoning or no zoning. The boundary between the core and rim is rounded, straight or embayed, suggesting possible resorption and recrystallization. In addition, the sample contains rounded grains up to 150 μm in diameter, which are similar to the weak luminescent rims in CL images, suggesting that nucleation of new zircon is coeval with the CL-dark zircon rims. These grains make up around 10% of the total zircon population. They will be discussed together with the zircon rims. Both the zircon...
Morphology and internal structure indicate that they are metamorphic in origin (Vavra et al., 1996, 1999; Corfu et al., 2003).

Twenty-three core analyses (Table 1) show \(^{206}\text{Pb}/^{238}\text{U}\) ages that cluster about a weighted mean \(^{206}\text{Pb}/^{238}\text{U}\) age of 24.0±0.3 Ma (2σ; MSWD=0.69), with two additional cores slightly older at ca.30 Ma (Fig.6a). Eight rim analyses define a cluster of \(^{206}\text{Pb}/^{238}\text{U}\) ages with a weighted mean \(^{206}\text{Pb}/^{238}\text{U}\) age of 18.8±0.3 Ma (2σ; MSWD=0.55; Fig.6a). The cores have U of 99~490 ppm, Th of 2.6~37.5 ppm and Th/U ratios of 0.02~0.08. The rims display higher U (1202~2112 ppm) and Th (42~98 ppm) than the cores, but their Th/U ratios (0.03-0.05) are not distinct from the cores (Fig.7). The low Th/U ratios for the cores and rims are consistent with a metamorphic origin (Rubatto, 2002), which is also consistent with the CL images. The total REE contents of the cores and rims (Table 2) range from 12.2 to 114.3 ppm and from 3242.5 to 88.2 ppm, respectively. The cores have slightly steep chondrite-normalized MREE-HREE patterns ((Yb/Gd)\(_N\)=3.4~15.4) with pronounced positive Ce anomalies (Ce/Ce*=9~67) and weakly negative or positive Eu anomalies (Eu/Eu*=0.56~1.16, cluster around 0.92) (Fig.8a). There is, however, a marked difference in REE composition between the rims and cores. The rims have apparent negative Eu anomalies (Eu/Eu*=0.39-0.54) and higher MREE contents, resulting in more flat chondrite-normalised MREE-HREE patterns ((Yb/Gd)\(_N\)=1.2-2385.3)) (Fig.8b).

**4.2 Sample T604**

Most zircons from T604 are short to long prismatic crystals, but generally have rounded terminations. They have grain sizes of 100~400 μm in length, with ratios of length to width ranging from 1:1 to 3:1. In CL images (Fig.5b), most zircons show weakly planar or sector zones, which are typically metamorphic (Vavra et al., 1996, 1999; Corfu et al., 2003). All twenty-two analyses on fifteen zircon grains yield \(^{206}\text{Pb}/^{238}\text{U}\) ages between 15.7±0.8
and 18.0±1.0 Ma (Table 1), with a weighted mean of 17.0±0.4 Ma (2σ; MSWD=0.96) 247(Fig.6b). The zircons have U of 67.4~ 448.4 ppm, Th of 4.7~29.6 ppm and Th/U ratios of 2480.03~0.10 (Fig.7). The total REE contents of these zircons range from 88.7 to 317.3 ppm. 249They have steep chondrite-normalized MREE-HREE patterns (Yb/Gd)N=47-77) with both 250pronounced positive Ce anomalies (Ce/Ce*=19-72) and negative Eu anomalies 251(Eu/Eu*=0.32-0.89; Fig.8c). The zircons from T604 show strikingly elevated HREE contents 252and much steeper REE patterns than the zircon cores and rims from T605 (Fig.8). 253

254.3 Sample T609

Zircons from T609 are long prismatic with an aspect ratio of ca. 4:1. Their CL images 256(Fig.5c) exhibit complicated core and rim structures. Rounded cores are rarely present. More 257common are angular cores with oscillatory zoning and forms of resorption, interpreted as 258inherited magmatic zircons (Corfu et al., 2003). The non-luminescent rims are weakly zoned 259or not zoned, implying that they are metamorphic (Vavra et al., 1996, 1999; Corfu et al., 2602003). The contacts between the luminescent cores and the non-luminescent rims are angular, 261sharp, and cut across the zonation patterns in the cores (Fig.5c).

Twelve zircon rims were dated (Table 1). Among them, one analysis (Th/U=0.05) has a 263206Pb/238U age of 17±0.5 Ma, and the remaining eleven analyses (Th/U=0.01 to 0.05) yield a 264cluster of 206Pb/238U ages with a weighted mean 206Pb/238U age of 24.2±0.4 Ma (2σ; 265MSWD=0.74; Fig.6d). Twenty-two analyses on oscillatory zoning cores (Th/U=0.22-0.60) 266form a coherent group with a weighted mean 206Pb/238U age of 490±3 Ma (MSWD=0.17) 267(Fig.6c). Two analyses on round cores (Th/U=0.34~0.56) have 207Pb/206Pb ages of 821±20 and 2681225±66 Ma (Table 1). It would appear that the protolith of this granitic gneiss was 490 Ma 269old with a small amount of older inheritance, and that it was metamorphosed to create rims 270during events mainly at 24 Ma but extending to as young as 17 Ma.
4.4 Sample T602
Zircons from T602 are characterized by round, sub-round and irregular crystals, indicating that they are detrital (Davis 2002). CL images reveal that most grains comprise a core, surrounded by a weak luminescent rim (Fig.5d). Most zircon cores exhibit clear resorption structures. The contacts between the cores and rims are angular or embayed, indicating the zircon rims have been produced by recrystallization.

Twenty-five zircon cores were dated (Table 1). They are concordant and near-concordant, and yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages of ~600 to ~2000 Ma with peak at 800-1200 Ma (Fig.6e and f). The cores have U of 111~2329 ppm, Th of 49.3~550.2 ppm and Th/U ratios of 2810.08~1.11. Twelve zircon rims were dated. Among them, one analysis has a $^{206}\text{Pb}/^{238}\text{U}$ age of 28224±0.7 Ma, and the remaining eleven analyses define a discordia chord with intercept ages of 283480±34 and 1459±91 Ma (MSWD=5.8) respectively (Fig.6e). Except that two analyses have high Th (1666 and 1704 ppm) and Th/U (1.08 and 1.22), the rims have U of 256~3138 ppm, Th of 3.2~193 ppm and Th/U ratios of 0.01~0.22. It is possible that during early Paleozoic time, the Proterozoic sedimentary rocks underwent high-grade metamorphism which results in the partial loss of radiogenic Pb of inherited zircon by recrystallization. Note that the two ~490 Ma zircon rims have high Th (1666.2 and 1703.8 ppm) and Th/U (1.08 and 1.22), possibly indicating a new zircon growth. Moreover, the Cenozoic age of metamorphism is also confirmed by a ~24 Ma U-Pb zircon age.

5. Discussion
5.1 Peak-retrograde metamorphic timing
The morphology (rounded and ovoid), CL images (sector, planar or homogeneous), and low Th/U ratios (0.01-0.1) of zircons grains or zircon domains in samples T604, T605 and
296T609 (other than the magmatic cores from T609) indicate that they are metamorphic in origin.

The consistent ages between the zircon cores from the mafic granulite T605 and the zircon rims from the orthogneiss T609 lead us to assign a metamorphic event at 300 Ma. The event has also been reported by other authors (Ding and Zhong, 1999; Liu et al., 2007) and is common elsewhere within the Greater Himalayan Sequence of the Himalaya.

Zircon rims from T605 and zircon grains from T604 yield two groups of younger ages of 303 Ma and ca. 17 Ma, implying an upper amphibolite/lower granulite retrogression occurred at 19-17 Ma.

The ca. 24 Ma zircon cores from T605 are MREE-HREE depleted, similar to values expected for HP metamorphic zircons that grew in competition with garnet (Fig. 8a) (Rubatto, 2002; Whitehouse and Platt, 2003; Tomkins et al., 2005; Rubatto and Hermann, 2007). The slightly negative or positive Eu anomalies (Eu/Eu*=0.65~1.16, cluster around 0.92) indicate growth in the absence of plagioclase (Rubatto, 2002). The presence of growing garnet and the absence of plagioclase are consistent with the HP granulite-facies assemblages (M1: garnet+clinopyroxene+minor quartz) in mafic granulites identified by Zhong and Ding (1996). Therefore, we suggest that the zircon core age of 24.0±0.3 Ma from T605 dates the HP granulite-facies peak metamorphism in the eastern Himalayan syntaxis. This is reinforced by the zircon metamorphic rim age of 24.2±0.4 Ma from the host orthogneiss (T609). A few cores in T605 display metamorphic ages of ca. 30 Ma, which are close to zircon metamorphic ages of 30–33 Ma obtained from a garnet-sillimanite gneiss in the Zhibai formation (Liu et al., 2007). Ding et al. (2001) proposed a HP event at ~40 Ma, which is not observed in this study. If ca. 24 Ma peak metamorphic age for the HP granulite-facies is correct, >30 Ma ages could record prograde metamorphic events. For sample T605, the ca. 19 Ma zircon rims are chemically distinct from the cores. The rims are enriched in U (1829~2112 ppm) and Th.
(41~98 ppm) relative to the cores (U: 144~499 ppm and Th: 4~37 ppm) (Fig.7). Moreover, these rims have flatter MREE-HREE patterns than the cores (Fig.8) and show moderately negative Eu anomalies (Eu/Eu*=0.39~0.54). Accordingly, we suggest that zircon rim growth occurred in the presence of garnet and plagioclase (Rubatto, 2002; Whitehouse and Platt, 2003; Tomkins et al., 2005; Rubatto and Hermann 2007), during the initial stage of garnet breakdown to clinopyroxene+plagioclase/amphibole+plagioclase as symplectite during the retrograde metamorphism of the mafic granulite (Fig.4a). Thus, 18.8±0.3 Ma could record the timing of the MP granulite-facies metamorphism, resulting from exhumation of the HP granulitic rocks.

The zircons from T604, an amphibolitized granulite, have high HREE concentrations and display steep MREE-HREE patterns, with negative Eu anomalies (Eu/Eu*=0.32-0.89). Their REE patterns (Fig. 8c) indicate that they formed without coexisting garnet under low-pressure conditions (Rubatto, 2002; Whitehouse and Platt, 2003; Tomkins et al., 2005; Rubatto and Hermann 2007). Accordingly, we interpret the age of 17.0±0.4 Ma to represent the timing of amphibolite-facies metamorphism during the exhumation of the HP mafic granulite. This age can be comparable with the Sm-Nd isochronal results (16.0±2.5 Ma) obtained on whole-rock and four garnet fractions from a metapelite (Burg et al., 1998), though it is difficult to directly compare these two dates as they are from different areas and dating approaches.

Recently, Booth et al. (2009) published U-Th-Pb monazite and titanite ages of 3-10 Ma, and interpret these ages to represent timing of prograde metamorphism within the Nameche Barwa. However, these HP rocks contain complex fluid inclusion, which were trapped during granulite-facies metamorphism and amphibolite-facies retrogression or even later (Shen et al., 2008). Infiltration of fluids during retrograde metamorphism is likely to cause monazite and titanite recrystallization (e.g., Villa, 1997; Crowley and Ghent, 1999; Townsend et al., 2000; Romer and Rötzler, 2003), and thus these ages probably indicate the time of retrograde fluid
infiltration (e.g., Ayers et al., 2002). Miocene and younger (13-3 Ma) anatexis occurred within the Namche Barwa syntaxis (Burg et al., 1998; Ding et al., 2001; Booth et al., 2004), which in turn may be related to decompression melting during rapid exhumation. Besides, fission-track ages of ~2.5 Ma for zircon and ~1.1 Ma for apatite recorded the following low-temperature events during exhumation within the Namche Barwa (Burg et al., 1998).

5.2 Two tectonic provinces in the eastern Himalayan syntaxis

U-Pb zircon ages and whole-rock Sm-Nd isotopic model ages ($T_{DM}$) of the metasedimentary rocks from the Greater Himalaya and the Lesser Himalaya reveal an important distinction between the two tectonic units (Parrish and Hodges, 1996; Whittington et al., 1999; Ahmad et al., 2000; DeCelles et al., 2000, 2004; Martin et al., 2005; Richards et al., 2005, 2006). For the Greater Himalayan Series (GHS), detrital zircon ages range from 0.8 to 2.7 Ga, with prominent peaks at 0.8-1.1, 1.5-1.7 and 2.5 Ga. By comparison, the Lesser Himalayan Series (LHS) contains detrital zircon ages ranging from ~1.6 to ~2.6 Ga with peaks at 1.8 Ga and 1.9 Ga (Parrish and Hodges, 1996; DeCelles et al., 2000, 2004; Matin et al., 2005; Richards et al., 2005, 2006). The deposition ages of the LHS and GHS could be constrained by the youngest date of detrital zircons and by the intrusion age of granite. Accordingly, the metasedimentary rocks of the LHS are most likely Early Proterozoic (~1900-3641600 Ma), and the Greater Himalayan sedimentary protoliths are bracketed between Late Proterozoic and Early Ordovician (~800-480 Ma) (Parrish and Hodges, 1996; Ahmad et al., 2000; DeCelles et al., 2000, 2004; Richards et al., 2006).

As stated above, the Namche Barwa Group in the Indian plate can be subdivided into three mappable lithological subunits: Zhibai formation, Duoxiongla migmatite and Paixiang formation (Fig.1). Our previous U-Pb zircon dating work on the migmatite of the Duoxiongla unit, the core of the Namche Barwa group, shows that the melanosome has a protolith age of
371±10 Ma and the leucosome formed in 1594±13 Ma (Guo et al., 2008). In addition, a
372granitic gneiss from the Duoxiongla unit gave a U-Pb zircon age of 1583±6 Ma representing
373its protolith age, which is identical with the leucosome of the migmatite in age. The 1.6-1.8
374Ga tectono-magmatic events are unique in the LHS, implying that the Duoxiongla unit has an
375affinity with the LHS (Guo et al., 2008). In contrast, detrital zircons of a metasedimentary
376rock (T602) from the Zhibai formation range from ~600 to ~2000 Ma with peak at 800-1200
377Ma. The sedimentary rock could have experienced metamorphism at ~480 Ma, which is close
378to the protolith age (~490 Ma) of the orthogneiss T609. The metamorphism and partial
379melting during Paleozoic time (~490 Ma) are also identified from a garnet-kyanite gneiss by
380Liu et al. (2007). The youngest detrital zircon age from the metasedimentary rock, together
381with the orthogneiss intruded at 490 Ma, suggest that the depositional ages for the Zhibai
382formation range between 490 and ~600 Ma. According to the age distribution of the detrital
383zircons and the depositional ages, we consider that the Zhibai formation has an affinity with
384the GHS. That is to say, the HP granulite terrane should belong to the GHS. Our study shows
385that the two main tectonic provinces (the LHS and GHS) also occur in the eastern Himalayan
386syntaxis, resembling those of the western Himalayan syntaxis in Pakistan (Argles et al.,
3872003).

388

3895.3 Tectonic implication

390Our zircon U-Pb dating and trace element compositions from the mafic granulites and
391the host orthogneiss in the eastern Himalayan syntaxis, define the timing of HP granulite-
392facies and an upper amphibolite/lower granulite-facies metamorphism at ca.24 Ma and 19-17
393Ma, respectively. In the context of the thermobarometric framework by Zhong and Ding
394(1996), the vertical exhumation rate of the Zhibai unit is between 2.5 and 10 mm/yr during the
395Early Miocene. It appears to be slower than the exhumation rate (~40 mm/yr) of the UHP
metamorphic terrane in the western Himalayan syntaxis during the Early Eocene (Yin, 2006).

In the western Himalaya, coesite-bearing eclogites have been discovered in the Tso Morari area of NW India and upper Kaghan valley of northern Pakistan (O’Brien et al., 2001; Mukherjee and Sachan, 2003). Petrological and thermobarometrical evidence indicates that they record an ultrahigh-pressure stage at \( P \geq 27 \text{ kbar} \) and \( T > 690 \degree \text{C} \) (O’Brien et al., 2001; Mukherjee and Sachan, 2003). Geochronological study shows that their peak-pressure metamorphism occurred in the Early Eocene (<55 Ma to ~46 Ma), and they exhumed rapidly to upper crust depth before ~40 Ma (de Sigoyer et al., 2000; O’Brien et al., 2001; Kaneko et al., 2003; Leech et al., 2005; Parrish et al., 2006; Yin, 2006). These events can be distinguished from underthrusting and subsequent exhumation processes of HP rocks in the eastern Himalaya that experienced granulite-facies metamorphism and Miocene exhumation (this study; Lombardo and Rolfo, 2000; Li et al., 2003; Ji et al., 2004; Groppo et al., 2007).

These differences are probably due to different processes and the location of the UHP-HP rocks. The western Himalayan UHP eclogites formed in low-temperature metamorphism, consistent with burial along a cold geothermal gradient (de Sigoyer et al., 2000). This can be ascribed to the early subduction of the distal part of the Indian margin with a very rapid burial/exhumation cycle (de Sigoyer et al., 2000; Parrish et al., 2006). Their exhumation occurred along the Main Mantle Thrust (MMT)/ITSZ. However, the HP rocks in the eastern Himalaya are exhumated within the MCT zone or the GHS unit, farther south of the ITSZ (this study; Guillot et al., 2008). The ~24 Ma peak time of the HP granulites in the eastern Himalayan syntaxis, coupled with the prograde metamorphism at ~30 Ma or even at ~45 Ma (Catlos et al., 2002) implies slower burial than for the UHP metamorphic rocks of the NW Himalaya (Kaneko et al., 2003; Leech et al., 2005). They are likely related to a second phase of crustal thickening coherent with the India-Asian continental collision. As this HP metamorphism is different from the previous UHP metamorphism, it is thus reasonable that its
peak-retrograde ages are younger. We cannot rule out the possibility that an early UHP metamorphic episode occurred along the ITSZ, north of the HP rocks in the eastern Himalaya. The record may be erased by the later thermal events related to MCT (Lombardo and Rolfo, 2000; Groppo et al., 2007).

By ~24 Ma, doming occurs in the western Himalayan syntaxis and its adjacent area, involving the Indian crust and the Karakorum (Asian) margin (Rolland et al., 2001, 2006a, 2006b). In the core of domes, some granulites are found which have ages in the range of ~20-25 Ma from 40Ar/39Ar amphibole dating by Rolland et al. (2006b). The phase of metamorphism may have initiated as early as 25 Ma in the Baltoro area (Rolland et al., 2001).

Thus, the peak-retrograde metamorphism of 24-17 Ma in the eastern Himalayan syntaxis is coherent with evolution of the western Himalayan syntaxis. Note that the age of ~24 Ma is also the timing of the initiation of exhumation of the GHS (e.g., Hodges, 2000; Yin, 2006), in agreement with initiation of the MCT (e.g., Daniel et al., 2003; Harris et al., 2004). Then the whole metamorphic history of the Himalayan belt becomes similar at ~24 Ma. The phase of metamorphism is spatially and temporarily associated with magmatism involving some asthenospheric component in the western Himalayan syntaxis (Rolland et al., 2001). This is in good agreement with ~24 Ma granites emplacement after a magmatic quiescent period of ~15 Ma along the suture zone west and north of Namche Barwa (Fig.1) (Booth et al., 2004).

Therefore, a common process can be invoked for the metamorphic and magmatic evolution. The most likely cause is a slab breakoff occurring at ~24 Ma (Rolland et al., 2001; Mahéo et al. 2002) (Fig. 9). The slab breakoff could also explain the onset of exhumation at ~24 Ma, as suggested by Rolland et al. (2001).

Conclusions

A combination of zircon U-Pb ages and trace element, and petrology for the mafic
granulites and their host orthogneiss in the eastern Himalayan syntaxis provide chronological constraints on the HP granulite-facies and upper amphibolite/lower granulite-facies metamorphism. The peak metamorphic age for the HP granulite is at ~24 Ma and subsequent moderate- and low-pressure retrograde metamorphism occurred at 19-17 Ma. The HP metamorphic events are significantly different from the UHP metamorphic events in the western Himalaya, but their metamorphic history becomes relatively similar after ~24 Ma.

The distribution of detrital zircon ages and the depositional age of the Zhibai formation provide a strong evidence that the granulite terrane has affinity with the GHS.

Acknowledgements

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Rolland, Y., Villa, I.M., Guillot, S., Mahéo, G., Pêcher, A., 2006b. Evidence for pre-Cretaceous history and partial Neogene (19-9 Ma) reequilibration in the Karakorum (NW Himalayan Syntaxis) from \(^{40}\)Ar-


Figure Captions

Fig.1 Sketch map of (a) the Himalaya orogen and (b) the eastern Himalayan syntaxis, showing sample location (modified after Burg et al. (1998) and Geng et al. (2006)). Zircon U-Pb ages are from Ding et al. (2001), Chung et al. (2003), Booth et al. (2004), Zhang et al. (2008) and Chiu et al. (2009). JSS=Jinsha suture zone; BNS=Bangong-Nujiang suture zone; IYS=Indus-Yarlung suture zone; STDS=South Tibetan detachment system; MCT=Main Central thrust; KF=Karakorum fault; QT=Qiangtang terrane; LB=Lhasa terrane; TH=Tethyan Himalaya belt; GH=the Greater Himalaya belt; LH=the Lesser Himalaya belt; WHS=the western Himalayan syntaxis; EHS=the eastern Himalayan syntaxis.
Fig. 2 Field view of gneiss containing mafic granulite boudins in the valley of Bulong, ~1 km north of Zhibai.

Fig. 3 P-T-t paths of the HP Namche Barwa complex and UHP Tso Morari and Kaghan units (modified after Guillot et al., 2008). See text for references. Abbreviations: Cpx-clinopyroxene, Opx-orthopyroxene, Grt-garnet, Ky-kyanite, Lws-lawsonite.
Fig. 4 Microstructures of (a) the weakly retrograde granulite T605, the inset show that the large garnet surrounded by a plagioclase-clinopyroxene and plagioclase-amphibole, set in the symplectite of plagioclase+orthopyroxene+clinopyroxene after garnet; (b) the amphibolitised granulite T604; (c) the orthogneiss T609 and (d) the high-grade metasedimentary rock T602. Grt=garnet, Amp=amphibole, Pl=plagioclase, Ilm=ilmenite, Bi=biotite, Qz=quartz, Kfs=K-feldspar.
Fig. 5 Representative cathodoluminescence images of zircons from (a) the weakly retrograde mafic granulite sample T605, (b) the amphibolised granulite sample T604, (c) the orthogneiss sample T609, and (d) the high-grade metasedimentary rock T602. The circles show LA-ICP-MS dating spots and corresponding apparent ages.
Fig. 6 Concordia diagrams of LA-ICP-MS U-Pb dating for zircons from (a) T605, (b) T604, (c, d) T609 and (e) T602. (f) U-Pb age distribution histogram for sample T602, the $^{207}$Pb/$^{206}$Pb ages for those >800 Ma and the $^{206}$Pb/$^{238}$U ages for those <800 Ma.
Fig. 7 Th versus U plot for the two granulites (T604 and T605) in the eastern Himalayan syntaxis.

Fig. 8 Chondrite-normalised REE patterns for zircons from the mafic granulites in the eastern
Himalayan syntaxis. (a) the ~24 Ma zircon cores from sample T605, (b) the ~19 Ma zircon rims from sample T605, (c) the ~17 Ma zircon grains from sample T604. Normalising values are from Sun and McDonoud (1989). The magmatic, LP and HP plots for comparison are from Rubatto and Hermann (2007). LP=low-pressure, HP=high-pressure.

Fig.9 Proposed geodynamic model of the eastern Himalayan syntaxis inferred from the analytical results obtained in this study. The India-Asian continental collision time for maximum burial of the eastern Himalayan syntaxis continental crust is at ~24 Ma, followed...
by extrusion and/or exhumation that result from a slab breakoff of the Indian plate.

MCT=Main Central Thrust.

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Table 1. Zircon U-Pb isotopic data obtained by LA-ICP-MS in the eastern Himalayan syntaxis.

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756
Table 2. Tracer elements data obtained by LA-ICP-MS for the granulites in the Eastern Himalayan system.

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Abbreviations: c. core; r. rim.
| 12c | 7350 | 0.00 | 2.15 | 0.02 | 0.18 | 0.64 | 0.44 | 1.91 | 0.89 | 3.87 | 3.00 | 11.17 | 2.14 | 20.31 | 3.64 | 0.61 | 17.4 | 8.5 |
| 12c | 7345 | 0.01 | 1.51 | 0.01 | 0.16 | 0.25 | 0.20 | 1.01 | 0.60 | 5.95 | 2.13 | 2.75 | 1.74 | 17.51 | 3.11 | 2.58 | 43.6 | 10.3 |
| 12c | 10603 | 0.00 | 2.50 | 0.01 | 0.17 | 1.14 | 0.43 | 6.40 | 1.73 | 13.58 | 3.59 | 12.21 | 2.56 | 17.31 | 3.49 | 1.73 | 49.0 | 3.4 |
| 12c | 782 | 0.01 | 1.92 | 0.02 | 0.32 | 1.03 | 0.66 | 4.15 | 1.27 | 11.95 | 3.36 | 15.69 | 3.27 | 30.32 | 5.68 | 0.84 | 27.8 | 9.1 |
| 12c | 9116 | 0.01 | 1.79 | 0.01 | 0.19 | 0.26 | 0.22 | 1.19 | 0.45 | 4.02 | 1.12 | 2.80 | 0.70 | 6.01 | 1.20 | 1.02 | 23.8 | 6.9 |
| 12c | 12501 | 0.01 | 2.40 | 0.04 | 0.67 | 2.93 | 1.44 | 5.53 | 1.56 | 23.55 | 4.92 | 19.39 | 2.01 | 14.24 | 2.10 | 0.49 | 15.9 | 1.2 |
| 12c | 739 | 0.02 | 2.33 | 0.01 | 0.17 | 0.46 | 0.33 | 1.34 | 0.60 | 3.32 | 2.05 | 7.83 | 1.63 | 14.86 | 2.29 | 0.79 | 42.8 | 7.9 |
| 12c | 8410 | 0.01 | 1.70 | 0.01 | 0.09 | 0.24 | 0.25 | 1.44 | 0.52 | 4.79 | 1.49 | 0.14 | 1.21 | 10.45 | 1.61 | 0.59 | 57.0 | 9.0 |
| 12c | 9590 | 0.01 | 0.34 | 0.01 | 0.10 | 0.29 | 0.28 | 1.47 | 0.53 | 4.08 | 1.23 | 4.23 | 0.31 | 5.91 | 1.31 | 1.08 | 9.0 | 5.5 |
| 12c | 7485 | 0.01 | 2.39 | 0.02 | 0.13 | 0.52 | 0.44 | 2.70 | 0.72 | 8.90 | 2.11 | 7.95 | 1.03 | 14.74 | 2.76 | 0.92 | 63.0 | 6.0 |
| 12c | 12288 | 0.01 | 1.84 | 0.01 | 0.36 | 1.41 | 0.53 | 1.91 | 0.22 | 16.91 | 3.81 | 11.19 | 1.85 | 13.45 | 2.17 | 0.41 | 10.8 | 1.9 |
| 12c | 7739 | 0.01 | 2.29 | 0.02 | 0.30 | 0.69 | 0.77 | 4.43 | 1.22 | 11.69 | 3.38 | 13.06 | 2.73 | 24.93 | 4.81 | 0.24 | 33.7 | 7.0 |
| 12c | 7801 | 0.01 | 1.71 | 0.01 | 0.06 | 0.33 | 0.33 | 1.07 | 0.57 | 4.01 | 2.38 | 10.01 | 2.34 | 20.08 | 4.09 | 1.03 | 50.5 | 15.4 |
| 12c | 10137 | 0.01 | 1.56 | 0.02 | 0.00 | 0.10 | 0.65 | 1.69 | 1.43 | 4.04 | 1.53 | 2.91 | 2.70 | 27.49 | 5.24 | 0.53 | 16.1 | 5.3 |
| 12c | 6791 | 0.01 | 2.00 | 0.01 | 0.33 | 0.94 | 0.67 | 3.50 | 0.97 | 8.69 | 2.97 | 5.74 | 1.04 | 11.18 | 3.25 | 0.64 | 37.7 | 6.0 |
| 12c | 7759 | 0.01 | 1.73 | 0.01 | 0.64 | 0.35 | 0.53 | 1.79 | 0.60 | 9.65 | 3.25 | 14.53 | 2.93 | 28.40 | 6.65 | 1.16 | 41.9 | 12.5 |
| 12c | 7781 | 0.01 | 1.92 | 0.02 | 0.46 | 1.12 | 0.70 | 4.64 | 1.33 | 12.74 | 2.93 | 16.01 | 3.07 | 29.49 | 5.40 | 0.01 | 55.2 | 7.9 |
| 12c | 11997 | 0.01 | 1.00 | 0.01 | 0.30 | 1.44 | 0.52 | 6.90 | 1.79 | 11.10 | 2.49 | 6.70 | 0.07 | 7.06 | 1.03 | 0.41 | 31.2 | 12.1 |
| 12c | 8546 | 0.01 | 1.00 | 0.02 | 0.07 | 0.62 | 0.23 | 0.11 | 0.85 | 0.23 | 2.14 | 0.72 | 2.10 | 0.59 | 5.42 | 1.61 | 0.66 | 37.5 | 7.9 |
| 12c | 10223 | 0.01 | 1.59 | 0.04 | 0.48 | 1.35 | 0.62 | 4.10 | 1.42 | 7.28 | 2.26 | 7.04 | 1.10 | 6.35 | 2.40 | 0.48 | 12.1 | 1.0 |

**Table 1**: Simulated results

**Notes**: All simulations were run for 200,000 iterations and the concentration is normalized to chlorophyll.