Probing the depths of the India-Asia collision: U-Th-Pb monazite chronology of granulites from NW Bhutan

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Abstract

Rocks metamorphosed to high temperatures and/or high pressures are rare across the Himalayan orogen, where peak metamorphic conditions recorded in the exposed metamorphic core, the Greater Himalayan Sequence (GHS), are generally at middle to upper amphibolite-facies. However, mafic garnet-clinopyroxene assemblages exposed at the highest structural levels in Bhutan, eastern Himalaya, preserve patchy textural evidence for early eclogite-facies conditions, overprinted by granulite-facies conditions.
Monazite hosted within the leucosome of neighbouring granulate-facies orthopyroxene-bearing felsic gneiss yields LA-MC-ICP-MS U-Th-Pb ages of 13.9 ± 0.3 Ma. Monazite associated with sillimanite-grade metamorphism in granulate-hosting migmatitic gneisses yields U-Th-Pb rim ages between 15.4 ± 0.8 Ma and 13.5 ± 0.5 Ma. Monazite associated with sillimanite-grade metamorphism in gneiss at structurally lower levels yields U-Pb rim ages of 21-17 Ma. These data are consistent with Miocene exhumation of GHS material from a variety of crustal depths at different times along the Himalayan orogen. We propose that these granulitised eclogites represent lower crustal material exhumed by tectonic forcing over an incoming Indian crustal ramp, and that they formed in a different tectonic regime to the ultra-high pressure eclogites in the western Himalaya. Their formation and exhumation in the Miocene therefore do not require diachronicity in the timing of the initial India-Asia collision.

1. Introduction

The pressure-temperature-time (PTt) evolution of metamorphic rocks provides insight into a range of tectonic processes including crustal recycling, crustal and mantle geochemical evolution, and convergent plate boundary processes. PTt data also provide valuable constraints on the development, testing and refinement of large-scale geodynamic models. In the Himalayan orogen, considered to be the type locality for continental collision, metamorphic rocks recording high pressures (HP, >1.4 GPa) and/or high temperatures (HT, >800°C) are rare, despite the extensively thickened crust (up to 70 km) and long-lasting convergence (since ~50-55 Ma, Rowley et al., 1996, 1998, Zhu et al., 2005). The majority of the rocks that form the exposed high-grade core of the
Himalayas (the Greater Himalayan Sequence or GHS), were metamorphosed at peak temperatures of ca. 650-750°C during the Miocene, and experienced Barrovian-style regional metamorphism during the Eocene-Oligocene [see review in Hodges, 2000].

Contrasting occurrences of HP rocks have been described from the NW and E Himalaya but are yet to be reported from the central part of the orogen [Lombardo and Rolfo, 2000]. In the NW Himalayan regions of Kaghan and Tso Morari (Figure 1a), rocks immediately south of the India-Asia suture preserve evidence for Eocene ultra-high-pressure (UHP) metamorphism to >2.7 GPa [de Sigoyer et al., 2000; Kaneko et al., 2003; Leech et al., 2005; Parrish et al., 2006; Epard and Steck, 2008]. These data suggest that the leading edge of the Indian continental margin was subducted, detached and exhumed to mid-crustal levels within 10 Ma of the India-Asia collision at ca. 55-50 Ma.

In contrast, rare exposures of HP rocks in the E Himalaya are exposed in the metamorphic core of the orogen (hundreds of km south of the India-Asia suture), and yield only cryptic evidence for >1.4 GPa HP metamorphism: the Ama Drime Range (Nepal/Tibet), Arun Valley (Nepal), Sikkim (India) and NW Bhutan (Fig. 1a). In general, these rocks have been pervasively overprinted at post-peak-pressure high-temperature granulite-facies metamorphic conditions [Lombardo et al., 1998; Liu et al., 2005; Chakungal, 2006; Groppo et al., 2007; Liu et al., 2007; Rolfo et al., 2008; Cottle et al., 2009a; Chakungal et al., 2010; Corrie et al., 2010; Kali et al, 2010]. It is as yet unclear whether these rocks formed in a subduction zone and therefore suggest diachronous India-Asia collision [Guillot et al., 1999, 2008], whether they represent a deeper structural level of the GHS not exposed, preserved, or yet recognized elsewhere in the orogen, or whether they record an eastward change in collision or subduction regime.
The thermobarometric conditions and timing of both HP metamorphism and the HT overprint in the E Himalaya remain unclear. Recent Lu-Hf analyses of garnets from putative eclogite-facies mafic rocks from the Arun Valley suggest that garnet grew at 20.7 ± 0.4 Ma [Corrie et al., 2010], which, if representative of garnet growth along the prograde path, indicates that eclogite-facies conditions were reached 20-25 Ma later than in the NW Himalaya. Monazite and xenotime U-Pb ages of granulitised eclogites in the Ama Drime Range (Nepal/Tibet) constrain granulite-facies metamorphism and associated anatexis to <13.2 ± 1.4 Ma [Cottle et al., 2009a]. Monazites in migmatitic para- and ortho-gneisses in the region yield similar ages from 13.4 ± 1.0 to 11.0 ± 3.3 Ma [Liu et al., 2007, Cottle et al., 2009a, Kali et al., 2010]. Following Kelsey et al., [2008], these ages are interpreted to represent monazite growth at the melt solidus during exhumation and cooling following the attainment of granulite facies conditions.

Rocks of similar texture, petrology and mineral chemistry are exposed in NW Bhutan at the highest structural levels of the GHS. Here we present petrographic descriptions and laser ablation - multi-collector - inductively coupled plasma - mass spectrometer (LA-MC-ICP-MS) U-(Th)-Pb monazite data from pelitic garnet-orthopyroxene granulites and their host garnet-biotite-sillimanite migmatitic gneisses. These rocks contain monazite, a potentially sensitive geochronometer that can be linked directly to bulk-rock metamorphic reactions and thus tied to P-T conditions of metamorphic events e.g. [Parrish, 1990; Foster et al., 2002, Kohn and Malloy, 2004]. We use integrated PTt data from these rocks, and further petrographical evidence from associated mafic rocks to elucidate the tectonic setting and the processes by which the granulites formed and were exhumed to their present-day position.
2. Geological Setting

All four main Himalayan lithotectonic packages are exposed in Bhutan, from the structurally lowest and southernmost Siwaliks, through the Lesser Himalayan Sequence (LHS), the Greater Himalayan Sequence (GHS) and up into the structurally highest and northernmost Tethyan Sedimentary Sequence (TSS) [e.g. Gansser, 1983; Bhargava, 1995]. Compared with a typical simplified cross-section through the central Himalayan orogen [Beaumont et al., 2001 and references therein], the Bhutan architecture shows distinct complexities. Firstly, the main structure bounding the top of the GHS, the South Tibetan Detachment (STD), consists of an older outer structure and a younger inner structure [Hollister and Grujic, 2006; Kellett et al., 2009]. The outer STD is preserved at the base of a series of klippen comprising erosional remnants of metasedimentary (Chekha Group) and TSS rocks [Grujic et al., 2002; Kellett et al., 2009]. It is interpreted to have formed during early Miocene top-to-the-north movement along the STD. The more northerly inner STD (Fig. 1b,c) separates the main body of the TSS from the GHS and is interpreted as representing the latest stages of ductile and brittle motion along the STD [Kellett et al., 2009].

Secondly, between the outer and inner STD systems, GHS rocks are deformed by an out-of-sequence, north-dipping, thrust-sense shear zone, the Kahktang Thrust, which doubles the map-view width of the GHS in central and eastern Bhutan. This shear zone locally places sillimanite-grade migmatites over garnet-staurolite schists interpreted as belonging to the Chekha Formation [Gansser, 1983; Bhargava, 1995; Davidson et al., 1997], and may have been involved in interrupting motion along the STD and the separation of the
inner and outer STD strands exposed in Bhutan [Kellett et al., 2009]. The continuation of the Kakhtang Thrust east and west of the type locality in central Bhutan remains uncertain although other out-of-sequence thrusts have been identified at similar structural positions along strike (e.g. the Khumbu Thrust in the Everest region, [Searle, 1999] and the High Himal Thrust in eastern Nepal, [Goscombe et al., 2006]).

Overall, the GHS in Bhutan consists of amphibolite-grade, sillimanite and/or kyanite-bearing para- and orthogneisses [Gansser, 1983; Swapp and Hollister, 1991; Davidson et al., 1997; Daniel et al., 2003] similar to the rock types described from the GHS elsewhere along the Himalayan chain [e.g. review by Hodges, 2000]. Early studies found cordierite-bearing rocks in NW Bhutan, suggesting that higher metamorphic grades had been reached in that region [Swapp and Hollister, 1991]. Mapping in NW Bhutan in the region surrounding the village of Laya [Chakungal, 2006] showed that a package of Sil + Grt + Bt + Pl + Kfs + Qtz ± Crd ± Spl migmatitic gneiss (mineral abbreviations after Whitney and Evans, 2010) is overlain by a package of similar gneiss intercalated with augengneiss, quartzite and cale-silicate with minor mafic and ultramafic lenses exposed in the core of a gentle regional E-W trending antiform (Fig. 1b, c). The nature and precise location of the boundary between these units remains cryptic. To the northeast, a structurally higher package of augengneiss and Miocene leucogranite extends to the base of the inner STD (Fig. 1b,c). Dykes, sills and irregular lenses of variably sheared Miocene-aged Ms + Tur + Crd ± And leucogranite are also locally exposed [Kellett et al., 2009]. These leucogranites preserve a condensed strain gradient within a ca. 1 km thick package from undeformed at the base to S/C mylonite at the top.
3. Sample descriptions

3.1 Mafic granulitised eclogites

Mafic layers and boudins, varying in size from the m- to the km scale are exposed in the core of a gentle antiform in NW Bhutan (Fig. 1b,c). They retain textural evidence for a complex metamorphic evolution [Fig. 2 and Chakungal, 2006]. Rutile inclusions in garnet, chemical evidence from Cpx + Pl symplectites indicating the presence of precursor omphacite and a lack of evidence for coeval matrix plagioclase all suggest eclogite-facies conditions [O'Brien, 1990; Möller, 1998; Zhao et al., 2001]. This textural evidence for HP metamorphism is now almost completely overprinted by granulite-facies assemblages: coronas of Opx around garnet and clinopyroxene, the breakdown of garnet forming wormy symplectites of Opx + Pl and Am + Pl, the breakdown of omphacite to form lacy symplectites of Cpx + Pl, and the replacement of rutile by ilmenite [Fig. 2 and Chakungal, 2006]. These rocks are similar, in texture, mineralogy and composition, to the granulitised eclogites described from Ama Drime in southern Tibet [Lombardo and Rolfo, 2000; Groppo et al., 2007] and nearby Arun Valley in Nepal [Corrie et al., 2010].

The Ama Drime PT path has been suggested to include decompression from HP conditions of >1.5 GPa and >580°C to HT conditions of 0.7-1.0 GPa and ca. 750°C, followed by final decompression to 0.3 GPa at ca. 630°C [Rolfo et al., 1998; Lombardo and Rolfo, 2000; Groppo et al., 2007; Cottle et al., 2009a]. A similar path is inferred for the Bhutan granulitised eclogites (this work and Chakungal 2006)

3.2 Metapelitic Granulites
The mafic rocks are hosted within Opx-bearing paragneiss which preserve evidence for granulite-facies metamorphism overprinted by amphibolite-facies metamorphism. The peak garnet-orthopyroxene assemblage in the paragneiss rules out very high pressures \[O'Brien and Rötzler, 2003\], and no textural or chemical evidence for pre-granulite-facies metamorphism is preserved.

Sample BH243 is compositionally banded on a mm-cm scale and is variably migmatitic (Fig. 3). Melanocratic layers contain Grt + Bt + Opx ± Oam. Leucocratic layers contain Crd + Pl + Qtz ± Kfs ± Spl. Accessory minerals include monazite (included in cordierite-bearing leucosome in BH243, Figure 3), tourmaline, ilmenite, and magnetite. To our knowledge, this is the first documentation of orthopyroxene in the GHS, although the Crd + Pl + Qtz ± Kfs ± Spl assemblage (“sillimanite granulite-facies”) has previously been described from equivalent structural levels in Bhutan \[Gansser, 1983, Swapp and Hollister, 1991; Davidson et al., 1997\] and from parts of Sikkim \[Neogi et al., 1998; Ganguly et al., 2000\]. The attainment of peak metamorphic temperature in the pelitic granulites is represented by the assemblage Grt + Opx + Pl + Rt + Qtz (representative mineral compositions are presented in Table 1). This assemblage suggests conditions of ca. 800°C and >0.8 GPa \[Carrington and Harley, 1995\]. These conditions are similar to the ca. 750°C and 0.7-1.0 GPa conditions reported for the granulite-facies overprint on the mafic eclogites in Ama Drime \[Groppo et al., 2007; Cottle et al., 2009a\].

Evidence for decompression is preserved in the minerals that overprint the granulite-facies assemblage. The migmatitic texture, abundance of K-feldspar and lack of muscovite suggest peak temperatures above the muscovite dehydration melting curve.
[e.g. _Patiño Douce and Harris_, 1998]. Matrix biotite shows embayed edges around cordierite, suggesting incipient melting (Fig. 3a,d). Locally, cordierite contains delicate undeformed symplectic inclusions of Spl \((\text{Fe}/(\text{Fe}+\text{Mg})=0.65) + \text{Sil}\), suggesting that cordierite crystallization at least partially postdated deformation (Fig. 3d). Cordierite and spinel may have been introduced during decompression during breakdown of garnet + sillimanite at ca. 0.3 GPa and >750°C [Spear _et al._, 1999]. Orthopyroxene crystals are locally adorned with orthoamphibole-dominated reaction rims involving sheaves of acicular crystals containing numerous Fe-oxide inclusions (Fig. 3c), suggesting hydration during decompression. Elsewhere in the matrix orthoamphibole forms coarser, equant grains associated with patchy intergrowths of biotite and cordierite.

### 3.3 Granulite-hosting gneiss

The majority of the granulite-bearing terrane consists of banded gneiss, with alternating Bt + Sil + Grt melanosomes and Qtz + Pl + Kfs leucosomes (Fig. 4a, representative analyses in Table 1). In sample BH 213a, the peak metamorphic assemblage contains Grt + Kfs + Pl + Bt + Sil + Qtz, with finer-grained leucosome and coarser-grained melanosome. In contrast to the pelitic granulites, this sample does not contain Opx or Crd, and does not appear to preserve mineralogical evidence for granulite-facies metamorphism. This sample yields conditions of ca. 700°C at 4.5 GPa using the conventional Bt-Grt thermometer and GASP barometer compiled by D.J. Waters (spreadsheet ‘pelite.barometers.xls’ at http://www.earth.ox.ac.uk/~davewa/pt/th_tools.html). These conditions are similar to
those suggested for a biotite-sillimanite-plagioclase-garnet gneiss from the Ama Drime range (sample EV97-60, [Groppo et al., 2007]).

3.4 Laya valley gneiss

South of the granulite-bearing region, the dominant rock type is also banded migmatitic gneiss with alternating Bt + Sil melanocratic and Qtz + Fsp leucocratic layers (Fig. 4b, representative analyses in Table 1). The peak metamorphic assemblage contains Grt + Bt + Kfs + Pl + Sill + Qtz. Cordierite (in sample BH 165) commonly contains inclusions of sillimanite and locally, wormy spinel. Larger equant spinel is also found associated with biotite-sillimanite sheaves and on garnet rims in sample BH 165 (Fig. 4b).

Sample BH 167 yields conditions of 650°C at 0.3 GPa using the conventional Bt-Grt thermometer and GASP barometer as detailed above. These conditions are within uncertainty of those reported for the granulite host gneiss above and the Grt-Sill-Bt gneiss from the Ama Drime range (sample EV97-60, Groppo et al., 2007). The KFMASH petrogenetic grid published by Groppo et al., [2007], suggests that the cordierite and spinel assemblage in sample BH165 represents decompression to <0.3 GPa at elevated (>600°C) temperatures.

3.5 Summary

The mafic and pelitic granulites, host gneiss and Laya Valley gneiss are texturally, mineralogically and compositionally similar to reports of granulitised eclogites and their host rocks in Ama Drime [Rolfo et al., 1998; Lombardo and Rolfo, 2000;
The attainment of plagioclase-absent (eclogite facies) peak pressure conditions is indicated by textures in the mafic eclogites, suggesting conditions >1.4 GPa at ca. 600°C. Decompression and further heating is indicated by the attainment of granulite facies conditions in both the mafic and pelitic rocks (ca. 750-800°C, 0.8-1.0 GPa), followed by decompression and cooling to amphibolite facies conditions of ca. 600-650°C and 0.3 GPa. These latter conditions are the peak conditions retained by the Grt-Bt-Sill gneisses which host the granulitised eclogites and which also crop out along the Laya valley.

4 Monazite Geochronology

4.1 U(-Th)-Pb Methods

Monazite was dated by laser ablation multi-collector inductively-coupled plasma mass spectrometry (LA-MC-ICP-MS) at the NERC Isotope Geosciences Laboratory, UK. Most monazite was dated in situ in polished sections, however monazite separates from four samples (RLB 17,18,19 and BH 243) were analyzed in polished epoxy discs. Monazites in all samples were mapped for U, Y, Th, Ce and Nd at 1 µm resolution (100 ms per pixel) on the Open University Cameca SX100 EMP prior to dating in order to identify elemental zoning, assist laser spot location and facilitate age interpretation.

The laser ablation instrumentation consists of a Nu Plasma MC-ICP-MS (Nu Instruments, Wrexham, UK) and a UP193SS laser ablation system (New Wave Research, UK). Detailed instrumental configuration and measurement procedures follow previous methods [Cottle et al., 2009a, b]. Analyses were achieved using a static ablation spot size of 15 µm and a laser fluence of 2–3 Jcm⁻² (equating to a crater depth of ~12 µm). U-Th-
Pb data were normalized to the 554 Ma “Manangotry monazite” [Paquette et al., 1994] primary reference monazite. An in-house secondary reference monazite (FC-1, 55.6 ± 1.3 Ma, [Horstwood et al., 2003]) was analyzed concurrently to monitor data accuracy. Overall uncertainties achieved on the secondary reference material were 3% (2 SD) for U-Pb and 4% (2 SD) for Th-Pb data. All quoted uncertainties include contributions from the external reproducibility of the standard for $^{206}\text{Pb}/^{238}\text{U}$, and $^{208}\text{Pb}/^{232}\text{Th}$ ratios.

All data (Table 2) were processed using an in-house spreadsheet calculation routine. Data recording $<<0.01$ mV $^{207}\text{Pb}$ were rejected and data points with $>300$ cps $^{204}\text{Pb}$ after correction for the isobaric interference of $^{204}\text{Hg}$ were assessed with respect to the contribution of common Pb. Because of their young age, radiogenic Pb signals are generally low ($^{207}\text{Pb} < 0.1$ mV). This resulted in imprecise $^{207}\text{Pb}/^{235}\text{U}$ ages and difficulty in applying common Pb corrections. The data are therefore plotted on Tera-Wasserburg diagrams uncorrected for common Pb, and with an unconstrained upper intercept calculated using Isoplot [Ludwig, 2001]. All uncertainties are quoted at 2σ confidence in the text and tables.

When monazite crystallizes it has the potential to incorporate excess $^{230}\text{Th}$ due to an initial U-Th disequilibrium. This results in ‘excess’ $^{206}\text{Pb}$ in young monazite [Schärer, 1984]. Several previous geochronological studies of monazite from similar metamorphic rocks in the Himalaya have demonstrated that in many cases, for the same crystals the $^{206}\text{Pb}/^{238}\text{U}$ ages are consistent with $^{208}\text{Pb}/^{232}\text{Th}$ ages; the latter being unaffected by excess $^{206}\text{Pb}$ [Cottle et al., 2009a, 2009c; Kellett et al., 2010]. We therefore suggest that the likely effect of excess $^{206}\text{Pb}$ on these samples is minor. Nevertheless we recognize the possibility that the ages reported may be over-estimated by maximum ca. 0.5 Ma.
4.2 U(-Th)-Pb Results

4.2.1 Granulite-bearing terrane: granulite, granite, and banded gneiss

Monazite in granulite sample BH 243 (Figs. 3a,b, 5a) is exclusively included in cordierite in the leucosome. Twelve data points from four monazite grains yield a weighted average \(^{208}\text{Pb}^{232}\text{Th}\) age of 13.9 ± 0.3 Ma (MSWD=0.5, Fig. 5a, Table 2). Although monazite in this sample is chemically zoned (mainly in Y and Th), there appears to be no consistent relationship between chemical composition and age.

In the granulite-hosting gneiss BH 213a (Figs. 4a, 5b, Table 2), monazite is included in garnet rims or associated with intergrown sillimanite + biotite. Ten analyses (not plotted) form a poorly defined discordia line with an upper intercept of ca. 550 Ma; these are interpreted as mixing ages between older cores and younger metamorphic rims and were thus rejected from the age calculations. These older cores coincide with zones of higher Y concentration (e.g. grain 6, analyses 3 and 4, Fig. 5b), and are within monazite hosted in both garnet rims and the matrix. The majority of the ten Miocene data points from lower-Y rims surrounding the high-Y old cores or in weakly-zoned low-Y monazite yield a weighted average age of 13.5 ± 0.5 Ma (MSWD = 0.1, Fig. 5b). A further five analyses are slightly older, yielding a weighted average \(^{208}\text{Pb}^{232}\text{Th}\) age of 15.4 ± 0.8 Ma (MSWD 0.4, Fig. 5b). It is unclear whether these data record continuous monazite crystallization between these two dates or whether there are two distinct age populations of monazite in this sample; weak chemical zoning in Th and Y does not correlate with age for the Miocene ages (Fig. 5b).
Twenty analyses from four monazite grains in granulite host gneiss RLB 19 yield a $^{207}\text{Pb}/^{206}\text{Pb} / {^{238}\text{U}}/{^{206}\text{Pb}}$ intercept age of 13.4 ± 0.5 Ma (Fig. 5c, Table 2). Strong zoning in Y and Th does not appear to be related to age (Fig. 5c). Since these monazites were analyzed from a mineral separate, their textural context was not preserved. The close field location and similar sample description, however, suggest that the rock is very similar to BH 213a. Therefore, based on their identical ages, we suggest that monazite in RLB 19 grew in the same context as in sample BH 213a.

Eleven analyses from five monazites in nearby granite RLB 18 yield a $^{207}\text{Pb}/^{206}\text{Pb} / {^{238}\text{U}}/{^{206}\text{Pb}}$ lower intercept age of 12.4 ± 0.3 Ma (MSWD = 0.6, Fig. 6, Table 2). Six analyses were rejected from the age calculation, one due to high levels of common-Pb and five due to apparent mixing with an older age domain ($^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 14-16 Ma, see spot locations in Fig. 6, especially grain 4). These older ages may relate to an extended period of monazite crystallization in the granitic melt or may be the result of inheritance.

4.2.2 Laya valley gneiss

Monazite from banded, migmatitic gneiss in the Laya valley is included in garnet rims associated with intergrown sillimanite and biotite, and included in matrix plagioclase. Twelve data points from gneiss CWB 22 yield a $^{207}\text{Pb}/^{206}\text{Pb} / {^{238}\text{U}}/{^{206}\text{Pb}}$ intercept age of 21.0 ± 0.6 Ma (MSWD 1.5, Fig. 7a, Table 2). A further nine points lie on a discordia line yielding an imprecise upper intercept age of 548 ± 42 Ma (Figure 7a). Three points were rejected due to high common-Pb concentrations. Old ages correlate
with high Y concentrations in the cores of some grains (e.g. grain 20, analyses 1,2,4, Fig. 7a); these older grains are found both in the matrix and included in garnet.

Seventeen data points from gneiss CWB 33 yield a spread of data with a $^{207}\text{Pb}/^{206}\text{Pb} / ^{238}\text{U}/^{206}\text{Pb}$ intercept age of $19.0 \pm 0.7$ Ma (MSWD 2.7, Fig. 7b, Table 2). Three younger (ca. 17 Ma) data points may record a younger (re-)crystallization event; however there is no strong link between variation in Miocene ages and chemical zoning. Monazite cores yield a discordant spread with a $^{207}\text{Pb}/^{235}\text{U} / ^{206}\text{Pb}/^{238}\text{U}$ upper intercept age of $583 \pm 51$ Ma. These Neo-Proterozoic to Cambrian ages are linked to zones of higher Y concentration (Fig. 7b).

The majority of twenty nine data points from five matrix monazite grains in gneiss BH 165 are slightly discordant, displaying linear arrays indicative of variable minor components of common-Pb (Fig. 8, Table 2). Twenty analyses yield a distinct array with a $^{207}\text{Pb}/^{206}\text{Pb} / ^{238}\text{U}/^{206}\text{Pb}$ lower intercept age of $20.5 \pm 0.6$ Ma (MSWD 0.4). A further three analyses yield a younger age of $18.5 \pm 1.1$ Ma (MSWD 0.1). No correlation is seen between Th and Y zoning patterns or spot location with respect to the grain rim, and the yielded Miocene age. One distinctly younger analysis (Fig. 8), not included the age calculations above, hints that there may have been monazite crystallization as recently as ca. 15 Ma. Fifteen core analyses (linked to high Y concentration) yield a spread along a discordia line, with five analyses yielding a concordant weighted average upper intercept age of ca. 536 Ma.

Nine analyses from six monazite grains in the matrix and in garnet in gneiss BH 167 yield a moderately-defined intercept age of $19.2 \pm 0.5$ Ma (MSWD 2.4, four data points rejected, two of which may indicate monazite growth at a later stage, Table 2).
There appears to be no link between Miocene age and chemical zoning patterns (Fig. 8). Nine points lie along a discordia line yielding a poorly constrained upper $^{207}\text{Pb}/^{235}\text{U} / ^{206}\text{Pb}/^{238}\text{U}$ intercept age of $599 \pm 45$ Ma; these older ages are linked to zones of high Y concentration.

Ten out of 24 data points from monazite rims in gneiss RLB 16 yield a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of $19.5 \pm 0.3$ Ma (MSWD 0.7), a further five points yield a younger age of $16.9 \pm 0.4$ Ma (MWD 0.1, Fig. 9, Table 2). Both sets of ages were obtained from grains with similar zoning patterns (Fig. 9); it remains unclear whether monazite crystallized over an extended period of time or whether there were two distinct monazite growth stages. Two points yield ages between the two end-member ages; these were rejected from the end-member age calculations as they may represent mixing between two end-member age domains. A further six discordant points were also rejected from the calculations. Miocene ages do not appear to be linked to minor chemical zoning in Y and Th (Fig. 9: grains 3 and 5 appear to have similar Y and Th concentrations yet grain 3 yields the older age and grain 5 the younger age).

5 Discussion and Tectonic Implications

5.1 Timing of monazite growth

Monazite in cordierite-bearing leucosome in the pelitic granulites suggests that crystallization at $13.9 \pm 0.3$ Ma coincided with cooling following anatexis [Kelsey et al., 2008]. Monazite included in garnet and associated with Sill + Bt mats in the granulate-hosting gneiss yields ages between $15.4 \pm 0.8$ Ma and $13.4 \pm 0.5$ Ma suggesting either two distinct episodes of monazite crystallization at this time or continuous crystallization.
during cooling. These ages are similar to 13.4 ± 1.0 to 11.0 ± 3.3 Ma U-Th-Pb ages of monazite and xenotime from para- and ortho-gneisses in Ama Drime, interpreted as constraining the timing of melt crystallization following granulite-facies metamorphism [Liu et al., 2007, Cottle et al., 2009a, Kali et al., 2010].

Monazite rims from a granite in the granulite terrane yield ages of 12.4 ± 0.3 Ma, suggesting slightly later crystallization of monazite in large granite bodies than in the surrounding migmatites. These data are consistent with previously published data from nearby granites: 15-11 Ma U-Pb SHRIMP zircon rim ages from the top of the GHS, closer to the inner STD, along the same valley [sample BH 225, Kellett et al., 2009], 12.1-11.6 Ma $^{207}$Pb/$^{235}$U TIMS monazite ages from a granite further north at Wagye La [Wu et al. 1998] and a 12.5 ± 0.4 Ma Th-Pb SIMS monazite age from the Khula-Kangri granite at the Bhutan-Tibet border [Edwards and Harrison, 1997]. Andalusite reported in granite sample BH 225 suggests low-pressure conditions (P ≤ 2.8 kbar) during crystallization at this time [Kellett et al. 2009].

Monazite in the gneiss outcropping in the Laya valley yields an array of significantly older 21.0 ± 0.6 to 16.8 ± 0.2 Ma crystallization ages. In addition, granites south of Laya yield zircon crystallization ages of 24-18 Ma [Carosi et al., 2006]. These ages are comparable with a 22 ± 1 Ma U-Pb TIMS monazite age from a St + Ky schist and 18-14.5 Ma TIMS monazite and xenotime ages from deformed leucogranites and Ky + Grt migmatites at the lowest levels of the GHS in SE Bhutan [Daniel et al., 2003].

Together these data suggest that the rocks now exposed at the structurally highest levels of the GHS in NW Bhutan were affected by partial melting and high-temperature recrystallization during decompression from at least granulite-facies conditions during the
mid-Miocene, with textural evidence in associated mafic rocks for earlier higher pressure conditions. The contrast between older ages to the south and younger ages to the north suggest the presence of a major structure separating a younger, structurally higher, cryptic eclogite- and granulite-bearing terrane from an older, structurally lower, granulite-free terrane. The nature of this boundary has important implications for the tectonic history of NW Bhutan.

A high strain zone identified in the field immediately above Laya, and above the trail leading to the west of it, may be the trace of a north-dipping, top-to-the-south, thrust-sense structure which has emplaced granulite-facies gneiss over amphibolite-facies gneiss (Fig. 1b,c); further detailed mapping and sampling are needed to confirm this. This “Laya Thrust” (Fig. 1b,c) may be the westward extension of the out-of-sequence Kakhtang Thrust [Gansser, 1983], thought to have been active between 10-14 Ma in central Bhutan [Grujic et al., 2002]. This thrust, in conjunction with leucogranite intrusion and tectonic denudation along the inner STDS until at least 11 Ma, may have partially or fully accommodated the rapid isothermal exhumation of the granulites from >1.0 to ca. 0.6 GPa at or shortly before 15-13 Ma, and juxtaposed these rocks over Grt-Sill-Bt gneiss in which monazite crystallized between 21-16 Ma. This tectonic event may be related to the reorganization of the STDS and the shift of the top-to-the-north shearing from the Outer to the Inner STDS [Kellett et al., 2009].

5.2 Exhumation of the granulite-bearing unit

Textural evidence from mafic rocks exposed in NW Bhutan (Fig. 2) suggest that eclogite facies conditions were reached prior to decompression and heating to granulite
Exhumation of deeply buried rock may be driven by buoyancy, tectonics, surface erosion, or a combination of these [England and Molnar, 1990; Platt, 1993; Ernst et al., 1997; Ring et al., 1999]. There are several lines of evidence which suggest that different tectonic regimes and exhumation mechanisms are responsible for the formation and exhumation of HP (> ca. 1.4 GPa) rocks across the Himalayan orogen [e.g. Guillot et al., 2008]. The driving force responsible for the exhumation of UHP (> ca. 2.6 GPa) terranes in the NW Himalaya is considered to be buoyancy [e.g. Ernst et al., 1997] as the thinned Indian continental margin was subducted beneath Asia during the earliest stages of continental collision e.g. [de Sigoyer et al., 2000; Leech et al., 2005; Parrish et al., 2006, Guillot et al., 2008]. Evidence for this includes the age of peak metamorphism (within ca. 10 Ma of India-Asia collision, Rowley et al., 1996, 1998, Zhu et al., 2005), the depth of subduction (pressures of >2.7 GPa equating to depths >95 km assuming an average crustal density of 2800 kg m$^{-3}$), their structural position immediately beneath (and south of) the India-Asia suture, and the amphibolite-facies overprint during exhumation e.g. [Leech et al., 2005; Parrish et al., 2006; Epard and Steck, 2008]. A quantitative model linking the structural setting and PTt evolution of these UHP rocks to their buoyancy-controlled exhumation was recently presented by Beaumont et al., [2009].

In contrast, the eastern Himalayan eclogites appear to have formed 20-25 Ma later, reached HP rather than UHP conditions (no coesite reported), are exposed within the metamorphic core of the Himalaya (GHS and/or LHS) hundreds of km south of the suture, experienced a granulite-facies overprint during exhumation, and are much smaller in volume [Lombardo and Rolfo, 2000, Groppo et al., 2007; Cottle et al., 2009a, Kali et al., 2010, Corrie et al., 2010]. Their recent, ca. 21 Ma [Corrie et al., 2010], formation in,
and rapid exhumation from, a steep, relatively cold collision-related subduction channel is incompatible with present day seismic observations of south Tibetan and Himalayan crust [Nelson et al., 1996; Hauck et al., 1998], and would suggest extreme diachroneity of the India-Asia collision which is inconsistent with other available geological data [Rowley et al., 1996, 1998, Zhu et al., 2005] and plate reconstructions [e.g. Molnar and Stock, 2009]. Buoyancy-related exhumation in a relatively cold geothermal regime is also inconsistent with the observed high temperature granulite-facies overprint, and is difficult to reconcile with coeval motion on the MCT and STD since ca. 22 Ma [see review in Godin et al., 2006]. Formation of the eastern Himalayan HP rocks deep within thickened orogenic crust (crustal thicknesses of ca. 70-80 km under southern Tibet equates to pressures of ca. 2.0 GPa) is more easily reconcilable with the available geological and geophysical data. Buoyancy cannot be the driving force behind exhumation as no buoyancy difference between the predominantly felsic exhuming rocks and the rest of the (assumed predominantly felsic) lower crust existed at the time of exhumation initiation. The older UHP eclogites found in the western Himalaya and the younger granulite-overprinted lower P eclogites found in the eastern Himalaya therefore formed and exhumed within different tectonic and kinematic regimes.

The structural, metamorphic and geochronological constraints on the mechanism responsible for exhumation of the granulitised eclogite terrane in Bhutan are that it is bound at its roof by a normal-sense boundary (the STD, active until at least 11 Ma, [Kellett et al., 2009]), at its base by a contemporaneously operating thrust-sense boundary (the "Laya Thrust", which, if the westwards extension of the Kakhtang Thrust operated after ca. 15 Ma, [Daniel et al., 2003]), that it reached higher metamorphic grade than the
terrane directly underlying it (eclogite and granulite rather than amphibolite), and that peak T metamorphism and anatexis occurred later (15-13 Ma) than in the underlying terrane (20-16 Ma). The granulite terrane in Bhutan may therefore be considered either as a coherent slab in which exhumation occurred contemporaneously across its breadth (the "wedge" model, [Vannay et al., 2004]) or as the solidified remains of weak rock that once flowed between more rigid boundaries as it exhumed (the "channel flow" model [Beaumont et al., 2001; Grujic et al., 2002; Beaumont et al., 2004; Godin et al., 2006; Jamieson et al., 2006]). There has been much debate about which of these models may provide a better explanation of Himalayan evolution [Harrison et al., 2006]; however the best-fit model to some extent depends on the time-frame under investigation e.g. [Harris, 2007, Beaumont and Jamieson, 2010]. The ubiquity of migmatitic textures across the unit attests to partial melting and consequent crustal weakening, even at <10% melt by volume [Rosenberg and Handy, 2005], during the granulite to amphibolite grade stage of the metamorphic history. This favours the channel flow mechanics for the exhumation of this terrane.

Channelized flow of relatively weak material in a near-horizontal crustal channel (as opposed to flow in a steep subduction channel) may be driven towards the surface by a combination of pressure gradient (here the difference between the thickened crust of the Tibetan Plateau and the foreland) and focused erosion (here at the Himalayan front). Among the array of numerical geodynamic channel flow models with relevance to Himalayan tectonics, Model HT111 [Jamieson et al., 2006] predicts the behavior of melt-weakened middle crust below upper crust containing a weak layer. This model shows features which are similar to those described from Bhutan, and may help provide insight
into the driving forces behind the exhumation of the eastern Himalayan high grade rocks. The embedded upper crustal weak layer facilitates the destabilization, detachment and foreland-directed flow of the upper crust, allowing the orogen to form a southward-propagating fold-thrust-belt in the foreland. This causes a rapid advance of the orogenic front, which combined with the rapid outward flow of the hot weak crustal channel, does not allow the incoming time to completely thermally re-equilibrate and hence forms a relatively cool, strong crustal ramp. Hot, weak, channel material in the interior of the orogen is forced over this ramp, destabilizing the weak overlying upper crust, which if it breaks, may form structures analogous to the north Himalayan gneiss domes [Beaumont et al., 2006; Jamieson et al., 2006]. In Model HT111, domes are extruded beneath the upper crust and towards the orogenic front, and are emplaced over previously exhumed channel material along an out-of-sequence thrust which duplicates the high grade section. Model P-T-t paths from the extruded dome display isothermal decompression from >1.3 GPa to <0.4 GPa between 18 Ma and 6 Ma model time [Fig. 9 of Jamieson et al., 2006], and record higher PT conditions than previously extruded material.

Although Model HT 111 was not specifically designed to reproduce particular cross-sections in the eastern Himalaya, data from NW Bhutan are consistent with, and may be compared to, the predictions of this model. Firstly, lower-grade metamorphic rocks yielding older ages (the granulite-absent, upper-amphibolite-facies terrane) are overlain by higher-grade rocks yielding younger ages (the granulite ± eclogite-bearing terrane), suggesting the presence of an out-of-sequence thrust (Figs. 1b,c and 10). The granulite terrane may therefore represent (part of) an exhumed dome, as recently proposed by Kellett et al. [2010]. Modeled peak P-T conditions, predicting a broad high-
grade region with >800°C and 0.8-1.2 GPa, are consistent with data from NW Bhutan [Jamieson et al., 2006]. Secondly, INDEPTH seismic reflections have been interpreted to show a ca. 35 km high ramp in the Main Himalayan Thrust at approximately the present latitude of the Kangmar Dome, ca. 40 km north of the Bhutan-Tibet border [Hauck et al., 1998]. We suggest that a similar structure may have been responsible for exhumation of granulite-facies and relict HP rocks above the Kakhtang Thrust in Bhutan at ca. 15 Ma.

The comparison between numerical model predictions and data suggests that exhumation of granulite-facies material from lower-crustal depths over a crustal ramp is physically plausible (Fig. 10) – in concept this idea has previously been explored [e.g. Guillot et al., 2008]. Rapid exhumation of deeply buried rocks may therefore be driven by tectonics as well as by buoyancy. Similar “plunger” mechanisms have previously been suggested for the exhumation of HP rocks in a subduction channel [Warren et al., 2008]. Model vertical exhumation rates in the plunger models are in the order of 0.5-1.7 cm a⁻¹ for initial exhumation from mantle depths to mid-crustal levels; these are comparable to buoyancy-driven models with exhumation rates of 1.2-1.5 cm a⁻¹ [Warren et al., 2008]. Model exhumation rates depend heavily on material viscosity and the viscosity difference between the plunger and the expelled material. Although absolute values are different, the pattern of faster exhumation for buoyancy-driven exhumation compared with slower exhumation for tectonically-driven exhumation is matched by data from the Himalayan eclogites: faster rates of 0.3-0.8 cm a⁻¹ for the Kaghan terrane [Parrish et al., 2006] and slower rates of ca. 0.3 cm a⁻¹ for the Bhutan terrane (assuming a crustal density of 2800 kg m⁻³ and granulite-facies pressures of 1.0 GPa at 14 Ma). These back-of-the-envelope calculations are by necessity averages, and it is plausible that initial exhumation over the
ramp could have been faster, followed by later, slower, surface-denudation-controlled exhumation.

Although similar PTt data have been reported for the Ama Drime/Arun eclogites, their structural position and hence the tectonic process driving their final exhumation to the surface, appears to be different [Cottle et al., 2009a, Corrie et al., 2010, Kali et al., 2010]. The Ama Drime range is bounded by north-south striking faults which appear to have accommodated significant orogen-parallel E-W extension since 13 Ma [Jessup et al., 2008, Cottle et al., 2009a]. These workers suggest that extension on these structures coupled with focused denudation in the Arun River gorge accommodated the exhumation of the high grade rocks in the footwall. Such large-scale orogen-parallel extension is not seen in Bhutan, whereas no south-directed out-of-sequence thrusting has been observed in the Ama Drime Massif. Therefore although comparable rocks appear to have originated from similar crustal levels, their exhumation, or at least the later stages of their exhumation, appears to have been driven by fundamentally different process.

6 Conclusions

U-Pb geochronology suggests that monazites in the leucosome of granulite-grade pelitic garnet-orthopyroxene-biotite-plagioclase migmatitic gneisses exposed in Bhutan, E Himalaya, crystallised at 13.9 ± 0.3 Ma. Evidence from associated mafic rocks suggests that granulite-facies conditions were reached following an earlier HP eclogite-facies event, the conditions and timing of which remain cryptic. Monazite associated with sillimanite-grade metamorphism in granulite-hosting garnet-sillimanite-biotite migmatitic gneisses yields rim ages between 15.4 ± 0.8 Ma and 13.5 ± 0.5 Ma. These
rocks structurally overlie older 21-16 Ma garnet-sillimanite-biotite migmatitic gneisses which do not record evidence for granulite-facies metamorphism. The geochronological, petrological and structural data suggest that an out-of-sequence thrust separates the two packages, although this hypothesis requires more detailed mapping.

The eastern Himalayan granulitised eclogites do not provide evidence for diachronous collision across the orogen. Instead they suggest a distinct episode of eclogite formation tectonically unrelated to the early subduction-related, buoyantly-exhumed eclogites in the western Himalaya. As there is no evidence for the presence of a subduction zone in the eastern Himalaya in the mid-Miocene, buoyancy-related exhumation in a subduction channel is not considered a viable mechanism for the exhumation of these high grade rocks. Instead, available seismic data combined with insight from previously published numerical models suggest that granulite ± eclogite facies rocks may have been exhumed over older, colder, previously exhumed middle crustal material during penetration of a strong Indian crustal ramp into the thickened weak Himalayan orogenic crust. Syn-convergent exhumation of lower crustal level eclogite-facies material may therefore be achieved by tectonic (plunger) forcing rather than by buoyancy in the absence of a subduction system.

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Chakungal and David Moynihan. Patricia Stoffyn and Andy Tindle are gratefully acknowledged help in the Dalhousie and Open University microprobe laboratories. Matt Horstwood, Vanessa Pashley and Nick Lloyd are gratefully acknowledged for analytical help at NIGL, and NIGFSC grant IP/1054/0508 covered analytical costs. Dick Brown is thanked for allowing us access to the RLB samples. Fantastic logistical support from numerous guides, drivers, cooks and camp crew in Bhutan eased our way during fieldwork. We thank two anonymous reviewers for constructive criticism and Onno Oncken for editorial handling.

References


**Figure Captions**


3. Thin section photomicrographs in plane polarized light of pelitic granulite sample BH 243. Mineral abbreviations after Whitney and Evans, [2010]. Field of view of top two images is 2.8 x 2.1 mm and lower two images 5.5 x 4.1 mm.


5. a, b) Th-Pb diagrams for pelitic granulite BH 243 and granulite host gneiss BH213a. c) Tera-Wasserburg U-Pb diagram for granulite host gneiss RLB 19. Chemical maps of Th and Y zoning in selected grains are also presented, including analytical spot locations (data in Table 2). The imaged grain analyses are labeled on the U-Pb diagram. The color scale on each element map is the same, and matches the scale in Figures 6-9.

6. Tera-Wasserburg U-Pb diagram for granite sample RLB 18 and chemical maps of selected grains showing zoning in Th and Y, as well as locations of analytical spots (data in Table 2). The imaged grain analyses are labeled on the U-Pb diagram. The color scale on each element map is the same, and matches the scale in Figures 5-9. Equivalent data points are labeled on the TW diagram. Data point error ellipses are 2σ.

7. Chemical maps showing element zoning in Th and Y in monazite from gneiss samples CWB 22 and CWB 33 from the Laya Valley (Fig. 1b) including spot locations (data in Table 2). The imaged grain analyses are labeled on the U-Pb diagrams. Miocene U-Pb monazite data are plotted on Tera-Wasserburg diagrams and Cambro-Ordovician
core data are plotted on concordia diagrams. Data point error ellipses are $2\sigma$. The color scale on each element map is the same, and matches the scale in Figures 5-9.

8. Chemical maps showing element zoning in Th and Y in monazite from gneiss BH 165 and BH 167 from the Laya Valley (Fig. 1) including spot locations for comparison with Table 2. The imaged grain analyses are labeled on the U-Pb diagrams. Miocene U-Pb monazite data are plotted on Tera-Wasserburg diagrams and Paleozoic core data are plotted on concordia diagrams. Data point error ellipses are $2\sigma$.

9. U-Pb concordia diagram for monazite from gneiss RLB 16 and chemical maps of selected grains showing zoning in Th and Y, as well as locations of analytical spots for comparison with Table 2. The imaged grain analyses are labeled on the U-Pb diagram.


**Table Captions**

1. Table of major-element mineral concentrations for representative samples of the Bhutan pelitic granulites and their host and neighbouring gneisses. Major-element concentrations were determined using the Dalhousie University JEOL 8200 5-spectrometer and the Open University Cameca SX-100 5-spectrometer Electron Microprobe (EM) using a 10 µm spot size with conditions of 15-20 kV.
and 20 nA. Natural standards were used for calibration and a ZAF matrix correction routine was used. Chemical formulas were calculated by stoichiometry. Unknowns were bracketed by analyses of internal secondary standards; uncertainty on major element concentrations is <1%.

2. Table of U-(Th)-Pb data for the samples discussed in the text. The context column indicates the major mineral textural association of monazite. RLB samples were analysed in grain mounts with no textural information available.
**Warren et al., Table 1: Mineral data**

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| Oxygen atoms | 12 | 8 | 18 | 23 | 4 | 12 | 23 | 8 | 8 | 8 |

**SiO₂** | **Si** | **Ti** | **Al** | **Fe** | **Mn** | **Mg** | **Ca** | **Na** | **K** | **Total**

| Oxygen atoms | 12 | 8 | 18 | 23 | 4 | 12 | 23 | 8 | 8 | 8 |

**SiO₂** | **Si** | **Ti** | **Al** | **Fe** | **Mn** | **Mg** | **Ca** | **Na** | **K** | **Total**

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* Denotes analysis that was rejected from final age determination. See text for explanation.

1. Rho calculations performed on unsupported Th.
2. Normalised to Th/U ratio of the standard.
a) Granulite host gneiss

BH 213a
Qtz + Pl + Kfs
Bt + Sill
Grt

1mm

b) Laya Valley gneiss

BH 165
Crd + Pl + Kfs
Bt + Sill
Grt

1mm

BH 167
Crd + Pl + Kfs
Bt + Sill
Bt
Grt

1mm

BH 165
Crd
Pl
Sill

BH 167
Bt
Grt
Pl
Spl
Sill
Crd

0.2 mm
0.5 mm
a. BH 243, pelitic granulite

Mean $^{206}\text{Pb} / ^{238}\text{U}$ age = 13.9 ± 0.3
MSWD = 0.5, probability = 0.9

All analyses used in final age calculation

b. BH 213a, granulite host gneiss

Mean $^{206}\text{Pb} / ^{238}\text{U}$ age = 15.4 ± 0.8
MSWD = 0.4, probability = 0.8

Analyses 6(1-2), 10(2,4)

Intercept at 13.4 ± 0.5 Ma
MSWD = 0.3

All analyses used in final age calculation
c. RLB 19, granulite host gneiss

data-point error ellipses are 2σ

Intercept at 13.4 ± 0.5 Ma
MSWD = 0.3
RLB 18, granite

Intercept at 12.4 ± 0.3 Ma
MSWD = 0.6