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Tectono-metamorphic evolution of the Jomolhari massif: Variations in timing of syn-collisional metamorphism across western Bhutan

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ABSTRACT

Our current understanding of the rates and timescales of mountain-building processes is largely based on information recorded in U-bearing accessory minerals such as monazite, which is found in low abundance but which hosts the majority of the trace element budget. Monazite petrochronology was used to investigate the timing of crustal melting in migmatitic metasedimentary rocks from the Jomolhari massif (NW Bhutan). The samples were metamorphosed at upper amphibolite to granulite facies conditions (~0.85 GPa, ~800 °C), after an earlier High-Pressure stage (P > 1.4 GPa), and underwent partial melting through dehydration melting reactions involving muscovite and biotite. In order to link the timing of monazite growth/dissolution to the pressure–temperature (P–T) evolution of the samples, we identified ‘chemical fingerprints’ in major and accessory phases that were used to back-trace specific metamorphic reactions. Variations in Eu anomaly and Ti in garnet were linked to the growth and dissolution of major phases (e.g. growth of K-feldspar and dehydration melting of muscovite/biotite). Differences in M/HREE and Y from garnet core to rim were instead related to apatite breakdown and monazite-forming reactions. Chemically zoned monazite crystals reacted multiple times during the metamorphic evolution suggesting that the Jomolhari massif experienced a prolonged high-temperature metamorphic evolution from 36 Ma to 18 Ma, significantly different from the P–T–time path recorded in other portions of the Greater Himalayan Sequence (GHS) in Bhutan. Our data demonstrate unequivocally that the GHS in Bhutan consists of units that experienced independent high-grade histories and that were juxtaposed across different tectonic structures during exhumation. The GHS may have been exhumed in response to (pulsed) mid-crustal flow but cannot be considered a coherent block.

1. Introduction

The determination of precise rates and timescales at and over which continental crust forms, is transformed and eventually destroyed is important for unravelling the rates and timescales over which different tectonic processes shape the surface and sub-surface of the planet. Collisions between large continental plates such as India and Eurasia create some of the most drastic changes to Earth's topography over geological timescales. Our understanding of crustal deformation during collisions is underpinned by the chronological determination of petrographical transformations and their relationships to strain markers in deformed rocks. U–Th-bearing accessory phases crystallising in these rocks may record and preserve geochronological evidence of overprinting metamorphic stages. Monazite and zircon are arguably the two most important chronometers for recording the timescales of tectonic processes at high temperature. Monazite is more reactive than zircon (both in the presence and in the absence of melt), however, giving it greater potential to respond to these processes (e.g. Parrish, 1990). It commonly reacts at various times during a metamorphic cycle and preserves evidence for multiple episodes of growth, dissolution and re-growth: ideally, each of these events is identifiable by their differing trace element concentrations (Foster et al., 2004; Gibson et al., 2004; Rubatto et al., 2013). These chemical variations provide the key to linking the timing of episodes of monazite growth to the petrological evolution of the host rock.

Exhumed metamorphic rocks within the Himalayan orogen provide suitable material for investigating the rates and timescales over which continental crust becomes transported, deformed and transformed. The prevailing model for at least the initiation and early exhumation of the partially-melted high grade core of the Himalaya (Greater Himalayan Sequence) is one of forcing by a topographic pressure gradient between the Tibetan Plateau and the orogenic foreland, coupled with erosion at the orogenic front (e.g. Beaumont et al., 2001). This numerically-verified conceptual model provides an explanation for numerous features of the Himalayan orogen: the “bright”, low-velocity mid-orogenic crustal region seen on the INDEPTH traverse (Nelson et al., 1996), the exhumation of the high-grade GHS against two relatively un-metamorphosed units by a thrust-sense fault at the base and a normal-sense fault at the roof, and the general P–T–t evolution and provenance of the GHS and Lesser Himalayan Sequences in the

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central Himalaya, Nepal (Jamieson et al., 2006). At its simplest, however, the channel flow model does not adequately describe the exhumation paths of various portions of the GHS across the whole orogen, especially in transects where there appear to be significant chronological and petrological discontinuities within the unit e.g. in eastern Nepal (Imayama et al., 2012), Sikkim (Rubatto et al., 2013) and western Bhutan (Grujic et al., 2011; Warren et al., 2011b). In these regions, different sections of deeply buried crust appear to have melted and exhumed diachronously — perhaps accommodated by "pulsed" channel flow (e.g. Hollister and Grujic, 2006; Warren et al., 2011a,b).

In order to understand the differences in timing and tectonic history across different structural levels between Sikkim and Bhutan (Grujic et al., 2011; Kellett et al., 2013; Rubatto et al., 2013; Warren et al., 2011b), this paper presents pressure–temperature–time data from the Jomolhari massif in western Bhutan. The Jomolhari massif has, until now, only been mapped at coarse resolution (Gansser, 1983), and its P–T–t evolution has never been described. However, detailed comparison between its evolution and other units in the GHS in Bhutan is important for determining spatial and temporal changes in exhumation rate and mechanism from the central to the eastern Himalaya.

The aim of the present paper is to define a detailed P–T–t path for the Jomolhari massif and compare it with the metamorphic evolution of the GHS terranes in northern and central Bhutan. The new data are also used to explore and compare exhumation mechanisms of deeply buried crustal rocks in the eastern Himalaya. High analytical resolution, micron-scale in-situ geochronological data provide tight control over links between monazite age, chemistry and microtextural association, whilst geochemical data help provide links between monazite chemistry and age. Finally, petrological models provide the predictive framework for linking time to the metamorphic evolution of the investigated samples.

2. Geological setting

The on-going collision between India and Asia, which initiated between 55 and 50 Ma (e.g., Leech et al., 2005; Tapponier et al., 1982; Zhu et al., 2005) produced the Himalayan orogen, one of the archetypical examples of continent–continent collision. Geologically, it is divided into four orogen-parallel tectonostratigraphic zones, bounded by major normal and thrust-sense structures (Gansser, 1964, 1983; Heim and Gansser, 1939; Le Fort, 1975). From south to north (structurally low to high), these units include (Fig. 1a): the Siwalik belt, the Lesser Himalayan Sequence (LHS), the Greater Himalayan Sequence (GHS), and the Tethyan Sedimentary Sequence (TS). Synorogenic deposits of the Subhimalayan zone are mostly exposed in the Miocene to Pliocene Siwalik Group (e.g. DeCelles et al., 1998, 2004; Gansser, 1964; Huyghe et al., 2005; Ojha et al., 2000). The Siwaliks are bound at their base by the Main Frontal thrust (MFT), that corresponds to the present Himalayan topographic front. The Lesser Himalayan sequence, which sits structurally above the Siwaliks across the Main Boundary thrust (MBT), contains greenschist-facies sedimentary units which were deposited on the northern margin of the Indian craton (e.g. Kohn et al., 2010; McQuarrie et al., 2008; Parrish and Hodges, 1996). The Greater Himalayan sequence consists of amphibolite- to granulite-facies metaigneous, metasedimentary, and Miocene igneous rocks, which sit structurally above the Lesser Himalayan sequence across the Main Central thrust (MCT) (e.g. Gansser, 1964; Heim and Gansser, 1939; Le Fort, 1975) whilst The Tethyan sedimentary sequence, which sits structurally (e.g. Burchfiel et al., 1992; Burg, 1983; Long and McQuarrie, 2010) above the Greater Himalayan sequence across the South Tibetan Detachment (STD), represents Neoproterozoic to Eocene deposition on the distal northern Indian margin of the Tethyan ocean basin (Brookfield, 1993; Gaetani and Garzanti, 1991; Garzanti, 1999).

This simple layer-cake tectonostratigraphy becomes more complicated towards the eastern end of the orogen, where additional tectonostratigraphic units with distinct metamorphic and geochronological histories have also been identified. In Bhutan these include the Chekha Formation, a high grade schist unit at the base of the TS, and the Paro Formation which is exposed in a shear-zone bounded window in western Bhutan (e.g. Gansser, 1983; Kellett et al., 2009; Tobgay et al., 2010; Fig. 1a,b).

A major out-of-sequence thrust (the Laya Thrust in NW Bhutan, Kakhtang Thrust in eastern Bhutan and the Zimithang Thrust in Arunachal Pradesh) cuts through the GHS and STD, nearly doubling the outcrop thickness (e.g. Gansser, 1983; Grujic et al., 2011; Warren et al., 2011a), and creating klippen of TS sedimentary rocks and metasedimentary rocks of the Chekha formation (CHf) preserved south of this structure (Fig. 1a). In NW Bhutan this thrust accommodates late-orogenic extrusion of a young granulite-facies terrane (15–13 Ma) over older (21–18 Ma) amphibolite-facies rocks (Chakungal et al., 2010; Grujic et al., 2011; Warren et al., 2011a,b). As a result of this complex tectonic setting, the GHS in Bhutan appears to consist of multiple units that preserve different P–T–t histories, separated by major metamorphic breaks and cryptically preserved tectonic structures. Preliminary geochronological data on titanite (Warren et al., 2011a), suggested that the Jomolhari massif preserved a unique tectonic history and experienced a different cooling history from the rest of the GHS in NW Bhutan (Warren et al., 2011a).

2.1. Metamorphism and geochronology

The majority of the rocks that form the high-grade core of the Himalaya (GHS) were metamorphosed at peak temperatures of 650–750 °C and pressures of 0.8–1.3 GPa during the Oligocene–Miocene (ca. 30–16 Ma, see review by Hodges, 2000 and recent work by Corrie and Kohn, 2011; Imayama et al., 2012; Kellett et al., 2013; Rubatto et al., 2013). Rare ultra-high-pressure rocks (>2.7 GPa) have been reported from Kaghan and Tso Morari in the NW Himalaya. Both eclogite bodies reside in the Greater Himalayan sequence immediately to the south of the Indus suture zone (e.g. O'Brien et al., 1999, 2001) and are inferred to record remnants of the distal margin of the Indian plate subducted beneath Asia (e.g. Guillot et al., 2008) during the early stages of continental collision at 55–45 Ma (Leech et al., 2005; Parrish et al., 2006; St-Onge et al., 2013).

'Lower' pressure rocks (HP stage at ~1.5 GPa and ~650–700 °C) have been reported in the eastern Himalaya (Ama Drime massif, Sikkim and NW Bhutan e.g. Chakungal et al., 2010; Cottle et al., 2009; Groppo et al., 2007; Lombardo and Rolfo, 2000; Lombardo et al., 1998; Rolfo et al., 2008; Warren et al., 2011a). The P–T–t evolution of the eastern HP rocks differs from the UHP eclogites from the northwest Himalaya in three fundamental ways: i) peak conditions are lower (e.g. Groppo et al., 2007), ii) eclogites were subjected to a strong granulite-facies overprinting at intermediate crustal levels (e.g. Cottle et al., 2009; Groppo et al., 2007, this study) and iii) they were metamorphosed 20–30 Myr later (U–Pb zircon/monazite: Cottle et al., 2009; Grujic et al., 2011; Warren et al., 2011b; Lu–Hf garnet: Corrie et al., 2010). It is currently unclear whether the eastern Himalayan high-pressure rocks also formed during the early steep subduction of India beneath Asia or whether they represent exhumation from deeper orogenic structural levels not exposed, preserved or yet recognised elsewhere in the orogen. The distinction between these end-member scenarios for eclogite formation has implications for exhumation mechanisms: subduction-related eclogites are typically exhumed within larger buoyant crustal slices whereas lower crustal eclogites require an external driver such as extension to force and assist their return (e.g. Grujic et al., 2011; Warren et al., 2011b).

At the highest structural levels of the NW Bhutan GHS, U–Pb geochronology suggests that zircons crystallised in mafic rocks under HP conditions at ca. 15–14 Ma (Grujic et al., 2011), i.e. 30–40 Myr later than the NW UHP samples. HP metamorphism was rapidly followed by a granulite facies overprint at ca. 14–13 Ma during which monazite crystallised in decompression-related leucosomes (Warren et al., 2011b). The granulitised eclogites are structurally