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Subduction metamorphism in the Himalayan ultrahigh-pressure Tso Morari massif: An integrated geodynamic and petrological modelling approach

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ABSTRACT

The Tso Morari massif is one of only two regions where ultrahigh-pressure (UHP) metamorphism of subducted crust has been documented in the Himalayan Range. The tectonic evolution of the massif is enigmatic, as reported pressure estimates for peak metamorphism vary from ∼2.4 GPa to ∼4.8 GPa. This uncertainty is problematic for constructing large-scale numerical models of the early stages of India–Asia collision. To address this, we provide new constraints on the tectonothermal evolution of the massif via a combined geodynamic and petrological forward-modelling approach. A prograde-to-peak pressure–temperature–time (P–T–t) path has been derived from thermomechanical simulations tailored for Eocene subduction in the northwestern Himalaya. Phase equilibrium modelling performed along this P–T path has described the petrological evolution of felsic and mafic components of the massif crust, and shows that differences in their fluid contents would have controlled the degree of metamorphic phase transformation in each during subduction. Our model predicts that peak P–T conditions of ∼2.6–2.8 GPa and ∼600–620 °C, representative of 90–100 km depth (assuming lithostatic pressure), could have been reached just ∼3 Myr after the onset of subduction of continental crust. This P–T path and subduction duration correlate well with constraints reported for similar UHP eclogite in the Kaghan Valley, Pakistan Himalaya, suggesting that the northwest Himalaya contains dismembered remnants of what may have been a ∼400-km-long UHP terrane comparable in size to the Western Gneiss Region, Norway, and the Dabie–Sulu belt, China. A maximum overpressure of ∼0.5 GPa was calculated in our simulations for a homogeneous crust, although small-scale mechanical heterogeneities may produce overpressures that are larger in magnitude. Nonetheless, the extremely high pressures for peak metamorphism reported by some workers (up to 4.8 GPa) are unreliable owing to conventional thermobarometry having been performed on minerals that were likely not in equilibrium. Furthermore, diagnostic high-P mineral assemblages predicted to form in Tso Morari orthogneiss at peak metamorphism are absent from natural samples, which may reflect the widespread metastable preservation of lower-pressure assemblages in the felsic component of the crust during subduction. If common in such subducted continental terranes, this metastability calls into question the reliability of geodynamic simulations of orogenesis that are predicated on equilibrium metamorphism operating continuously throughout tectonic cycles.

1. Introduction

The Tso Morari massif, northwest India (Fig. 1), is one of only two examples of ultrahigh-pressure (UHP) metamorphism in the Himalayan Range and provides evidence for deep subduction of the Indian continental margin beneath Asia during the early Eocene (Epard and Steck, 2008). Constraining the petrological and metamorphic pressure–temperature–time (P–T–t) evolution of such eclogite-facies rocks is critical to understanding the geodynamic processes responsible for the burial and rapid exhumation of crustal material during collisional orogenesis (e.g. Warren et al., 2008). However, the tectonothermal evolution of the massif is controversial, with reported conditions of peak metamorphism varying from around the quartz–coesite transition (∼2.4–2.8 GPa and ∼420–650 °C: St-Onge et al., 2013;

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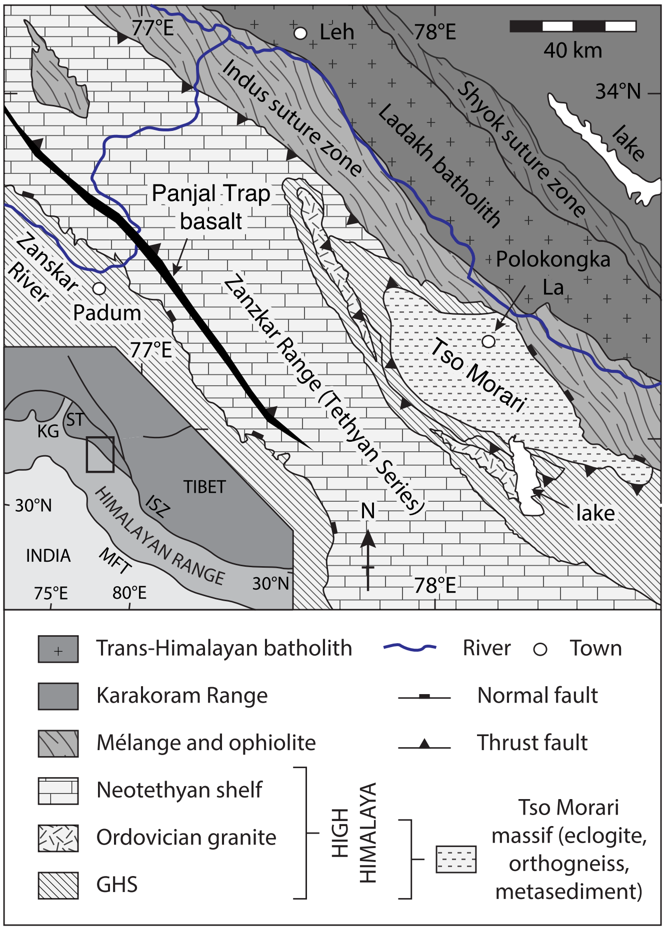

Fig. 1. Simplified geological map of the Tso Morari region, northwest India, modified after Epard and Steck (2008), and Shellnutt et al. (2014). Inset shows its location within the Himalayan–Tibetan orogen. GHS = Greater Himalayan Series, ISZ = Indus Suture Zone, KG = Kaghan Valley, MFT = Main Frontal Thrust, ST = Stak Valley.

Chatterjee and Jagoutz, 2015) to within the diamond stability field (∼3.9–4.8 GPa and ∼550–800 °C: Mukherjee et al., 2003; Wilke et al., 2015). This uncertainty hinders reliable large-scale tectonic reconstruction of the early stages of India–Asia collision.

Thermomechanical modelling of heat transfer during plate-tectonic interactions allows calculation of theoretical P–T(–t) paths that a metamorphic rock may follow in a given geodynamic environment (Peacock, 1989). The P–T–t paths that these models produce may then be compared to the results of thermobarometric calculations performed on natural rocks. Forward modelling of slab-surface P–T conditions at subduction zones allows the influence of different geological variables on subduction zone thermal structures to be examined (Gerya et al., 2002), though the simulations are subject to significant uncertainties in the values of key parameters, including slab age, dip angle, and convergence velocity. The calculated evolutions of pressure and temperature with time provide tests of the geodynamic model within the uncertainty envelope.

We have combined geodynamic and petrologic parameters specific to Eocene subduction of Indian-plate crust in the northwest Himalaya in simulations that provide new constraints on the prograde-to-peak P–T–t evolution of the Tso Morari massif. Petrological modelling was used to calculate bulk-rock properties for the main lithologies exposed in the massif at P–T conditions applicable to Phanerozoic subduction. These results provided inputs for a forward numerical model constrained by geodynamic criteria specific to India–Asia convergence, which predicted peak metamorphic conditions of ∼2.6–2.8 GPa and ∼600–620 °C. Extremely high pressures up to ∼4.8 GPa inferred by some workers (Mukherjee et al., 2003; Wilke et al., 2015) are to be geodynamically implausible. Further, diagnostic high-P metamorphic mineral assemblages predicted to form in felsic crust under equilibrium conditions are absent from the massif itself, suggesting widespread metastability during subduction. Our calculated P–T conditions are similar to those documented in the nearby UHP Kaghan Valley in Pakistan, which suggests that the northwestern Himalaya contains fragments of what may have been a coherent UHP terrane ∼400 km long and ∼150 km wide, comparable in size to the Western Gneiss Region, Norway, and the Dabie–Sulu belt, China.

2. Geological background

The Tso Morari massif, Ladakh Himalaya, is a structurally coherent block of thinned Indian continental margin (Mascle et al., 1994) exposed between Neotethyan sedimentary units of the Zanskar Range, and mélange and ophiolite of the Indus Suture Zone (Fig. 1). The massif is ∼100 km long, ∼50 km wide, and ∼7 km thick, and comprised primarily of quartzofeldspathic orthogneiss that hosts metre- to decametre-scale boudins of coesite-bearing mafic eclogite (De Sigoyer et al., 2004). Rare metasedimentary units also occur (Guillot et al., 1997). Field relations, major and trace element geochemistry, and U–Pb age data show that outcrops of Ordovician S-type granite exposed at Polokongka La, a low-strain portion of the massif (Fig. 1), represent relics of the orthogneiss's protolith (Girard and Bussy, 1999). Eclogite boudins represent dismembered and metamorphosed mid-crustal doleritic dykes associated with Permian–Carboniferous Panjal Trap flood basalts exposed to the west (Fig. 1: Berthelsen, 1953; De Sigoyer et al., 2004).

Geochronological and petrological work performed on both lithologies has identified multiple stages in the massif's tectonothermal history. U–Pb zircon dating shows that the subduction of Indian continental crust initiated no later than c. 58–57 Ma (Guillot et al., 2003; Leech et al., 2005) and peak UHP conditions were reached at c. 51 Ma (St-Onge et al., 2013). These ages delimit a subduction duration of ∼6–7 Myr, which correlates well with a ∼7–9 Myr period inferred by Kaneko et al. (2003) for subduction of UHP eclogites in the nearby Kaghan Valley (Fig. 1, inset). Initial and rapid exhumation to the base of the continental crust was followed by slower tectonic exhumation involving an amphibolite-facies metamorphic overprint at c. 45 Ma (U–Pb zircon, Leech et al., 2005; Th–Pb monazite, St-Onge et al., 2013). Ar–Ar data suggest exhumation through ∼300–350 °C at 30 Ma (De Sigoyer et al., 2000), although the timing of surface exposure is unknown.

Despite the P–T conditions of retrograde amphibolite-facies overprinting in the crust being tightly constrained at 1.0 ± 0.4 GPa and 650 ± 50 °C (e.g. De Sigoyer et al., 1997), estimates for peak pressure conditions fall into two distinct groups. Some workers suggest that subducted crust reached 80–100 km depth, inferred from P–T conditions of ∼2.4–2.8 GPa and ∼420–650 °C around the quartz–coesite transition (St-Onge et al., 2013; Chatterjee and Jagoutz, 2015). However, others suggest subduction up to ∼150 km depth, implied by putative P–T conditions of ∼3.9–4.8 GPa and ∼550–800 °C (Mukherjee et al., 2003; Wilke et al., 2015) well within the diamond stability field (Fig. 2). Notably, these discrepant P–T estimates were derived from rocks collected from the same roadside outcrop.

Eclogite-facies metamorphism is recorded in mafic boudins by the assemblage garnet, omphacite, phengite, rutile, sodic–calcic/sodic amphibole, and quartz or coesite (De Sigoyer et al., 1997; Epard and Steck, 2008). Diamond has not been identified in the region. The host orthogneiss records negligible petrological evidence of UHP metamorphism, being characterised by the