Journal of Asian Earth Sciences 101 (2015) 83–100

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Characterising the metamorphic discontinuity across the Main Central Thrust Zone of eastern-central Nepal

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ARTICLE INFO

Article history:
Received 8 November 2014
Received in revised form 25 January 2015
Accepted 30 January 2015
Available online 11 February 2015

Keywords:
Main Central Thrust Zone
Metamorphic discontinuity
Pseudosection
P–T path

ABSTRACT

The Main Central Thrust Zone (MCTZ) is a top-to-south shear zone that has exhumed the high-grade Himalayan metamorphic core during the orogeny. Identifying the location of the MCTZ is a major challenge and the characteristics of the metamorphic discontinuity remain under debate. To clarify this issue, petrologic and thermobarometric studies were carried out on metapelites and metapsammites that were collected from the basal Nyalam transect in eastern-central Nepal. Results reveal that the metamorphic discontinuity across the MCTZ is characterised by a continuous increase in peak *P–T* conditions toward higher structural levels, a relatively high field temperature gradient (25–50 °C km^{-1}) and different types of *P–T* paths. Specifically, representative rocks in the MCTZ record sub-solidus peak conditions (637 ± 16 °C and 9.2 ± 1.0 kbar) and a hairpin-type *P–T* path. The lower GHC rocks record supra-solidus peak conditions (690 ± 32 °C and 10.3 + 1.1/−1.4 kbar) and a prograde loading path with a small segment of decompression. The presence of a high field pressure gradient across the MCTZ is debatable in the Nyalam transect due to the large uncertainties in pressure estimates. Comparison between obtained *P–T* results and model predictions indicates that a multiple thrusting process dominated exhumation of the MCTZ and lower GHC rocks, while crustal flow contributed partly to exhumation of the lower GHC rocks.

1. Introduction

The Himalayan belt is a continent–continent collisional orogen produced by the Cenozoic India-Asia collision. It serves as the best example for understanding the evolution of large thrust systems and the burial – exhumation mechanism of metamorphic rocks. Within the architecture of the Himalayan orogen, the metamorphic core is divided into two distinct lithotectonic units: the overlying upper-amphibolite- to granulite-facies Greater Himalayan Crystalline Complex (GHC) and the underlying greenschist- to amphibolite-facies Lesser Himalayan Sequences (LHS) (Le Fort, 1975; Burchfiel and Royden, 1985; Hodges, 2000; Yin, 2006). The boundary of the two units is marked by a top-to-south ductile shear zone, the Main Central Thrust Zone (MCTZ, Gansser, 1964; Le Fort, 1975; Arita, 1983).During the Indo-Asia collision, the MCTZ is thought to have accommodated at least 140 km of displacement (Schelling and Arita, 1991). Meanwhile, exhumation of the GHC and burial of the LHS are closely related to movement along the MCTZ, which makes the MCTZ a key area for investigating the evolution of the Himalayan orogen. Consequently, the MCTZ has been the focus of Himalayan research for decades (i.e. Le Fort, 1975; Arita, 1983; Pêcher, 1989; Kohn et al., 2001; Harrison et al., 1997, 1998; Daniel et al., 2003; Goscombe et al., 2006; Searle et al., 2008). In addition, many thermo-tectonic models, such as the channel flow model (Beaumont et al., 2001; Jamieson et al., 2004) and ductile extrusion model (Grujic et al., 1996), have been proposed based on the simultaneous movement along the MCTZ and the South Tibetan Detachment System (STDS, top-to-north shear zone on top of the GHC).

Locating the position of the MCTZ using various criteria is one of the basic tasks for Himalayan geologists. Unfortunately, the exact position of the MCTZ is still controversial because it has been mapped at several different locations. Generally, the MCTZ should be defined according to structural criteria and efforts have been made to map the MCTZ across several transects in Himalaya (Arita, 1983; Schelling, 1992; Goscombe et al., 2006; Searle et al., 2008; Larson and Cottle, 2014). However, some geologists argue that shear deformation is uniformly distributed across the GHC and LHS (Kohn, 2008; Mosca et al., 2012; Larson, 2012), which can hardly define a specific position for the MCTZ. Therefore, other criteria are also important for placing constraints on the location of

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http://dx.doi.org/10.1016/j.jseaes.2015.01.027
1367-9120/

the MCTZ, which include (i) U–Pb ages of detrital zircons and Nd isotopic ratios (Parrish and Hodges, 1996; Robinson et al., 2001; Martin et al., 2005); (ii) U–Th–Pb geochronology of metamorphic monazite (Harrison et al., 1997, 1998; Catlos et al., 2001; Kohn et al., 2004); (iii) metamorphic *P*–*T* conditions and *P*–*T* paths (Kohn et al., 2001; Groppo et al., 2009; Imayama et al., 2010; Corrie and Kohn, 2011; Larson et al., 2013).

As one of the criteria to locate the MCTZ, *P*–*T* conditions and *P*–*T* path studies are thought to be powerful tools for revealing hidden discontinuities across large tectonic boundaries (Groppo et al., 2009). Given that the topology of the *P*–*T* path is a function of the burial, thrusting, unroofing and heat transfer rates (Ruppel and Hodges, 1994), *P*–*T* paths can also be used to unravel the burial and exhumation history of metamorphic sequences during orogenic events (England and Thompson, 1984; Ruppel and Hodges, 1994; Vance and Mahar, 1998) and hence, test tectonic models. However, controversies remain when applying metamorphic criteria to identify the MCTZ. (i) Some argue that the MCTZ is marked by high field pressure gradients (Kohn, 2008; Imayama et al., 2010; Corrie and Kohn, 2011), whereas other studies reveal normal field pressure gradients (Catlos et al., 2001; Goswami-Banerjee et al., 2014; Mottram et al., 2014). (ii) A *P*–*T* path discontinuity across the MCTZ has been proposed a decade ago (Kohn et al., 2001) and further work has also been done to investigate this *P*–*T* path discontinuity (Groppo et al., 2009; Imayama et al., 2010; Larson et al., 2013). However, no *P*–*T* path discontinuity was revealed across the MCTZ in some other section (e.g. Mottram et al., 2014). In addition, the morphologies of the *P*–*T* paths also differ in different Himalayan sections. Therefore, it is unclear whether a *P*–*T* path discontinuity is a universal characteristic for the MCTZ. These questions highlight the need to characterise the metamorphic discontinuity across the MCTZ in a region where the MCTZ has been well mapped using other criteria.

Our study was carried out on the basal Nyalam transect of eastern-central Nepal (Fig. 1a), where the position of the MCTZ has been well mapped by several studies using both structural and geochronological criteria (Schelling, 1992; Larson et al., 2013; Larson and Cottle, 2014). To characterise the metamorphic features across the MCTZ, petrologic and thermobarmometric studies were carried out on metapelitic and metapsammitic samples using pseudosection modelling (THERMOCALC; Powell et al., 1998), average *P*–*T* thermobarometry (Powell and Holland, 1988) and conventional thermobarometry. Our results provide new constrains on the *P*–*T* conditions and morphologies of *P*–*T* paths in a petrologically poorly studied area. Tectonic evolution of the MCTZ was also discussed by comparing published data and model predictions.

2. Geological setting

2.1. Position of the MCT in Nepal

The location of the MCT has been constrained in Nepalese Himalaya using various criteria. In central Nepal (Annapurna-Langtang), Arita (1983) mapped the MCTZ as a 2–3 km thick high strain ductile shear zone bounded by an upper thrust, MCT-II (MCT in Fig. 1a), and a lower thrust, MCT-I (Munsiari Thrust). The upper thrust (MCT) is also consistent with a discontinuity revealed by detrital zircon ages and Nd isotopes (Martin et al., 2005), a peak temperature gap of ~100 °C (Kohn, 2008; Corrie and Kohn, 2011) and a monazite Th–Pb age gap of ~5–15 Myr (Catlos et al., 2001; Kohn et al., 2004). In eastern Nepal (Tumlingtar-Taplejung transect), Goscombe et al. (2006) suggested locating the MCT beneath the Ulleri-Phaplu augen gneiss (similar position as MCT-I in central Nepal). However, further work mapped the MCT at the upper thrust of the MCTZ, which was revealed by a discontinuity of Nd isotopes (Imayama and Arita, 2008), metamorphic *P*–*T* conditions and *P*–*T* paths (Imayama et al., 2010, Imayama et al., 2010; Imayama, 2014). In the Arun Valley transect of eastern Nepal, Groppo et al. (2009) defined a much broader unit (~10 km) as the MCTZ and identified two metamorphic discontinuities across it.

2.2. Geology of the Nyalam transect

The study area (Nyalam transect) is located west of Mount Everest and east of the Langtang valley (Fig. 1a). Its geology is similar to the adjacent regions. In the study area, the GHC rocks (hanging wall) are mainly composed of amphibolite- to granulite-facies migmatitic paragneiss, Paleoproterozoic augen orthogneiss, quartzite and calc-silicate gneiss (Wang et al., 2013). The protolith of the GHC paragneiss is Ordovician-Neoproterozoic sediment (Schelling, 1992). Oligocene–Miocene leucogranite plutons or dykes crop out mainly in the upper portion of the GHC (Liu et al., 2012). Toward structurally higher levels, the metamorphic grade gradually increases from kyanite-grade to cordierite-grade (Fig. 1b; Hodges et al., 1993; Wang et al., 2013; Groppo et al., 2013). Within the GHC, the Nyalam Thrust was recognised by a *P*–*T* inversion of ~50 °C and ~3 kbar upward (Wang et al., 2013). The LHS rocks (footwall) mainly consist of greenschist- to amphibolite-facies metasediment, Paleoproterozoic Melung-Salleri augen orthogneiss (Schelling, 1992), marble, calc-silicate and graphitic schist (Rai, 2011; Larson, 2012). The protolith of the LHS metasediment is Paleo- and Neoproterozoic sediment (Schelling, 1992).

In this transect, the MCTZ was mapped as a few hundred metres wide shear zone (Lesser Himalayan Shear zone, Schelling, 1992) and is composed of mylonitic Melung-Salleri augen orthogneiss and garnetiferous pelitic schist (Fig. 2). Schelling (1992) identified a single thrust plane (MCT) on top of the MCTZ. A structural discontinuity was subsequently revealed across the MCT by a deformation temperature discontinuity inferred from quartz lattice preferred orientation data (Larson and Cottle, 2014). Across the MCTZ, the metamorphic grade increases dramatically from garnet-grade within the LHS, staurolite/kyanite-grade in the MCTZ to kyanite-grade within the GHC over a distance of less than 2 km (Rai, 2011; Larson et al., 2013). The staurolite-in and kyanite-in isograds are too close to be distinguished. Monazite U–Pb ages from Larson et al. (2013) revealed that kyanite-grade metamorphism in the GHC occurred at ~19 Ma, while staurolite-grade metamorphism in the MCTZ occurred at ~10–8 Ma.

3. Petrography and mineral chemistry

Twelve of the collected metapelitic and metapsammitic samples were selected for petrographic and chemical composition studies (Fig. 2; Table 1). Chemical compositions of the minerals were determined using a JEOL JXA-8100 electron microprobe at Peking University. The working conditions were set to 15 kV accelerating voltage, a 10 nA beam current and a counting time of 20–30 s. The beam diameter was 2 μm for all phases except mica, for which it was 5 μm. Backscattered electron images (BSE) and compositional X-ray maps were obtained using an FEI Quanta 650 FEG scanning electron microscope, coupled with an Oxford INCA X-MAX50 250+ energy dispersive X-ray spectrometer. The representative mineral analyses are reported in Tables 2–4.

3.1. Sample A05-2 (MCTZ)

Sample A05-2 is a medium-grained pelitic schist, collected from the MCTZ. The preferred orientation of biotite, muscovite and kyanite defines the main foliation (S_m), which wraps around garnet porphyroblasts (Fig. 3a). Another generation of muscovite is