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The nature and evolution of the Main Central Thrust: Structural and geochronological constraints from the Sikkim Himalaya, NE India

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ABSTRACT

The Main Central Thrust (MCT) is a prominent continental-scale fault within the Himalaya. Its definition has been the topic of some debate in the literature. After a brief consideration of the state of discussion to clarify the definition we use in this work, we report features from the field- to the microstructural- scale of a particularly well-exposed section in Sikkim, NE India. The nature of the protoliths as well as the overlying and underlying rocks is characterized in terms of ε-Nd. The dates of motion on the fault are constrained using U–Pb geochronology of zircon and monazite from pegmatitic dikes that cross-cut the deformation fabric. It is found that the mechanism of deformation recorded in the fault zone rocks is different compared to that found in the overlying Greater Himalayan (GH) or the underlying Lesser Himalayan (LH) rocks. The GH and LH have different protolith characteristics as well. Combined with existing data on P–T history, dates of metamorphism, and cooling- and exhumation-rates of the GH and the LH, our measurements show that major motion on this fault occurred before 20 Ma at 450–700 °C but after peak metamorphism of rocks (750–800 °C) in this zone. Isolated events occurred in this zone as late as 11 Ma, possibly in the brittle domain. This underscores the pulsed nature of movement over an extended period on such major faults, and the related difficulties in dating fault movement, determination of the rates of movement, and designating a fault plane as in- or out-of-sequence within a propagating deformation front.

1. Introduction

In spite of the multi-disciplinary attention that has been focused on the Himalayan range, there remain many first order questions that need to be clarified. One of these questions is: what is the nature (definition, location, nature and timing of movement, and metamorphic implications) of the prominent range-scale fault related structures (such as the Main Central Thrust), that are considered to be intracontinental thrusts (e.g. Valdiya, 1980)? The question is significant beyond issues of regional structural and stratigraphic correlations and nomenclature. The significance stems from the intimate association of the MCT with the metamorphic evolution, and through that, with the thermal structure and evolution, of this prototype collision zone. Reconstructing the thermal history and nature of motion on this fault zone is therefore central to the understanding of the evolution of collision zones in general. We use data from Sikkim in NE India to address this issue.

The Main Central Thrust (MCT) was recognized and named by Heim and Gansser (1939) in their pioneering studies on the Himalayan range and has found its way into textbooks in a number of sub-disciplines of geology (e.g. see Kearey et al., 2009; Moores and Twiss, 1995; Rogers et al., 2007; Winter, 2001). Since the original coining of the name, however, the definition has evolved and there is an ongoing discussion and debate related to the criteria used to recognize and define this structure in different segments (locations along the lateral extent) of the Himalayan range. In a fold-thrust belt where faults are not hard to find, features such as splaying, duplexing and thrust-stacking are expected and common, and intensity and style of deformation vary along the lateral extent, disagreements have led to such compromise

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solutions as the definition of a MCT-I and a MCT-II (e.g. Arita, 1983; Valdiya, 1980), or of a broad Main Central Thrust Zone (MCTZ) (Hodges et al., 1996; Stephenson et al., 2001). Some recent studies have attempted to consolidate the arguments and come up with suitable criteria for a definition of MCT (e.g. Martin, 2016; Martin et al., 2005; Searle et al., 2008), but they reached different conclusions. Both groups of authors agree that a thrust (or a thrust zone) is characterized by "the identification of a strain gradient and clear localization of strain" (Searle et al., 2008, citing Hanmer and Passchier, 1991; Passchier and Trouw, 2005) or almost equivalently, "a region of maximum in shear strain" (Martin et al., 2005). Martin et al. (2005) recall the definition of MCT given by Heim and Gansser (1939) as "a south-vergent thust fault that places Greater Himalayan [GH] metasedimentary rocks on Lesser Himalayan [LH] metasedimentary rocks along a sharp contact". They interpret this definition to have two components: (1) MCT as a south-vergent shear zone, and (2) MCT as a tectonostratigraphic boundary between greater- and lesser Himalayan rocks. It is the second part of the definition that causes differences. In sedimentary rock sequences, stratigraphic inversion is the most important criterion for recognition of thrust faults on both ramps and flats unless thrusting affects an already deformed sequence (e.g., Tertiary rock sequences such as Subathu–Dharamshala–Siwalik Groups in the western Himalaya, Mishra and Mukhopadhyay, 2012). The main problem of recognition of thrusting in metamorphic rocks in the Himalaya (and elsewhere), is that one loses the unequivocal stratigraphic relations because stratigraphy in metamorphic rocks is usually uncertain and faulting affects rocks that are already deformed. The only way to recognize a fault *within* metamorphic rocks is then to find fault rocks: cataclasites in brittle faults and mylonites in ductile shear zones (Killick, 2003; Sibson, 1977), a strategy recommended by Searle et al. (2008). They also observe that although a thrust fault is a structural element, "*very few papers incorporate any structural data in justifying the position of the MCT*" (Searle et al., 2008), a situation first pointed out by Le Fort (1975). Searle et al. (2008) draw on evidence from different regions of the Himalaya as well to argue why the stratigraphic component of the definition may be problematic; they also argue convincingly why other criteria that have often been used in the literature e.g. metamorphic grade (kyanite isograd) or age of metamorphism (e.g. monazite dates) are problematic for demarcating a thrust. Martin et al. (2005), on the other hand, advocate the use of stratigraphic criteria (protolith boundaries, as identified through isotopic work) combined with the location of a maxima in shear strain as the means for distinguishing one fault among many as the MCT and show that this definition coincides with the faults originally termed MCT by Heim and Gansser (1939). This approach requires, however, the coincidence of protolith boundaries and maxima in shear strain, and the question arises whether this is always obtained. Martin et al. (2005) found such a continuously mappable boundary in five different transects in Nepal, including one of the sections (the Kali section) originally used by Heim and Gansser (1939) to coin the term *Main Central Thrust*, and Imayama and Arita (2008) found this to be the case in other sections of Nepal. Martin (2016) considers other, more recently proposed definitions as well (e.g. based on age of movement on the fault — Webb et al. (2013)) and concludes that the definition of Martin et al. (2005), in spite of having a few shortcomings, may be the most pragmatic. Our results from this study (see below) provide further reasons why an age-of-movement based definition of a fault may be problematic.

A major fault on a continental scale has many facets and one can consider it from different perspectives, some of which are illustrated in Fig. 1. For large-scale faults (both reverse and normal), the nature of deformation is expected to change along the fault plane where viscous behavior at depth grades to more brittle behavior at shallower levels (Ramsay, 1980), and different levels may be exposed in different segments along the strike of the belt (Fig. 1). Knipe (1990) provides an example in the Moine Thrust and Searle et al. (2008) and Yin (2006) discuss such aspects in the context of the MCT. This poses a challenge for the lateral correlation along the strike of the fault based on exposures at different levels. In the case of large, continental scale faults, an alternative to the study of the fault zone rocks themselves is the study of the thermal imprint of such faults on their hanging- and foot-walls. This was explored in the classic studies of England and Thompson (England and Thompson, 1984; Thompson and England, 1984). When metamorphism is caused by thrusting along such a fault, the P–T paths of rocks on the hanging- and footwall follow very specific geometries (Fig. 1) and bear specific temporal relations to each other. More complex thrusting scenarios yield different P–T-t paths for the hanging- and foot-walls (e.g. Herman et al., 2010), but there is always a relationship between the two. So, if P–T-t paths of metamorphism of hanging wall and foot wall rocks are known, these can be used to evaluate the connection between motion on the fault and metamorphism using thermal models (e.g. those of England and Thompson or later generation, more sophisticated models). Thus, an ideal situation for the study of such faults is when both kinds of information are available – the P–T-t paths of the hanging wall and footwall rocks, as well as the history recorded in the fault zone rocks themselves.

The rock sequence exposed in Sikkim (NE India) provides an excellent natural laboratory to study the nature and evolution of the MCT because P–T-t paths of the units above and below the fault zone are available. Exposures in Sikkim allow a clear high strain zone, along with protolith relationships to be identified and studied. At least along a central N–S transect it is possible to independently locate a mechanical thrust fault (earlier mapping as well as this work, see below for details) as well as a geochemical protolith boundary (Mottram et al., 2014a, this work). The mechanical and stratigraphic (protolith) boundaries coincide in a manner that allows us to revert to the original definition of Heim and Gansser (1939) of the MCT as the boundary between high grade migmatitic and lower grade metamorphic rocks. This fault within the metasedimentary sequence shows a "recess" in map pattern allowing the orientation relationships between the fault plane and the metasedimentary units to be studied as orientations change toward the east and west, with the exposures enhanced by the formation of a domal structure (Teesta dome). Finally, the metamorphic sequence above and below this fault zone is an exceptionally complete and well-preserved sequence of metapelites in which determination of P–T conditions are possible. Detailed P–T-t (dates as well as durations) history of these rocks is now available and has been reviewed in Chakraborty et al. (2016).

The objective of this paper is to present information on the fault zone rocks themselves (field relations, microstructural data, nature of protolith, and geochronological data) and to combine these with the available P–T-t histories of the hanging wall and footwall rocks to better understand the nature of motion on the MCT. In a companion paper (Chakraborty et al., 2017) we use this evolutionary history in combination with structural, geophysical and geodynamic constraints to define the 3D geometry of the system and address the debate on large scale tectonic style in the Himalaya (and by implication, other collisional orogens): channel flow, or localized fault-bounded slice tectonics (LFBST)?

2. The Main Central Thrust Zone in Sikkim

2.1. General description with field and petrographic observations

The problem of definition of the MCT is well illustrated by the example of Sikkim. In Fig. 2a we show the different locations where the MCT has been plotted by different authors in Sikkim (see figure caption for details). On the N–S transect along the Teesta valley it is possible to map (Fig. 2) a prominent shear zone between the Daling–Paro Group and the Darjeeling Group that also coincides with a protolith discontinuity (identified on the basis of isotopic signatures). This zone is marked by (a) the occurrence of a garnetiferous granitic gneiss (termed the *Chungthang gneiss* here), (b) mylonites (Fig. 3), and (c) difference in