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Thermal characteristics of the Main Himalaya Thrust and the Indian lower crust with implications for crustal rheology and partial melting in the Himalaya orogen

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ABSTRACT

The Main Himalaya Thrust (MHT) is the current tectonic boundary between the subducting Indian lithosphere and the overlying Himalayan orogenic prism and the Tibetan crust. We present thermo-kinematic calculations and metamorphic P–T–t paths of the Indian lower crust (ILC) that constrain the thermal structure of the MHT and the southern Tibetan crust (Lhasa Block) and explain the origin of a thin, seismic low velocity zone that was revealed by the recent Hi-CLIMB experiment from receiver functions of teleseismic waves. Northward of the Himalayas, the low velocity zone occurs within the ductile regime of the crust and is thought to extend along the MHT into the Lhasa Block. In the Lhasa Block, the low velocity zone occurs directly above the ILC. Predicted evolution of mineralogy of the ILC along its subduction P–T–t path shows that its dehydration can potentially induce wet melting within the orogenic prism above the inclined portion of the MHT. However, north of the Yarlung Tsangpo Suture (YTS) below the southern Lhasa Block, where subduction of the ILC is flat, the ILC is predicted to be anhydrous eclogite and therefore, it cannot supply H_2O to the overlying crust. The seismic low velocity zone above this portion of the ILC is best explained by dehydration melting due to strain heating. The MHT there appears to be localized by the rheological contrast between the ductile lower Lhasa Block and the strong eclogitic ILC.
Southward thrusting of the Himalaya orogenic prism, which contains accreted Indian upper crust, causes advection of hot middle-crustal rocks to shallower levels, thereby producing a shallow ductile regime between the Himalayas and the YTS. The shallow ductile regime is evident in the limit of upper crustal earthquake foci to shallow depths in this region.

1. Introduction

The Earth's largest orogen, the Himalayas, preserves structures that have evolved since the incipient collision of India with Eurasia about 50 Ma ago. The collisional front has moved southward from the Yarlung Tsangpo Suture (YTS) to the present-day Main Himalaya Thrust, which is exposed in the Siwalik Hills of southern Nepal (Lavé and Avouac, 2000). In its wake, the front has left the Himalayan orogenic prism that consists of variably metamorphosed crustal slices (Hodges, 2000; Yin and Harrison, 2000). Understanding the present-day thermal structure of the Himalaya orogen is essential for explaining the depths of earthquakes, surface heat flow, and partially molten regions within the crust that have been imaged by various geophysical techniques. In this contribution, we examine several thermo-kinematic numerical models that show the plausible thermal and rheologic structures of the Himalaya orogen and the underlying Indian lower crust (ILC). The models are based on the detailed structure of the Himalaya orogen that was revealed by the recent Hi-CLIMB seismic experiment (Náběleket al., 2009).

The Hi-CLIMB seismic experiment deployed an array of 233 densely spaced seismometers from the 27° N to the 34° N latitude (Náběleket al., 2009). The structure of the lithosphere was imaged from receiver functions of teleseismic body waves. The data show the Moho dipping from the 44 km depth (relative to sea level) beneath India to the depth of 70 km at the YTS, and then it continues horizontally up to approximately the 31° N latitude, or perhaps up to the Banggong–Nujiang Suture. A narrow low velocity zone, interpreted to define the location of the MHT, occurs at shallow depths under Nepal and then it abruptly steepens

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from about the 15 km depth at the 28.5° N latitude to about the 55 km depth at the latitude of the YTS and then continues horizontally beneath the Lhasa Block to the 31° N latitude, interpreted to be the northernmost extent of the Indian crust. The low velocity zone is characterized by a sharp decrease is P-wave velocity from ~6.1 to 5.8 km/s. (The low velocity zone is shown as a stippled region in Fig. 1a and Figs. 2b–e.) Along the deep, flat portion of the subduction, the low velocity zone occurs directly above the ILC, which is thought to be eclogitized (Hetényi et al., 2007). Although in deep parts of the crust the low velocity zone could be attributed to partial melting, the receiver functions do not make this interpretation unique (Nábělek et al., 2009). There is no evidence in the Hi-CLIMB data for extensive partial melting in the Himalaya orogenic prism and the Lhasa Block, except for possible melt lenses at the 20 ± 10 km depth below sea level in the upper Lhasa Block. A gap in earthquake foci between the shallow crust and the ILC, from the Greater Himalayas to the YTS, indicates that the mid-crustal ductile regime extends here to shallow depths (Monsalve et al., 2006; Nábělek et al., 2011).

We use the thermo-kinematic modeling and predicted metamorphic P–T–t paths for the ILC to explore the origins of the <20 km thick seismic low velocity zone along the MHT. We test the proposed hypothesis that the low velocity zone could be a partially molten region in the orogenic wedge and the Lhasa Block. In addition, we model the kinematics of the orogen to explain the shallow ductile region between the Himalayas and the YTS, and we explore how elevated radiogenic heat production in the crust would influence the distribution of partial melting in the upper crust (cf. Beaumont et al., 2001; Huerta et al., 1998). In the examined models we strive to reproduce the inferred extent and location of the seismic low-velocity zone as imaged by the Hi-CLIMB experiment because they constrain its origin, and consequently the thermal structure in the vicinity of the MHT. We use published earthquake locations in particular to constrain the rheological structure of the crust, which is one of the outcomes of the thermo-kinematic models. We use published surface heat flow measurements, magnetotelluric data, and gravity data for eclogitization of the ILC to support our best model. Determining the metamorphic P–T–t paths of the subducting ILC is essential for constraining the origin of the seismic low velocity zone above it.

2. Model domain and initial conditions

The model domain reproduces the interpreted structure of the lithosphere from 50 km south of the MHT surface exposure to 450 km north of the exposure and includes topography (Fig. 1). The lithospheric boundaries in the domain correspond exactly to the interpreted boundaries from the seismic data (Nábělek et al., 2009), but extend for additional 20 km to the north of the evident extent of the low velocity zone and the ILC. Furthermore, due to heat transfer requirements noted below, in the presented models the MHT (the zone of localized shear and subduction boundary) was placed at the bottom of the seismic low velocity zone. With this geometry the Indian upper crust (IUC) becomes pinched-out before it reaches the YTS, after which the MHT becomes the boundary between the Lhasa Block and the ILC. In agreement with previous studies (e.g., Huerta et al., 1998; Nábělek et al., 2009), this geometry implies that there is mass transfer from the IUC into the Himalaya orogenic prism. In the model, the transfer occurs along the whole inclined portion of the MHT because the dip of the MHT is greater than the angle of subduction. The amount of mass transfer decreases northward as the IUC becomes progressively thinner. Other essential features of the numerical solutions, parameters, and boundary conditions are given in the supplementary materials.

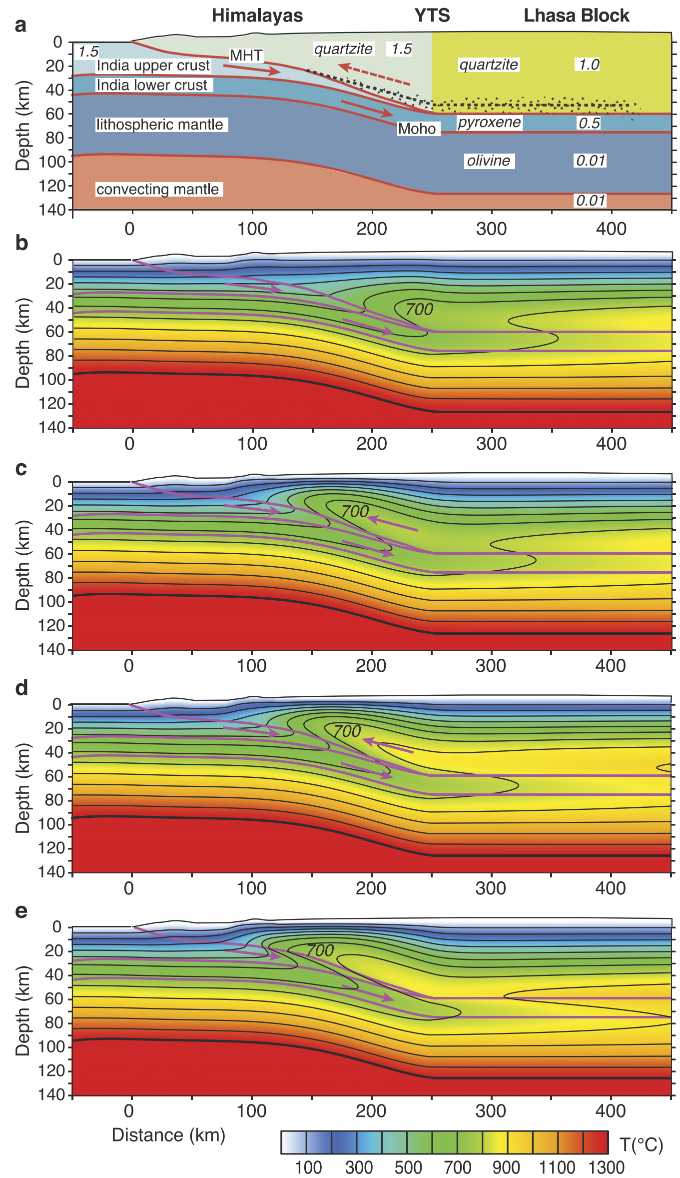

Fig. 1. Model domain (panel a) and calculated lithospheric temperature fields. The model domain is based on the crustal structure interpreted from teleseismic data (Nábělek et al., 2009). Italics show radiogenic heat production values and minerals whose rheological flow laws were applied (supplementary materials). The stippled region is the imaged seismic low velocity zone. Black dashed line is the assumed location of the MHT within the low velocity zone by Nábělek et al. (2009). Location of the MHT in the present contribution is shown by a red line, as are other lithospheric boundaries. Zero distance for the model domain is set at the intersection of the MHT with the surface. Panel b shows the initial steady-state conditions, assuming subduction of the Indian lithosphere beneath the Himalaya and Tibet at 1.5 cm/a (endmember model). Contour interval is 100 °C with the 700 °C contour marked for reference. Panel c shows the steady-state temperature field for Model 1 with both subduction (1.5 cm/a) and southward thrusting of the Himalaya orogenic prism (0.5 cm/a). Panel d shows the steady-state temperature field for Model 2 with the same parameters as Model 1, except for 2 $\mu W/m^3$ radiogenic heat production in the IUC, the orogenic prism, and the Lhasa Block. Panel e shows the steady-state temperature field for Model 3, which has the same parameters as Model 1, except that it also includes strain heating along the MHT. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The convergence rate between India and Asia is thought to have slowed down approximately 17 Ma ago and then has become constant ~11 Ma ago (Molnar and Stock, 2009). The current convergence rate between India and the latitude of Lhasa is ~2 cm/a (Avouac, 2008; Jouanne et al., 2004). Of this rate, approximately 1.5 cm/a is attributable to the subduction of the Indian