Magnitude of Strain in a Low-Grade Greater Himalayan Section, Central Bhutan: Implications for Channel Flow

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The recognition of potential crustal melt under the Tibetan plateau, in conjunction with ubiquitous partial melt textures and shear indicators within the Greater Himalayan (GH) sequence has led to the development of kinematic and numerical models that argue for the southward extrusion of weak crust between the Main Central Thrust (MCT; top-to-south) and the Southern Tibetan Detachment (STD; top-to-north). This ductile extrusion of the GH section driven by gravitational potential energy of the Tibetan plateau and focused erosion along the topographic front, may be as great as 400-600 km (e.g. Jamieson and others, 2006), implying coeval and roughly equal displacements across the MCT and STD. However, seemingly pervasive ductile deformation within GH rocks and a lack of exposed cut-offs for the MCT and STD have hindered efforts of evaluating the magnitude of extrusion through field studies. We present geologic mapping, stratigraphic columns, metamorphic mineral assemblages, and structural and strain data from GH and TH rocks in central Bhutan, which allow us to quantify the magnitude, direction and temperature of deformation. These data collectively argue for: 1) a depositional contact between the TH and GH sections in central Bhutan, and 2) the presence of a low-grade GH section in central Bhutan that exhibits the kinematic profile of a channel. Our observations contribute to the channel flow debate by 1) placing constraints on the magnitude of displacement on a portion of the STD, and 2) quantifying the maximum top-to-the-north component of channel flow through the upper part of the GH and TH section. While these data support a kinematic model of channel flow in central Bhutan, the magnitude of ductile extrusion of the GH section is minor (Long and McQuarrie, 2010).

In central Bhutan, the GH section is 5-10 km thick, and consists of a lower granitic orthogneiss unit and an upper metasedimentary unit, comprised of quartzite, schist, phyllite, and paragneiss (Fig. 1). The overlying TH section consists of quartzite and schist of the Chekha Formation, and phyllite of the Maneting Formation (Long and McQuarrie, 2010). Kyanite and partial melt textures are only observed in the lower-mid parts of the GH orthogneiss unit, and the overlying parts of the GH and TH sections are dominated by a melt-free, biotite-muscovite-garnet mineral assemblage (Long and McQuarrie, 2010). The basal-mid GH orthogneiss unit section was deformed at ~500°-700°C (grain-boundary migration quartz recrystallization; Stipp and others, 2002). An upsection transition to subgrain rotation quartz recrystallization, accompanied by K-feldspar recrystallization, indicates that the higher part of the GH section and full exposed TH section underwent deformation at temperatures between ~450°-500°C. Similar mineral assemblages and deformation temperatures that persist for several km structural distance across both sides of the GH-TH contact, combined with interfingering of distinct biotite-porphyroblast schist and quartzite across a significant structural thickness at the GH-TH contact, indicate that TH strata are in depositional contact above GH strata in central Bhutan (Long and McQuarrie, 2010). This stratigraphic contact is in contrast to observations in eastern Bhutan, where melt-free TH rocks are separated from GH rocks displaying partial melt textures by a top-to-the-north sense shear zone correlated with the STD (Grujic and others, 2002). Peak temperature conditions for GH rocks in eastern Bhutan are estimated at 750-800°C (Daniel and others, 2003). These data indicate a ca. 250°-300°C along-strike decrease in GH deformation temperature from eastern to central Bhutan (Long and McQuarrie, 2010). In central Bhutan, thin-section scale kinematic indicators in the composite GH-TH section fit the profile of an asymmetric channel, with a 2-3 km-thick section exhibiting a top-to-the-south shear sense at the base overlain by an ~11-km thick section exhibiting a top-to-the-north shear sense (Long and McQuarrie, 2010). Using the Rf-φ method, we quantified crystal-plastic strain of sand-size quartz porphyroclasts for 41 GH and TH samples. Two bedding- or foliation-perpendicular oriented thin sections were analyzed from each sample, with the XZ thin section cut parallel to lineation (~N-S trending) and the YZ thin section cut perpendicular to lineation (~E-W trending), allowing us to calculate 3-D strain ellipsoids (Fig. 1B). GH and TH rocks in central Bhutan show evidence for heterogeneous layer-normal flattening strain, with the XY strain plane deviating from bedding/foliation by median values of only 6° (N-S; Fig 1B) and 8° (E-W). We observe significant lithologic control on strain magnitude, with XZ and YZ elongations varying between 1.2-4.1 and 1.1-2.8 for quartzite, and between 1.6-8.5 and 1.4-3.8 for phyllite and schist. Layer-normal flattening strain can be approximated with median strain ellipsoids of 3.0:2.2:1.0 for phyllite/schist, 1.6:1.5:1.0 for quartzite, and 2.1:1.8:1.0 for all lithologies, with the X direction trending approximately N-S. Assuming only simple shear, integrating these median strain values across the 11-km thick section indicates that the top-to-the-north component of channel flow was between ~23-34 km. However, kinematic vorticity numbers range between ca. 0.0-0.7, with over half of analyses ≤0.4, indicating that pure-shear was the dominant strain mechanism with a simple shear component of only ~8-11 km. The stratigraphically-continuous GH-TH section discussed here limits slip on a portion of the STD system to ~20 km. A low-offset STD combined with a low-displacement channel have implications for the role of channel-flow processes in the Himalaya. We document a dramatic along-strike gradient in metamorphic grade from cool in central Bhutan to hot in eastern Bhutan. If these temperature gradients were matched by comparable changes in viscosity, there would be potential for significant along-strike differences in flow velocity and material transport. If the melt rich, potentially low-viscosity region experienced large magnitudes of flow, GH rock would have been emplaced on LH rocks as much as ~300 km south of its modern southern extent, or similar magnitudes of material would have to had been removed via erosion at the same time as extrusion. For erosion to keep pace requires rates of ~30-50 mm/yr and erosion to vary spatially with displacement gradients. We conclude that, when present, the magnitude of channel flow must be small with respect to the total mass balance of material in the system. In central Bhutan, the top-to-the-north component of channel flow represents <5% of the mass added by shortening within the Himalayan orogenic belt (Long and McQuarrie, 2010; Long and others, in press).

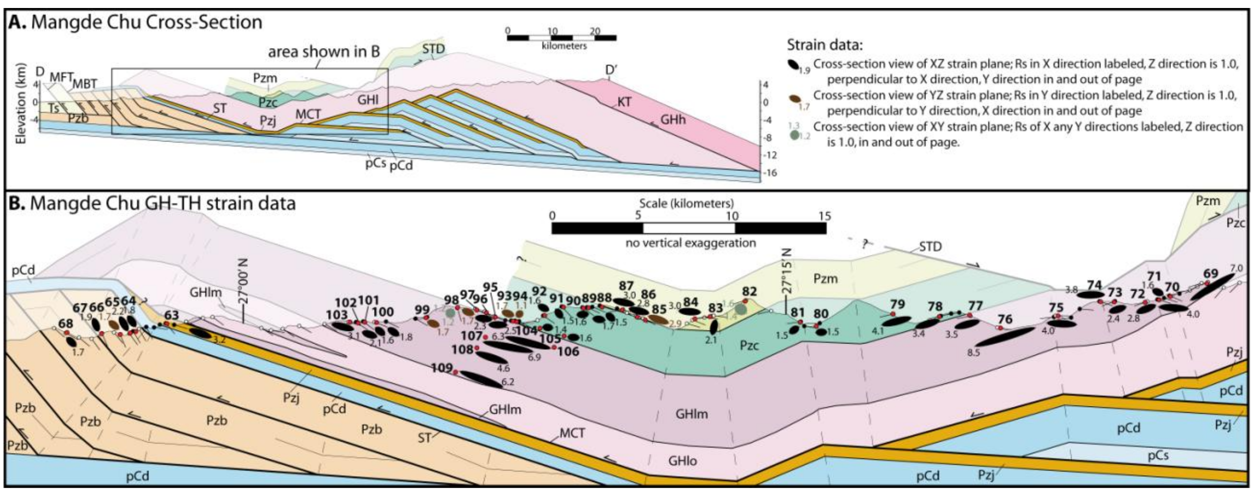

Figure 1. A) Mandge Chu cross-section, simplified from Long and others (in press). Unit abbreviations: pCs – Shumar Formation, pCd – Daling Formation, Pzb – Baxa Group, Pzj – Jaishidanda Formation, Ts – Siwalik Group, GHlm – Greater Himalayan metasedimentary unit, GHlo – orthogneiss unit, Pzc – Chekha Formation, Pzm – Maneting Formation. B) Inset showing strain data from GH and TH rocks on the Mandge Chu cross-section. Strain ellipses from N-S (generally XZ) thin sections are projected directly onto the cross-section.

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