Internal Strain and Deformation Temperature of Lesser Himalayan Thrust Sheets, Bhutan

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Analysis of quartz deformation microstructure in concert with quantification of crystal-plastic strain of quartz clasts constrains deformation temperature ranges and internal strain magnitude and orientation within thrust sheets of Subhimalayan (SH) and Lesser Himalayan (LH) rocks in eastern and central Bhutan. Quantifying strain geometry and magnitude provides a better understanding of the 3-D evolution of deformation, allows assessment of the relative contribution of internal strain to large-scale deformation, and illuminates the sequential development of strain patterns.

The LH zone displays an inverted gradient in metamorphic grade (Gansser, 1983) and deformation temperature between the MBT and MCT (Fig. 1A). From foreland to hinterland, deformation temperatures constrained by quartz recrystallization microstructure (e.g. Stipp et al., 2002) show that: 1) thrust sheets of the Permian Diuri Formation and Permian Gondwana succession were deformed at ca. 250-310ºC (transition to bulging recrystallization); 2) multiple horses of the Neoproterozoic-Cambrian(?) Baxa Group in the upper LH duplex were deformed at temperatures between ca. 280º-400ºC (bulging recrystallization), with Baxa strata just under the Shumar Thrust (ST) recording deformation temperatures up to ca. 450 ºC (subgrain rotation recrystallization); 3) deformation temperatures of horses of the Paleoproterozoic Daling-Shumar Group and Neoproterozoic-Ordovician(?) Jaishidanda Formation in the lower LH duplex increase from ca. 400-450ºC (subgrain rotation recrystallization) at the ST to ca. 500-670ºC (grain-boundary migration recrystallization, combined with ca. 640-670ºC garnet peak temperatures; Daniel et al. [2003]) at the MCT, with the majority of the change (ca. 140-170ºC) occurring within ca. 350 m of the MCT. Thus, the LH inverted deformation temperature gradient can be attributed to: A) stacking of discrete thrust sheets of upper LH rocks below the ST that were deformed at progressively higher temperatures (and presumably depths) toward the hinterland, and B) the 'hot-iron' effect of the MCT hanging wall, which only affected thrust sheets of the lower LH duplex above the ST. The repetition of stratigraphy (Long and others, in press), metamorphic isograds, and inverted temperatures emphasizes the discrete stacking of thrust sheets of lower LH rocks between the ST and the MCT.

3D strain ellipsoids were determined by quantifying the elongation and orientation of strained sand-size quartz clasts for 68 SH and upper LH samples, using the Rf-φ and Normalized Fry methods. In general, 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). In eastern Bhutan, the XY strain plane of ellipsoids from foreland thrust sheets of the Baxa Group, Gondwana succession, and Siwalik Group are oriented at moderate to high angles (θ', the angle between the X direction and bedding/foliation, ~45-90º) to bedding, and exhibit Rs (tectonic ellipticity) values between ~1.1-1.2 (n=7). This is indicative of low-magnitude (~7%) layer-parallel shortening (LPS) strain. Further to the hinterland, upper LH map units, including the Diuri Formation thrust sheet and multiple horses of the Baxa Group in the upper LH duplex, exhibit layer-normal flattening (LNF) strain, with the XY strain plane oriented subparallel to bedding or tectonic foliation. Baxa Group quartzite and phyllite show similar strain magnitude.

We propose the following sequential development of strain patterns. First, low-magnitude (7%) LPS strain developed foreland-ward of the thrust deformation front (Fig. 1B-D) as seen in frontal thrust sheets in eastern Bhutan. Previous studies have suggested that LPS strain initiates from an increase in burial depth (and corresponding temperature) from subsidence and sedimentation in the foreland basin, and/or an increase in deviatoric stress near the leading edge of the approaching thrust wedge (e.g. Yonkee and Weil, 2009). We interpret the transition from LPS to LNF strain observed further to the hinterland as the result of tectonic loading due to emplacement of thick overriding thrust sheets (Fig. 1B, C). As deformation propagated toward the foreland, the record of early LPS fabrics in hinterland units, if it was ever present, was overprinted by higher-magnitude LNF fabrics when units were tectonically buried (Fig

1B-D). The transition between low-magnitude (Rs~1.1-1.2) LPS and higher-magnitude (Rs~1.8-2.0) LNF strain occurs approximately at the lower temperature limits for crystal-plastic quartz deformation (ca. 250-270ºC), which illustrates the strong control of deformation temperature on strain magnitude and orientation. Thrust sheets comprised of quartz- or mica-rich rocks above this temperature range were sufficiently weak enough due to loss of shear strength to cause far-field tectonic stresses oriented at a low angle to layering to rotate into a layer-normal orientation (e.g. Means, 1989). The bedding/foliation-subparallel orientation of the XY strain plane for the LNF ellipsoids persists regardless of dip angle and dip direction at any given location. The orientations of the LNF ellipsoids are folded to the same degree as the thrust sheets in which they lie, which indicates that LNF strain preceded thrust imbrication and southward translation. LNF strain observed in Baxa Group horses (upper LH duplex) is attributed to burial and loading from emplacement of lower LH thrust sheets (lower LH duplex), which in turn were loaded by the GH-TH section (Fig. 1C). Subsequently, deformation became localized along thrust faults, as these previously-strained rocks were imbricated and translated in thrust sheets separated by discrete fault zones (Fig. 1C, D). After thrust emplacement, strata retaining older LNF fabrics were then passively folded and translated as thrusting propagated toward the foreland, creating the upper LH duplex (Fig. 1C, D). A lack of increase in Rs with decreasing structural distance above thrusts in the upper LH duplex supports the interpretation that LNF strain pre-dated thrust imbrication and translation. This indicates that significant internal strain did not extend outside of fault zones during thrusting, which requires that fault zones were significantly weaker than the previously-strained rocks carried in their hanging wall. This supports the existence of discrete faults with large translations, as generally depicted in balanced cross-sections, even when the rocks within the thrust sheets have undergone significant internal strain.

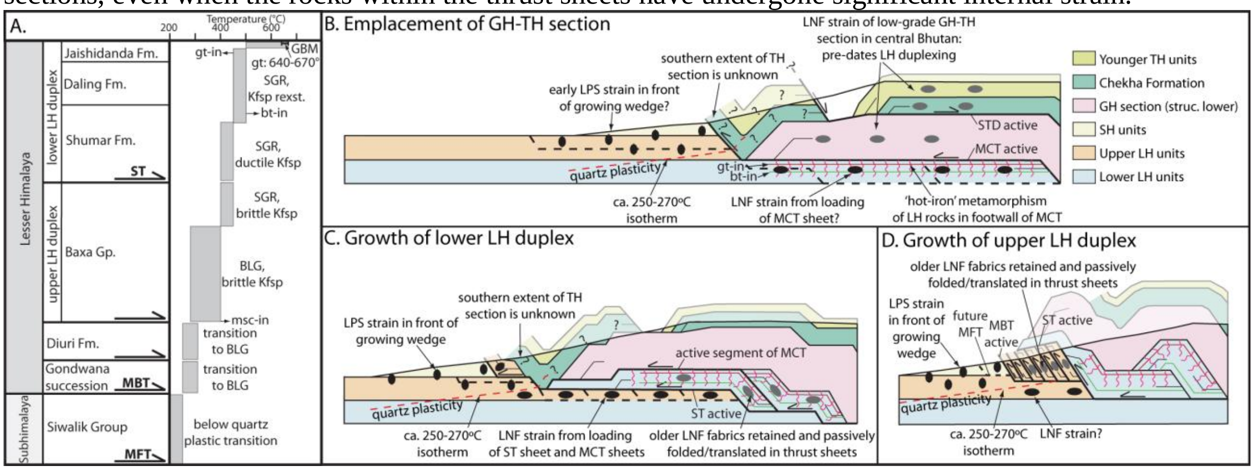

Figure 1. A) Deformation temperature profile through Bhutan SH and LH zones. Quartz recrystallization abbreviations: BLG - bulging, SGR – subgrain rotation, GBM – grain-boundary migration. B-D) Schematic cross-sections illustrating sequential development of strain patterns during specific deformation increments. Layer-parallel shortening (LPS) strain in SH and upper LH units in front of the growing wedge preceded layer-normal flattening (LNF) strain of LH units that accompanied tectonic burial. LNF strain occurred at temperatures above ca. 250-270ºC (quartz plastic transition). LH thrust sheets retaining LNF fabrics were then translated, folded and exhumed by motion along discrete thrust faults.

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