Deformation of the Greater Himalayan Sequence, Garhwal Himalaya via Sheath Folding and Late-Stage Brittle Extension: Implications for Channel Flow

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Fold axes within the Greater Himalayan Sequence from the Garhwal region of India display nearly 150º of variability to the general assumed transport direction based on mineral stretching lineation and fold asymmetry data (Figure 1). Previous studies report fold axes that cluster in two distinct populations separated by 90º with an overall spread of 150º (Gairola and Srivastava, 1987; Vannay and Grasemann, 2001). This geometry was interpreted by these authors as evidence for two deformational events oriented ~90º apart. One of these deformational events would have a maximum stress oriented parallel to the current strike of the range. Because the major rivers of the Garhwal Himalaya cross the Greater Himalayan Sequence approximately perpendicular and parallel to the overall strike of the range, the majority of exposed outcrop is oriented in these two directions. This access and exposure bias may explain why previous measurements cluster in two distinct populations. Our investigation of structures throughout the region shows a spread of fold hinge-line trends ranging ~150º with axes trending from NW to SSE (Figure 1). The spread of fold hinge-line orientations is consistent with observations of sheath folds observed at several different scales. Sheath folds are characterised by curvilinear axes that are progressively rotated by general shear from high angles to the transport direction into parallelism with the transport direction (Figure 2). Stretching and/or mineral lineation is nearly parallel to the fold axes and reflects the direction of flow. This relationship is also documented in Himachal Pradesh (Vannay and Grasemann, 2001) and the Pakistani Himalaya (Treloar and others, 2007).

The Greater Himalayan Sequence is dominantly defined by top-to-the-south ductile flow and is bounded above by the South Tibetan Detachment and at the base by the Main Central Thrust. The antithetic shear sense of these bounding faults facilitate SW extrusion of the Greater Himalayan Sequence. Isoclinal to recumbent structures associated with sheath folding are found throughout the Greater Himalayan Sequence with the highest amount of strain localized at the Main Central Thrust. Most folds are top to the SW with the exception of folds those found near the South Tibetan Detachment, which are top to the NE. The opposite vergence directions of folds at the base and top of the Greater Himalayan Sequence are consistent with ductile extrusion of the Greater Himalayan Sequence while both the Main Central Thrust

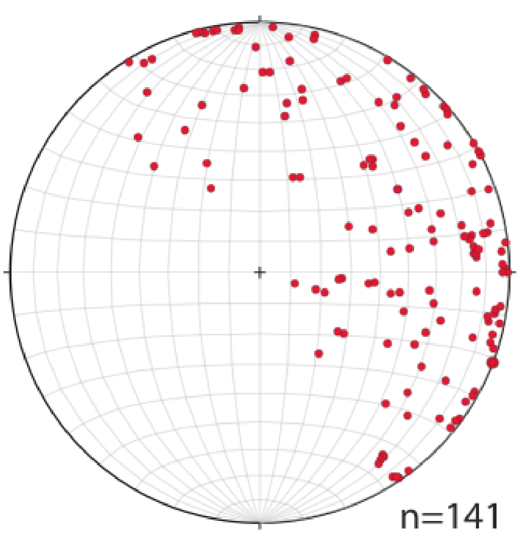

Figure 1: Stereographic plot of fold axes measured throughout the Greater Himalayan Sequence. Variation in fold axes is due to the curvilinear nature of fold axes within sheath folds.

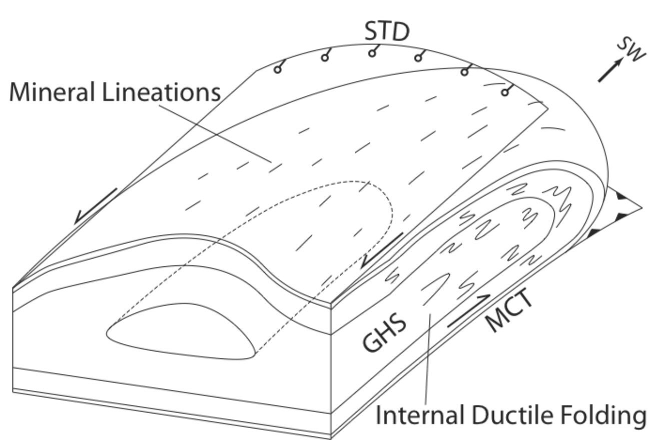

Figure 2: Idealized 3D cross section throught the Greater Himalayan Sequence showing the formation of sheath folding as the result of ductile shear along the Main Central Thrust and the South Tibetan Detachment. Dominant mineral lineation is oriented in the direction of flow (after Searle and Alsop, 2007)

and South Tibetan Detachment were active.

The ductile deformation of the Greater Himalayan Sequence was following by a brittle extensional phase. This extensional phase is expressed throughout the Greater Himalayan Sequence and into the Lesser Himalayan Sequence and Tethyan Himalayan Sequence as conjugate fractures and normal faults. The frequency of these features increases up structural section toward the South Tibetan Detachment. Conjugate fractures and en echelon fracture arrays exhibit a vertical $\sigma 1$ and $\sigma 3$ predominately toward the NE. Normal faults are mostly top down to the NE with minor normal faults with top down to the NW. Lesser amounts of conjugate fractures and normal faults are oriented north-south to northeast-southwest. These extensional features might represent orogen perpendicular extension resulting from the Indo-Asian collision as discussed by Kapp and Guynn (2004). The top of the Greater Himalayan Sequence is bounded by the brittle South Tibetan Detachment and juxtaposes unmetamorphosed Tethyan Himalayan Sequence with migmatitic grade Greater Himalayan Sequence.

Our study indicates that despite the similarities between a sheath-fold model and the channel-flow model, the uniform brittle structures that cross major tectonic boundaries can not be explained by channel flow. The most recent brittle exhumation appears to have been controlled by wedge-taper-adjustment normal faults. It also shows that the zone of hinterland extension in the Garhwal Himalaya is much broader than previously reported. This implies that the amount of extension across the range may be underestimated.

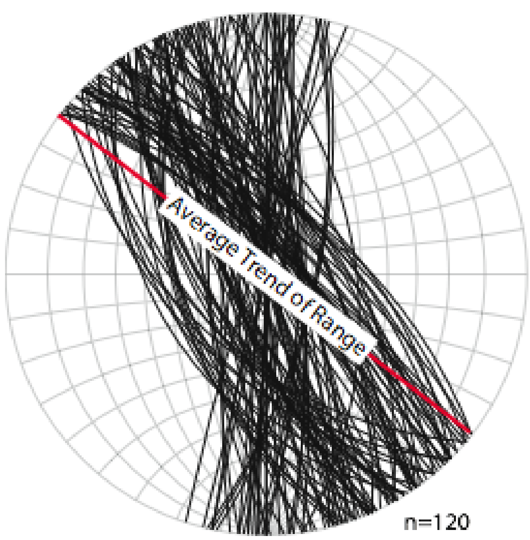

Figure 3: Stereographic plot of conjugate fractures trending nearly orogen parallel.

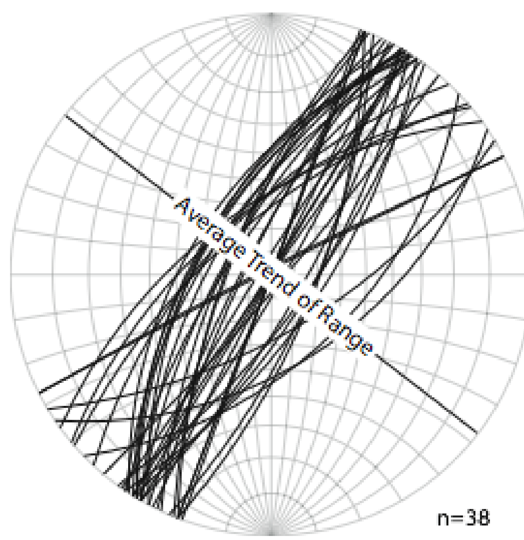

Figure 4: Stereographic plot of conjugate fractures trending nearly orogen perpendicular.

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