

## **CWU Thesis Proposal**

### ***Timing of slip along the Zaskar normal fault, Greater Himalayan Range, NW, India: Constraints from apatite and zircon (U-Th)/He thermochronometry***

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#### **Hypothesis**

I propose to document the timing and slip along the Zaskar fault, a moderately northeast-dipping northwest-striking normal fault bounding the northeastern flank of the Greater Himalaya Range, India using low-temperature (U-Th)/He thermochronology. The Zaskar fault is the far western extent of the ~2200 km long South Tibetan Detachment System (STDS), a shallow north dipping normal sense shear zone. The Zaskar Shear Zone (ZSZ) fault is unique in that it accommodates extension parallel to contractional deformation due to the collision between India and Asia (Figure 1) (Herren, 1987; Searle, 1986). Along this segment of the STDS, the Zaskar fault juxtaposes unmetamorphosed to weakly metamorphosed Tethyan sediments in the hanging wall upon metasedimentary, igneous, and migmatites of the Greater Himalaya Sequence (GHS) in its footwall (Figure 2) (Searle, 1986, and references therein). Structurally below the STDS and defining the base of the GHS is the Main Central Thrust (MCT) fault. Thrust fault slip history along this north-dipping thrust-fault zone, which accommodated much of the Indo-Asian convergence, is broadly synchronous with slip along the STDS. Geochronologic data from the central (Nepal) and eastern (Bhutan) segments of the STDS (Figure 1) indicate a normal slip history that is between ~23 Ma to ~12 Ma (Godin et al., 2006 and references therein). However, the timing of slip along the Zaskar segment of the STDS has long been debated (Harrison et al., 1997). Geochronologic data from the Zaskar region along the STDS suggest a normal slip

history between ~26 Ma (Dèzes et al., 1999; Robyr et al., 2002) and ~8 Ma (Kumar et al., 1995), somewhat younger than farther to the east.

The Zaskar fault near Padum, India displays well-developed triangular facets (Figure 3) suggesting that normal slip along this part of the STDS could be Pliocene in age or younger. If true, then this slip history is younger than what has been previously documented elsewhere along the ZSZ segment of the STDS. To test this hypothesis, I propose to use (U-Th)/He thermochronology, a low-temperature thermochronology dating technique, on rock samples collected from the footwall of the Zaskar fault. (U-Th)/He thermochronology on apatite and zircon grains will constrain the time-temperature cooling history of footwall rocks as they were exhumed, during normal slip, through temperatures of ~180-60°C. Apatite and zircon (U-Th)/He ages will allow me to document the timing of normal slip along the Zaskar fault, which will have spatial-temporal implications for the tectonic evolution of the Himalayan orogen.

### **Scientific Rationale**

The development of the ~2500 km long High Himalaya and high standing Tibetan Plateau is the consequence of the Eocene- Recent continental collision between Indian and Asian plates (e.g. Searle, 1986). This collisional margin, which marks the northward subduction of continental India beneath Eurasia, exposes a series of north-dipping low angle normal and thrust faults, the STDS and MCT, respectively. Slip along these faults, is parallel to the contraction between India and Asia (e.g. Burchfield & Royden, 1985; Herren, 1987; Searle, 1986). A wealth of geochronologic data indicates the STDS was active from the late Oligocene, maybe as earlier as late Eocene/early Oligocene (Lee and Whitehouse, 2007), to Late Miocene (Godin et al., 2006 and references therein). Normal slip along the STDS is broadly contemporaneous with thrust slip along the MCT (Godin et al., 2006).

To explain simultaneous slip along the STDS and MCT, Burchfiel and Royden (1985) proposed that the middle-crust formed a rigid wedge, bounded above and below by the STDS and MCT, respectively, that was extruded southward as a consequence of the gravitational collapse between the topographic high of Tibet and low elevation of India. More recently, the thermal-mechanical channel flow hypothesis was developed to explain the simultaneous normal slip movement along the STDS and thrust slip movement along the MCT (Beaumont et al., 2001, 2004). In this model, south-directed flow and exhumation of middle crust results from three components: low viscosity, a horizontal gravitational potential energy gradient between the high standing Tibetan Plateau and lowlands of India, and focused high rates of erosion along the southern flank of the Himalaya. Geochronologic data from along the STDS and MCT (Godin et al., 2006 and references therein) in connection with decreased sedimentation rates (Clift, 2006), suggest that channel flow had ceased by the middle Miocene due to the cessation of slip along Himalayan fault structures.

The ZSZ exposes well-developed triangular facets, suggesting normal slip as young as Pliocene, or maybe younger. If true, then this suggests that in this region of the Himalaya, channel flow continued after the middle Miocene or some other process drove normal slip along the ZSZ fault while slip along the STDS to the east had ceased.

### **Local Geology**

In the NW High Himalaya, the Zaskar fault is a shallow to moderate northwest-striking northeast-dipping ( $10-53^\circ$ ) (Epard and Steck, 2004) normal fault that extends ~600 km along the western segment of the STDS (Herren, 1987; Searle et al., 1992). Recent field studies of the Zaskar fault escarpment near Padum reveal accentuated and well exposed triangular facets. The fault juxtaposes unmetamorphosed to weakly metamorphosed Cambrian to Eocene Tethyan

sedimentary rocks in the hanging wall against high-grade metamorphic (amphibolite to migmatite) rocks of the GHS in the footwall (Herren, 1987; Searle, 1986). The GHS is composed of a Barrovian metamorphic series that record metamorphic grades from biotite- to sillimanite + K-feldspar in paragneisses associated with orthogneisses, minor mica schists, and metabasic rocks (Herren, 1987; Pognante, 1990; Searle et al., 1992). These footwall rocks are cross-cut by tourmaline-bearing leucogranitic sills and dikes (Dèzes et al., 1999; Searle et al., 2007). Kinematic analyses on footwall and hanging-wall rocks indicate a top down to the northeast sense of shear across the ZSZ (Dèzes et al., 1999; Herren, 1987; Searle et al., 1992)

### **ZSZ Slip History**

Previous geochronologic studies along the ZSZ segment of the STDS have utilized U/Pb (Dèzes et al., 1999), Rb/Sr (Inger, 1998),  $^{40}\text{Ar}/^{39}\text{Ar}$  (Dèzes et al., 1999), and fission-track (Kumar et al., 1995) dating methods with a closure temperature range of ~650-120°C to quantitatively document the timing of slip (Godin et al., 2006). Rb-Sr geochronology on metamorphic muscovite and biotite along the Zaskar fault yielded an age of ~26 Ma, which was interpreted by Inger (1998) as the initiation age of ductile extension in the footwall of the ZSZ. Metamorphic muscovite  $^{40}\text{Ar}/^{39}\text{Ar}$  and monazite U-Pb geochronology on leucogranitic rocks along the ZSZ led Dèzes and others (1999) to suggest that ductile shear in the footwall of the Zaskar fault occurred at a somewhat younger time period between 22.2-19.8 Ma, with brittle slip ending at ~19.8 Ma. Apatite fission-track geochronology on footwall rocks near Padum by Kumar and others (1995), yielded cooling ages between ~11.7-8.0 Ma suggesting a slightly older normal slip history than elsewhere along the STDS. Geomorphological observations of the well-developed triangular facets along the Zaskar fault zone imply that normal slip may be as young as Pliocene. To test this hypothesis, I will complete (U-Th)/He thermochronology on apatite and

zircon taken from ZSZ footwall rocks to document the low-temperature cooling history. Apatite and zircon (U-Th)/He thermochronology has not been applied to this segment of the STDS to evaluate its low-temperature cooling history.

### **Proposed Research**

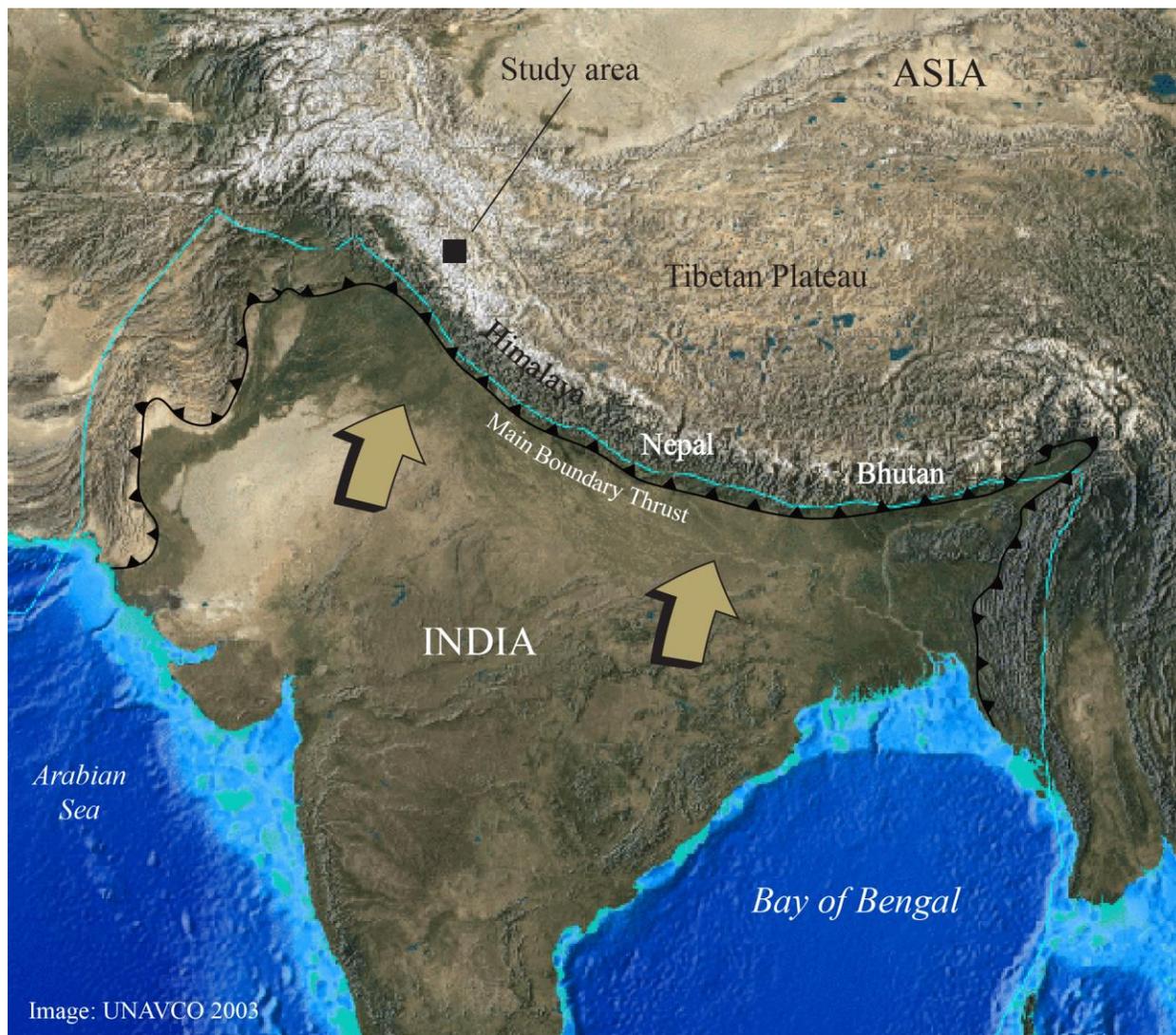
To test my hypothesis, I will apply low-temperature (U-Th)/He thermochronology on zircon and apatite grains separated from samples obtained from the footwall of the Zanskar fault. Samples were collected at ~50 m intervals along three vertical transects up the Zanskar triangular facets (the escarpment) between elevations of ~3722 m and ~4650 m (Figure 4). (U-Th)/He dating of apatite and zircon is an effective and well-established low- to moderate-temperature thermochronometric technique used to quantify the low-temperature cooling and exhumation history of exposed footwall rocks along a normal fault (Reiners et al, 2005; Stockli, 2005; and references therein). The closure temperatures for (U-Th)/He in zircon and apatite are ~185°C and ~70°C, respectively, and with partial retention zones that are ~190-130°C and ~80-40°C, respectively (Stockli, 2005). (U-Th)/He thermochronometry will provide time-temperature constraints for each mineral along the sampling transects, from which the timing of slip along the Zanskar segment of the STDS can be assessed (Figure 5). Modeling of (U-Th)/He data using the software program HeMP (Lee et al., 2011) will provide model cooling histories and geothermal gradients for each suite of samples. Constraints on the young slip history along the ZSZ will allow me to assess the validity of the channel flow model for the development of the NW Himalaya.

### **Anticipated Results**

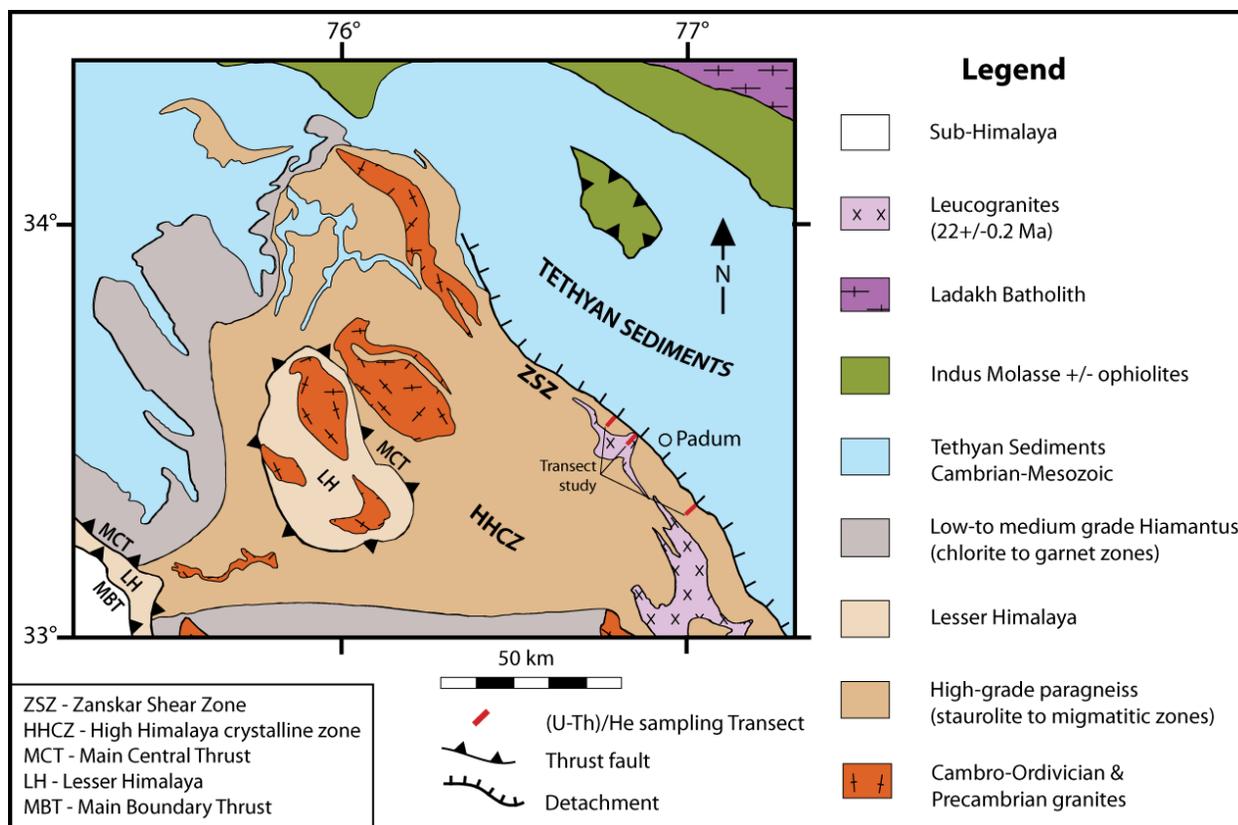
The geomorphological expression of the ZSZ near Padum suggests that this normal fault records slip as young as Pliocene, if not younger. To test the implications of this observation, I

will apply (U-Th)/He thermochronology to zircon and apatite minerals from high-grade metamorphic quartzite, and leucogranites taken along the Zaskar fault escarpment. The results should show that normal slip has occurred along this segment of the STDS since the Pliocene. In the central Himalayas, the channel flow model predicts the southward flow of the GHS bounded above by the STDS and below by the MCT. Geochronologic data suggest that slip along these two fault systems ceased during the Middle Miocene. A Pliocene slip history along the Zaskar fault will imply that the channel flow hypothesis will have to be re-evaluated for the NW Himalaya.

## Figures



**Figure 1.** Satellite image showing Indian plate moving northeastward with respect to the Asian plate (Tibet). The Main Boundary Thrust fault (sawteeth) marks the boundary between the two continental plates. Black box shows location of the study area relative to central (Nepal) and eastern (Bhutan) regions of the Himalaya.



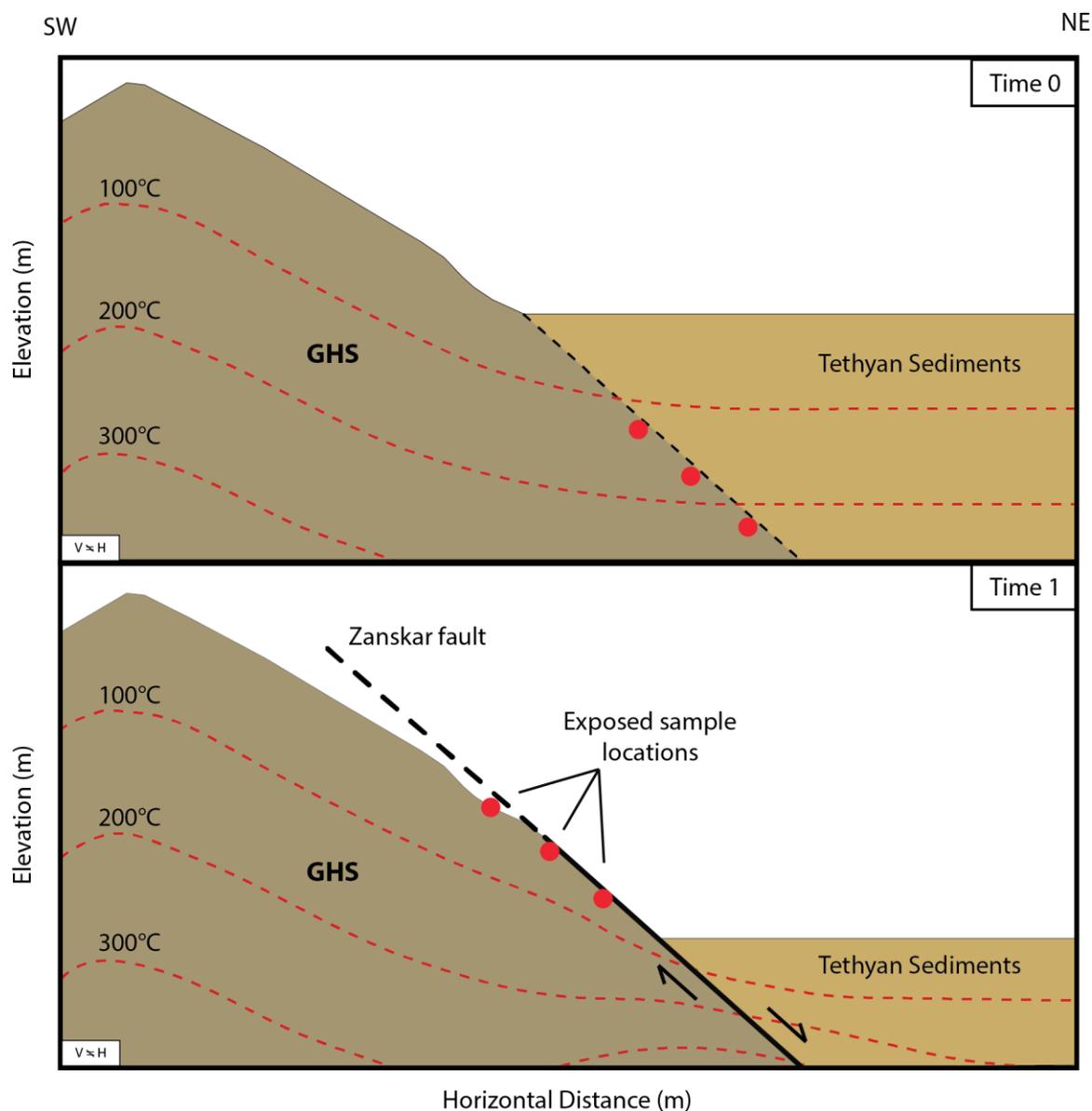
**Figure 2.** Simplified geologic map of the Zaskar Region showing location and orientation of the three vertical (U-Th)/He sampling transects (orange lines) that cross the exhumed footwall of the Zaskar fault. Map modified from Robyr et al. (2002), and (2006); and Searle et al. (1992).



**Figure 3.** Oblique view of Zanskar fault scarp (FS) showing well-exposed triangular facets near Padum, India. Arrows below FS indicate approximate dip-direction. Mountains in the background are the Greater Himalaya Range (GHR) with Quaternary alluvium (Qa) in the foreground. View is to the southwest.



**Figure 4.** Google Earth oblique image showing vertical sampling transect (T2) along the exhumed footwall of the Zanskar fault.



**Figure 5.** Conceptual model illustrating the location of a vertical sampling array (red dots) within the footwall of the Greater Himalayan Sequence (GHS) prior to extension (Time 0). Active normal slip along the Zanskar fault exhumes the sampling array from lower depths which are above (U-Th)/He closure temperatures (Time 1); towards the surface and below (U-Th)/He closure temperatures, samples accumulate geochemical data that record the timing of slip events. (U-Th)/He geochronometry on apatite and zircon from exposed footwall rocks provide essential time-temperature data used for constraining the slip history along the fault. Modified from Lee et al. (2011) and Stockli, (2005).

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