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Reactivated normal-sense shear zones in the core of the Greater Himalayan Sequence, Solukhumbu District, Nepal

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ABSTRACT

We present preliminary observations from the Solukhumbu region of Nepal, coupled with structures described in the literature, to suggest the importance of structural and metamorphic discontinuities within the Himalayan metamorphic core (Greater Himalayan Sequence) and reactivation of at least one of these thrust discontinuities with a normal (down-to-the-north) sense of displacement. Based on preliminary geochronologic data, development of these discontinuities may have evolved over time. In the Dudh Kosi Valley near Ghat, gneissic rocks and pegmatites exhibit tectonized fabrics and yield argon cooling ages of ~4 Ma for K-feldspar and ~9 Ma for biotite. Just north of Khumjung there is a prominent topographic break from which sheared gneissic rocks indicate a top-to-the-north, or normal, sense of shear. Near Pangboche, a repeated section of kyanite-bearing rocks interleaved with sillimanite-muscovite schist suggests structural imbrication and/or interleaved retrograde metamorphism. Below the peaks of Nuptse and Lhotse, the Khumbu thrust (Searle 1999) appears to form the floor of a thick succession of leucogranite sills. We suggest that these discontinuities were formed over time, possibly from early MCT and STDS deformation at ~21 Ma to as recent as ~4 Ma, and need to be considered in kinematic models that combine channel flow with critical taper and tectonic denudation. Moreover, orogenic collapse in the Himalayan core may be migrating southward through time as the orogenic wedge continues to uplift in response to underthrusting of India and southward propagation of the Main Frontal Thrust system.

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INTRODUCTION

Orogenic systems produced by large-magnitude collisions of continental lithosphere are known to result in an entwined history of convergent, extensional, and transpressional structures with accompanied surface uplift, metamorphism, exhumation and igneous activity (Heim and Gansser 1939; Burg et al. 1984; Burchfiel and Royden 1985; Fort et al. 1982; Cottle et al. 2015). The creation of regions of heightened elevation from these collisional zones are also credited with having an impact on local and global climate (Molnar and England 1990). The Himalayan mountain belt is one of the best modern examples of continental collision and has also been used to better understand ancient collisional systems such as the Appalachian orogen (Coward 1994). During recent years, there has been significant research on the details of the structural, petrologic and thermo/geochronologic aspects of the Himalayan orogenic processes. Geoscientists have also proposed many tectonic models for the evolution of the Himalaya based on the overall structural architecture of the range (Beaumont et al. 2001; Robinson et al. 2006; Cottle et al. 2015 and references therein). A number of field studies inspired by these models have resulted in data that illustrates the complexity of minor shear zones and metamorphic discontinuities in light of some of the major structures that have been studied for almost a century (Groppo et al. 2009; Larson et al. 2013; Montomoli et al. 2013, 2014; Cottle et al. 2015). The purpose of this paper is to present preliminary field data from the Solukhumbu District of Nepal (Mount Everest/ Qomolangma region) that show cross-cutting relationships of shear zones with opposite sense of motion, as well as other structural discontinuities within the Greater Himalayan sequence.

Early workers subdivided the Himalaya into three major lithotectonic domains separated by major north-dipping thrust faults (Heim and Gansser 1939). From south-to-north, these are: Lower or Lesser Himalaya, Higher or Greater Himalaya, and the Tethyan Himalayan. The High Himalaya of Nepal's Solukhumbu District – the Roof of the World – display one of the best 3-d exposures of mid-crustal rocks in the core of an active collisional orogenic belt found anywhere in the world. This orogenic core, named the Greater Himalayan Sequence (GHS), is subtended by the Main Central Thrust (MCT) and is capped to the north by at least two splays of the South Tibetan Detachment (Lhotse and Qomolangma detachments; Jessup et al. 2006). Despite extensive research over the years, however, fundamental gaps in knowledge remain regarding: (1) the partitioning of structural deformation across the >30 km thickness of the GHS between these two great faults; (2) the details of timing of motion on the Main Central Thrust relative to progressive unroofing of the orogen by multiple splays of the South Tibetan Detachment; and (3) the geologic significance of young isotopic ages in the "deep core" of the GHS, as reported in earlier literature (e.g., Hubbard and Harrison 1989; Catlos et al. 2002). All of these outstanding issues have relevance to the fundamental geometric architecture of the GHS in the Solukhumbu, its kinematic development over the past ~40 Ma, and most fundamentally on the choice of a tectonic mechanism(s) for emplacement of the Greater Himalaya. The focal point of our ongoing research, therefore, is to study several suspect faults, shear zones and metamorphic discontinuities (identified by Hubbard (1988) that appear to partition discrete structural domains within the GHS. Our central hypothesis is that these structural/metamorphic discontinuities may be early contractile faults that were subsequently reactivated with normal (top-to-the-north) displacement during more recent unroofing of the GHS.

STUDY AREA AND METHODS

Our work presented in this paper combines field observation with kinematic analysis from asymmetries in thin-section for samples collected along an iconic north-south transect through the Greater Himalaya in the Solukhumbu District, Nepal. This world-famous trekking route, being the main route to Everest Base Camp on the Nepal side of Everest, encompasses some of the best-exposed and accessible outcrops in the High Himalaya, following the Dudh Kosi River upstream from Lukla to Namche Bazaar, Phortse and Gokyo, and the Imja Khola River upstream to Dingboche and Periche (Fig. 1). We used topographic maps and Google Earth imagery to identify lineaments and/or prominent topographic breaks that may represent 'cryptic' mid-crustal structural discontinuities within the slab, coupled with documentation of shear zones with anomalous shear sense or cooling age presented in Hubbard (1988), to guide reconnaissance fieldwork that involved structural measurements and sampling at four sites. Rock sampling permits were obtained through official channels in Kathmandu (initially from the Nepal Bureau of Mines and Geology and subsequently from the Department of Geology at Tri-Chandra Campus, Tribhuvan University), in as much as all field sites were within Sagarmatha National Park – a UNESCO World Heritage Site.

Our work followed a traverse from Lukla northwards through Namche Bazar to a site north of Khumjung on the trail to Gokyo. This transect is north of the Main Central Thrust as it was mapped by Hubbard (1988) and is entirely within the GHS and below the STDS. Heim and Gansser (1939) defined the MCT in India based on the superposition of high-temperature, upper amphibolite facies gneisses of the Greater Himalayan Sequence (GHS) on lower-temperature amphibolite and greenschist facies rocks of the Lesser Himalayan sequence. The MCT is the largest single contractile structure at the leading edge of the Indian plate, with a strike length of around 2200 km and as much as 600 km of displacement (Srivastava and Mitra 1994; Kohn et al. 2001). The MCT is a thick ductile shear zone marked by strong top-to-the-south kinematic indicators and by inversions in metamorphic grade, producing the classic 'inverted metamorphic isograds' of sillimanite-kyanite-garnet-biotite (Hubbard 1996). Following the interpretation of Hubbard (1988), we took the top of the MCT to be marked by decreased strain and the appearance of migmatites of the GHS orthogneiss, about 5 km south of Lukla. Exposures are not continuous from Lukla north towards Namche Bazar due to dense vegetation and landslide deposits. There are, however, dispersed outcrops some of which include zones of high

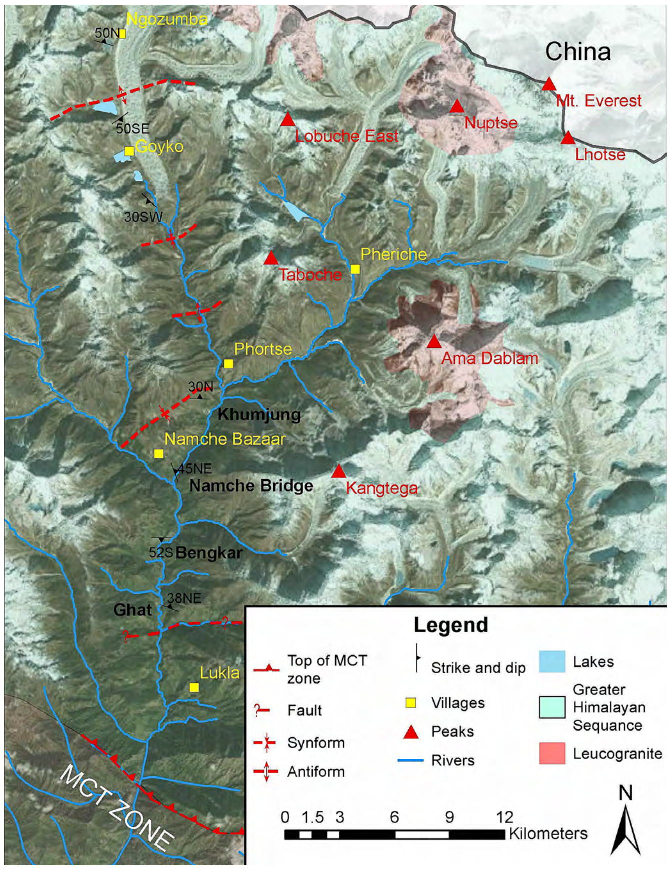


Fig. 1: Location map of the Solukhumbu District between Lukla and Mount Everest showing four sampling locations (Ghat, Bengkar, Namche Bridge and north of Khumjung), as well as major villages (yellow) and major peaks (red).

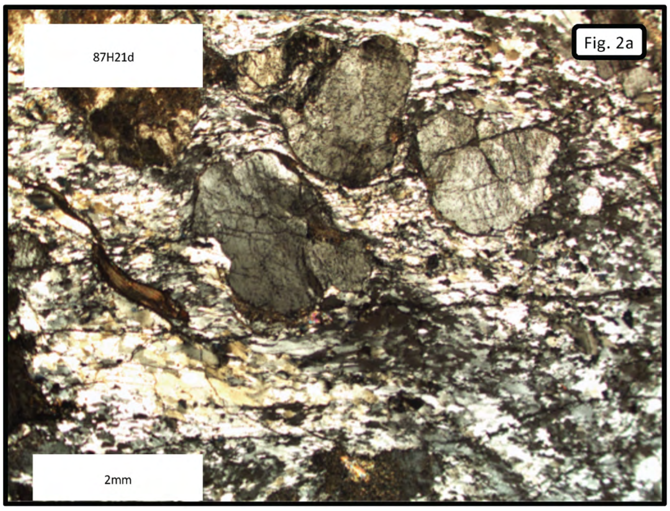
strain. Lithologies are typically orthogneiss, biotite schist and minor calc-silicate rocks. Banded leucosomes of migmatite in orthogeniss become more abundant at Namche Bazaar, but yield to metapelitic sillimanite-grade paragneiss (black schist and biotite-rich gneiss) further north towards Everest (Searle et al. 2003). We present herein results from three locations south of Namche Bazaar (Ghat, Bengkar and Namche Bridge) and one site north of Khumjung-Khunde.

FIELD AND PETROGRAPHIC RESULTS

Ghat

There are excellent exposures immediately south of Ghat, due east of the main trekking trail against the base of imposing cliffs (GPS: 0472139, 3067253). Ghat also lies immediately north of a prominent east-west topographic lineament marked by the valleys of the Thado Koshi Khola and Kamsyawa Khola drainages to the east and west, respectively, possibly marking an east-west trending structural discontinuity. It was here that Hubbard sampled for geochronologic constraints on deformation (Hubbard 1988; Hubbard and Harrison 1989; Hubbard and House 2000; Catlos et al. 2002). The lithology is a biotite gneiss that consists of quartz, plagioclase, biotite and K-feldspar. A deformed pegmatite dike cuts the gneiss with domains of recrystallized quartz, biotite, and muscovite surrounding relict K-feldspar (Fig. 2a); tourmaline is also present. The strike/dip of the gneiss is N70W/38NE with a lineation plunging 38^{o} N2^{o}E.

Due to limited sampling, we were unable to determine a clear sense of shear at this location, however the cooling ages for this sample from previous studies suggest young cooling with ^{40}Ar/^{39}Ar ages for biotite and muscovite in the range of 7-9 Ma and a minimum age for K-feldspar as low as 4 Ma (Hubbard and Harrison 1989). (U-Th)/He apatite ages for this site are <1Ma (Hubbard and House 2000)(Fig. 2b). This sample contains matrix monazite that yielded a ~15Ma in situ Th-Pb ion microprobe date (Catlos et al. 2002). The proposed interpretation by Hubbard and Harrison (1989) was for metamorphism at ~15 Ma, followed by shearing at 7-9 Ma. (See Hubbard 1988) for further presentation of petrography and thermochronology.)



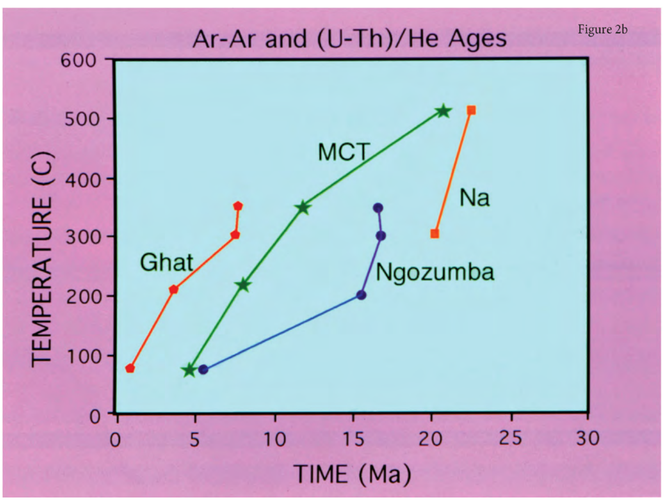


Fig. 2: Ghat field site (a) Protomylonitic texture in pegmatite near Ghat. ^{40}Ar-^{39}Ar cooling ages of 9 Ma for biotite and 4 Ma for K-feldspar came from this sample (Hubbard and Harrison 1989), (b) Published age data from the deformed pegmatite at Ghat shows a younger cooling history than MCT samples and samples from further north (Ngozumba and Na) in the Greater Himalaya (Hubbard and Harrison 1989; Hubbard and House 2000).

Bengkar

An exceptionally well-exposed ductile shear zone is located on the west side of the Dudh Koshi River just south of Bengkar, best seen from a small bridge over a creek (GPS: 0471651, 3070851) (Figs. 3a and b). A distinct recessed zone of anastomosing, lenticular "pods" of shear rock separates two prominent cliff bands. We were unable to directly measure the thickness of the sheared zone, but estimate it to be ~2-3 meters thick. The lithology at this site is a biotite schist with a mineralogy of quartz, biotite, garnet and K-feldspar. The strike/dip of foliation is NS/10E with a 10^{o} due-East lineation. Asymmetries were not evident in our one thin-section from this site, but the fabric seen at the outcrop scale provisionally suggests a top-to-the-south sense of shear.

Fig. 3: Bengkar field site: (a) View to the west of the Bengkar shear zone sloping gently to the right (middle of the photo) at the base of the upper, near-vertical cliff face, (b) Close-up of the wavy, anastomosing pods of rock (phacoids) that comprise deformation at Bengkar.

Namche Bridge

We sampled rocks on the west side of the high bridge that leads to Namche Bazaar, at the confluence of the Bhote Koshi and Dudh Koshi Rivers (GPS: 0472482, 3074633) (Fig. 4a). The lithology from this outcrop consists of a biotite gneiss with quartz, biotite, garnet, and sillimanite. The strike/dip of foliation is N20W/45NE with a lineation plunging due North. The sense of shear interpreted from thin-section is top-to-the-north, suggesting sinistral normal displacement (Fig. 4b).

Fig. 4: Namche Bridge field site: (a) Sample site adjacent to the trail at the west end of the new, upper bridge leading to Namche Bazaar, (b) Namche Bridge photomicrograph. Thin section of biotite-garnet gneiss showing a top-to-the-north sense of shear on this sample. This interpretation represents a sinistral-normal shear sense for this zone. The small arrow in the upper left points in the down-dip direction. The inset equal-area stereonet shows the orientation of the shear fabric foliation and the stretching lineation.

North of Khumjung

An imposing topographic ridge and probable structural discontinuity is located immediately northeast of Khumjung (Fig. 5a). The high trekking trail to Mong, Gokyo and Phortse

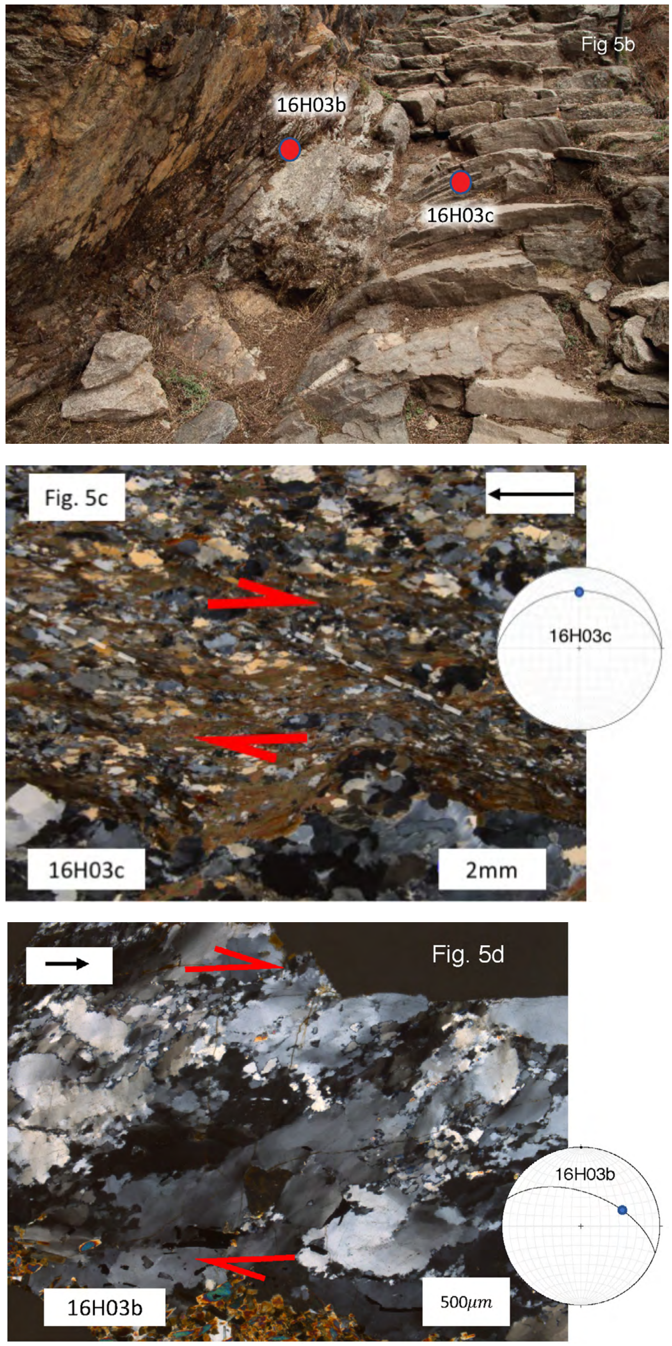


Fig. 5: Khumjung field site: (a) Photograph of the prominent ridge north of Khumjung showing the trail (lower right) that leads to Mong, Gokyo and Phortse. View towards the ENE. The white circle shows approximate sampling region. Ama Dablam is shown in the distance (6,812 meters; 22,349 ft.), (b) Cross-cutting shear zones. Sample site 16H03c sits on an older fabric that has been folded into and cut by a younger fabric from which sample 16H03b was collected. The older fabric has been interpreted from thin section to have a thrust sense-of-shear, while the younger fabric has been interpreted to have a dextral-normal shear sense. Photo taken looking to the east, (c) Photomicrograph from sample 16H03c from north of Khumjung. Thin section of a biotite gneiss sample with a deformation foliation that is folded into a younger shear zone. Small arrow in upper right of the image is the lineation direction. The inset equal-area stereonet shoes the strike and dip of this older deformation

foliation and the plunge and bearing of the stretching lineation. The light dashed lines show the orientation of a shear band fabric that led to the interpretation of a thrust sense of shear, (d) Photomicrograph from sample 16H03b from north of Khumjung. Thin section of a deformed quartz vein in amphibolite from a younger shear zone that cuts an older fabric (see Fig. 5d, sample 16H03c). Small arrow in upper left of image is the lineation direction. The inset equal-area stereonet shows the strike and dip of the shear fabric and the plunge and bearing of the stretching lineation. Asymmetric grain shapes in the quartz led to the interpretation of a dextral – normal shear sense.

cuts across the lower portions of this ridge, providing easy access to well-exposed, in-place rocks. This site is located at the intersection of two trails marked by signs, one pointing the way back to Khumjung Khunde and the other to the lower trail to Namche Bazaar (GPS: 0473772, 3078690). Hubbard (1988) noted shear fabrics with normal sense of shear near this location on a sample from an outcrop of biotite gneiss with the strike/dip of foliation of N83W/78NE and a stretching lineation plunging 62^{o} N62^{o} E. During our 2016 field season, we found a site where this fabric truncated an older fabric (Fig. 5b). The older fabric has a strike/dip of EW/16NE with a 30^{o} due North lineation. The sense of shear we interpret from this older fabric in thin-section is top-to-the south, or thrust sense of shear (Fig. 5c). The younger fabric had a strike/dip of N70W/55NE with a lineation plunging 42° N71E. The sense of shear on the younger fabric is dextral-normal and consistent with the earlier interpretation of Hubbard (1988)(Fig. 5d).

DISCUSSION

Other workers have recognized shear zones and/or structural-metamorphic discontinuities in this region during previous field projects (e.g., Larson et al. 2014), as have members of our team. For example, a repeated section of kyanite-bearing rocks interleaved with sillimanite-muscovite schist near Pangboche suggests structural imbrication and/or interleaved retrograde metamorphism. Below the peaks of Nuptse and Lhotse, the Khumbu thrust (Searle 1999) appears to form the floor of a thick succession of leucogranite sills. Searle's (2007) map of the region around the Everest massif shows the extent of the South Tibetan Detachment (Qomolangma and Lhotse detachments) in the high peaks, as well as the dashed trace of the inferred Khumbu thrust fault. The Khumbu thrust traverses the south base of the Nuptse-Lhotse ridgeline and turns south just west of Island Peak to wrap around Baruntse; its extent west of the lower Khumbu Glacier is uncertain. The Khumbu thrust places Everest Series sillimanite-grade pelites and sheeted leucogranite sills over sillimanite gneiss; although leucogranite sills also occur in the footwall of the Khumbu thrust (at Island Peak, Ama Dablam, etc.), sills are much thicker and more abundant in the hanging wall. Although shown as a discrete thrust fault on Searle's (2007) map, we suspect the Khumbu thrust may be a zone of distributed shear and we have no kinematic data to suggest normal-sense reactivation, although this may be a possibility for further investigation. In this regard, Carosi et al. (1999) proposed that Miocene extension was partitioned between the South Tibetan Detachment and its footwall in the Solukhumbu region, particularly in the middle to upper parts of the Greater Himalayan Sequence below the STD. Extensional displacement on the STD resulted in nearly isothermal decompression of its footwall succession, resulting in rapid tectonic denudation and the development of 'isostatic instabilities' which became manifested as reactivated normal-sense shear zones and other extensional structures ("collapse folds") below the STD (Carosi et al. 1999). It was further proposed that coaxial footwall extension may be several million years younger than noncoaxial extension accommodated by the STD, further suggesting that extension may be migrating south through the Greater Himalayan Sequence as the orogenic wedge builds southward over the subducting Indian plate.

The vast majority of published papers on the Greater Himalayan Sequence focus on the top of the GHS near the South Tibetan Detachment (e.g., Searle et al. 2003; Law et al. 2004, 2011), or the bottom of the GHS adjacent to the inverted metamorphic isograds of the Main Central Thrust (e.g., Hubbard 1989; Searle et al. 2008). Significantly less work has been focused on the >10-15 km-thick core of the Greater Himalayan Sequence between these two bounding fault systems, a point underscored by published cross-sections often depicting the GHS as a continuous slab of early Miocene sillimanite gneiss, often labeled the Namche orthogneiss in the Khumbu (e.g., Searle et al. 2006; Jessup et al. 2006, 2008). Cottle et al. (2015, p. 123) offers an alternative view: '*While detailed characteristics from within the interior of the HMC [Himalayan Metamorphic Core] are rare, the limited data indicate the presence of otherwise cryptic structural discontinuities. The presence of such structures…indicates that the HMC, which for some time had been treated as a homogeneous body is significantly more structurally complex than previously thought'*. Our limited and preliminary work supports the viewpoint of Cottle et al. (2015) and a hybrid model for the GHS, whereby convergence was accommodated by tectonic wedging of the mid-crust, involving a temporal and spatial interplay of critical taper thrusting and deep channel flow (Frassi 2015; Cottle et al. 2015), largely coeval with tectonic denudation. It is also intriguing to consider the possibility that extension of the GHS has migrated southward throughout the Miocene as the footwall of the STD was unloaded and unroofed (e.g., Carosi et al. 1999), coeval with southward emplacement of successively younger thrust faults at the toe of the orogenic wedge in the Frontal Himalaya. Thus, understanding the evolution of modern and ancient orogenic systems produced by continent-continent collision requires a detailed knowledge of not only how the thermally-weakened mid-crust has been spatially and temporally shortened and stacked, but also the history of progressive top-down tectonic denudation into the metamorphic core of the orogen. As found in the summit rocks of Mount Everest at the Qomolangma detachment (Corthouts et al. 2016), extensional faulting is often superimposed on preexisting, reactivated contractile shear zones. Therefore, we propose that the core of the GHS may be undergoing north-to-south migrating collapse along an array of cryptic, reactivated shear zones such as found just north of Khumjung.

Future/ongoing research

We plan to continue our research in the Solukhumbu by focusing on the identification of structural and metamorphic discontinuities in the core of the Greater Himalayan Sequence between the STD and the MCT. Our goal will be to gain a better understanding the spatial and temporal relationship between contractile deformation and tectonic denudation and, in particular, to test the model of southward-migrating collapse of the core of the Greater Himalaya. Several field sites in the lower Khumbu (below Namche) have promise for future detailed work on shear zone kinematics and timing relationships. Ghat and Bengkar, in particular, need more focused work to understand the extremely young ages derived from earlier radiometric analyses. Above Namche Bazaar, the apparent reactivation of shear zones at Khumjung will be a focused study to better document the north-directed sense of [normal] shear on the younger fabric and establish timing relationships with the older fabric. The larger research program will involve a long-term, collaborative effort involving geoscientists from Tribhuvan University in Kathmandu and Montana State University (and potentially other universities) to undertake the tasks of field mapping, sample collection, kinematic analysis, petrography, geochronology, geochemistry, structural analysis and, ultimately, tectonic modeling of the metamorphic core of the Greater Himalaya. We cannot do this without our colleagues and students from Nepal.

CONCLUSIONS

Our preliminary work suggests that the lower half of the Greater Himalayan Sequence between the MCT and just north of Khumjung is characterized by numerous structural discontinuities that may have partitioned the GHS into structural and/or 'flow' domains during emplacement of the MCT. The few examples cited appear to be ductile shear zones and at least one, Khumjung, shows clear evidence of reactivation with top-to-the-north displacement in the younger fabric (dextral normal). This interpretation tends to support the earlier conclusions of Carosi et al. (1999) that nearly isothermal decompression in the footwall of the STD resulted in tectonic denudation and the development of “isostatic instabilities” which became manifested as reactivated normal-sense shear zones. Furthermore, this opens the door to the possibility that extension may be migrating south through the Greater Himalayan Sequence since the mid-Miocene as the orogenic wedge builds southward over the subducting Indian Plate.

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