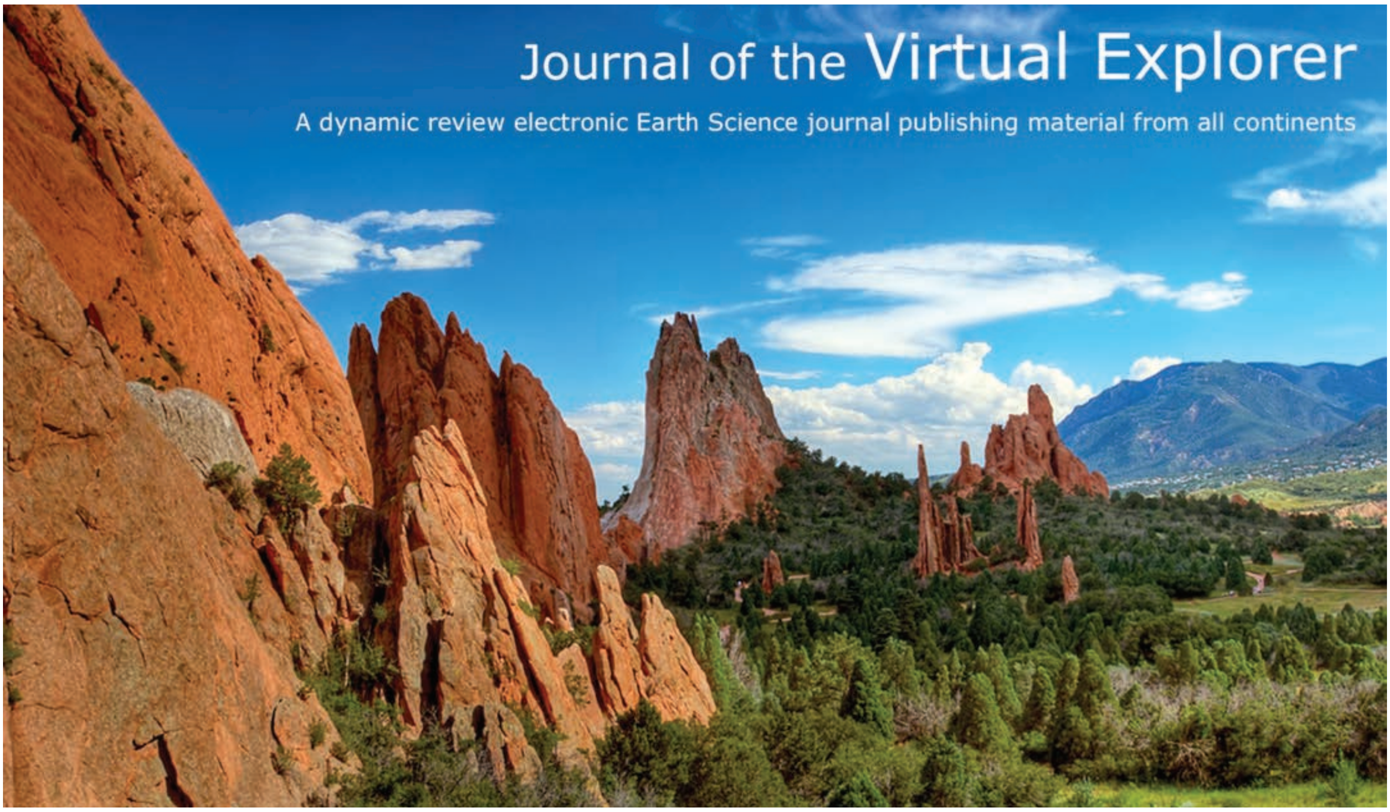

Structural and Metamorphic Traverse across the northwestern Kathmandu Nappe, central Nepal

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Journal of the VIRTUAL EXPLORER, Electonic Edition, ISSN 1441-8142, volume 47, Paper 6, DOI: 10.3809/jvirtex.2014.00338, In: (Eds) Chiara Montomoli, Rodolfo Carosi, Rick Law, Sandeep Singh, and Santa Man Rai, Geological field trips in the Himalaya, Karakoram and Tibet, 2014

Journal of the VIRTUAL EXPLORER

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GUIDE INFO

Keywords
Lesser Himalaya
Kathmandu Nappe
Mahabharat thrust
Galchi shear zone

Citation
Webb, A. and Upreti, B. 2014. Structural and Metamorphic Traverse across the northwestern Kathmandu Nappe, central Nepal. In: (Eds.) Chiara Montomoli, Rodolfo Carosi, Rick Law, Sandeep Singh, and Santa Man Rai, Geological field trips in the Himalaya, Karakoram and Tibet, Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume 47, paper 6, DOI: 10.3809/jvirtex.2014.00338.

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IN THIS GUIDE

This contribution describes an easy-access, one-day field excursion across the northwestern Kathmandu Nappe along the Kathmandu-Pokhara Highway. The Kathmandu Nappe is one of the best-studied members of the Lesser Himalayan Crystalline Nappes, an enigmatic series of klippen and half-klippen that occur across the central southern Himalaya. Various workers have assigned different tectonic affinities to these Nappes, with possibilities including all of the three major Himalayan units (the Lesser Himalayan Sequence, Greater Himalayan Crystalline complex, and Tethyan Himalayan Sequence) or some combination thereof. The field trip introduces the basic geology of the Kathmandu Nappe, and allows participants to explore the possible implications of long-standing and recent findings from this area for our understanding of Himalayan thrust tectonics. Highlights include stops at the Mahabharat thrust and the Galchi shear zone, which may represent the major faults bounding the Greater Himalayan Crystalline complex. The Mahabharat thrust is widely interpreted as the southern trace of the Main Central thrust, whereas the Galchi shear zone is proposed to represent the southern strand of the South Tibet detachment. These interpretations and their broader implications, including the possibility that the Greater Himalayan Crystallline complex was not extruded towards the surface between its bounding faults, can be readily explored during this one-day excursion.

INTRODUCTION

The Kathmandu Nappe is one of a series of klippen and half-klippen in the southern Himalaya which are collectively referred to as the Lesser Himalayan Crystalline Nappes or the Outer Crystalline Klippen (Figure 1). These rocks outcrop across the Nepal Himalaya, throughout the Kumaun and Garhwal regions of northwestern India, and perhaps as far west as Kashmir (Stöcklin, 1980; Windley, 1988). Equivalents may also occur in Bhutan (Bhargava, 1995). Rocks are divided into two sequences: the Bhimphedi Group below and the Phulchauki Group above (Stöcklin, 1980).

The Lesser Himalayan Crystalline Nappes remain an enigma within the context of the three layers, two fault stack that dominates the Himalaya (i.e., the Lesser Himalayan Sequence below, Greater Himalayan Crystalline complex in the middle, and Tethyan Himalayan Sequence above, with the Main Central thrust separating the Lesser Himalayan Sequence from the Greater Himalayan Crystalline complex and the South Tibet detachment dividing the Greater Himalayan Crystalline complex from the Tethyan Himalayan Sequence above). Each of the three major tectonic units have been put forward by different workers as correlative to the Lesser Himalayan Crystalline Nappe rocks; alternatively these rocks may be broken into different sub-units that variably correlate to the different tectonic units (e.g., Upreti and Le Fort, 1999; Webb et al., 2011). Likewise, the basal fault may represent the southern extension of the Main Central thrust or a distinct structure (e.g., Upreti and Le Fort, 1999; Johnson, 2005).

The one-day field trip described herein allows consideration of the problem of the Lesser Himalayan Crystalline Nappes in the context of the stratigraphy, metamorphism, and structure exposed across the northwestern Kathmandu Nappe (Figure 2) and provides a fun, fast excursion into the rich geology of Nepal. It is based on a one-day field excursion organized by the authors in support of the 2012 Himalaya-Karakoram-Tibet Workshop, which was hosted by the Nepal Geological Society in Kathmandu. The trip assumes an early start from Kathmandu (before the heavy traffic starts), and largely follows the highway heading northwest out of the city towards Pokhara (Figure 3). Most stops are in the vicinity of the village Galchi, near the confluence of the Mahesh Khola and the Trishuli River. Expect to eat lunch at Galchi. Time permitting; the trip includes an excursion ~20 km farther west to just south of the village Malekhu. This excursion offers a section through the base of the Kathmandu Nappe that contrasts in metamorphic grade and deformation history vs. the Galchi section, promoting consideration of the implications of these differences.

REGIONAL GEOLOGIC FRAMEWORK

The base of the Kathmandu Nappe is defined by the Mahabharat thrust, which is widely but not universally interpreted as the southern trace of the Main Central thrust (e.g., Stöcklin, 1980; Fuchs, 1982; Pêcher and Le Fort, 1986; Pandey et al., 1995; Arita et al., 1997; Upreti and Le Fort, 1999; Johnson et al., 2001; cf. Searle et al., 2008). Early Proterozoic Lesser Himalayan Sequence rocks occur in the Mahabharat thrust footwall, whereas the hanging wall is dominated by the Late Proterozoic Bhimphedi Group and overlying Ordovician-Devonian Phulchauki Group (Figure 2) (e.g., Stöcklin, 1980; Pearson and DeCelles, 2005; Gehrels et al., 2006). The Bhimphedi and Phulchauki Groups are deformed in an elongated bowl-shaped synform, the Kathmandu synform, which forms the bulk of the Kathmandu Nappe.

The Phulchauki Group is generally dominated by unmetamorphosed (anchizone) limestone, shale, and sandstone, with a conglomeratic horizon and associated unconformity at or near the base. These rocks are generally accepted as correlative to age-equivalent Tethyan Himalayan Sequence rocks exposed to the north (e.g., Upreti, 1999). The Bhimphedi Group consists of pelites, quartzites and carbonates which are locally intruded by Cambro-Ordovician granitoids (Stöcklin, 1980; Gehrels et al., 2006). The Bhimphedi rocks display a progressive increase in grade with structural depth, from chlorite phyllites at the top to garnet schists at the base (Figure 4) (Johnson et al., 2001).

The Bhimphedi Group forms the immediate hanging wall of the Mahabharat thrust / Main Central thrust throughout the Kathmandu synform, except in the north. There, the Sheopuri gneiss occurs directly along the thrust (Stöcklin and Bhattarai, 1982; these rocks are alternatively named the Gosainkund gneiss). The Sheopuri gneiss consists of kyanite- / sillimanite-bearing paragneisses, orthogneisses, and migmatites (e.g., Rai et al., 1998). The Sheopuri gneiss appears contiguous with the Greater Himalayan Crystalline complex to the north, and thus may be the same tectonic unit.

The nature of the contact between the Sheopuri gneiss and the adjacent Bhimphedi Group is disputed. The Sheopuri gneiss may transition laterally to lower metamorphic conditions, such that the Bhimphedi Group is the low temperature equivalent and there is no sharply defined contact between these units (e.g., Stöcklin, 1980). Alternatively, a fault zone may separate the units: (1) the Main Central thrust may place Sheopuri gneiss above Bhimphedi rocks (with the Mahabharat thrust interpreted as a structurally lower splay of the Main Central thrust) (Rai et al., 1998; Upreti and Le Fort, 1999), or (2) the South Tibet detachment may place the Bhimphedi Group rocks atop the Sheopuri gneiss (Webb et al., 2011).

Such uncertainties are the essence of the Lesser Himalayan Crystalline Nappe problem, i.e., what are the tectonic positions of the Bhimphedi and Phulchauki Group rocks? If the Phulchauki Group is accepted as Tethyan Himalayan Sequence, then is there a South Tibet detachment-type contact separating them from the metamorphic rocks of the Bhimphedi Group below? If the Bhimphedi Group rocks are taken as frontal equivalents of the Greater Himalayan Crystalline complex, which famously has an inverted metamorphic field gradient, then why does the Bhimphedi Group display a right-way-up gradient?

Below, we discuss the implications of different Lesser Himalayan Crystalline Nappe interpretations for tectonic models for the assembly of the main three Himalayan units (i.e., the Lesser Himalayan Sequence, the Greater Himalayan

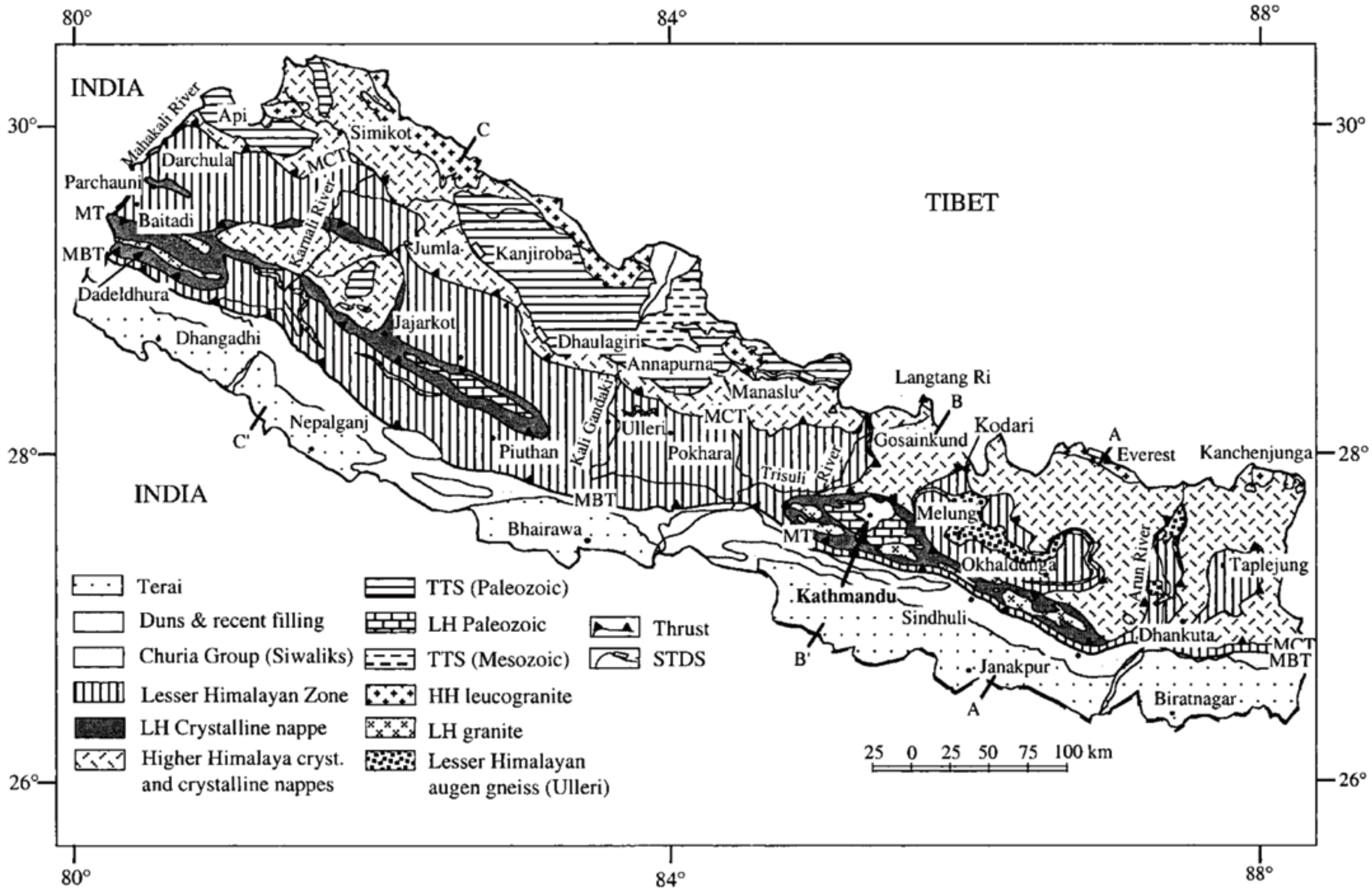


Figure 1

Unit abbreviations: the acronym "LH" means "Lesser Himalayan," but in this legend it is always used in reference to the Lesser Himalayan Crystalline Nappes (which have disputed tectonic affinity, see text). TTS = Tibetan-Tethys Series ≈ Tethyan Himalayan Sequence; HH = High Himalayan ≈ Greater Himalayan Crystalline complex. Fault abbreviations: MBT = Main Boundary thrust; MCT = Main Central thrust; MT = Mahabharat thrust; STDS = South Tibet detachment system.

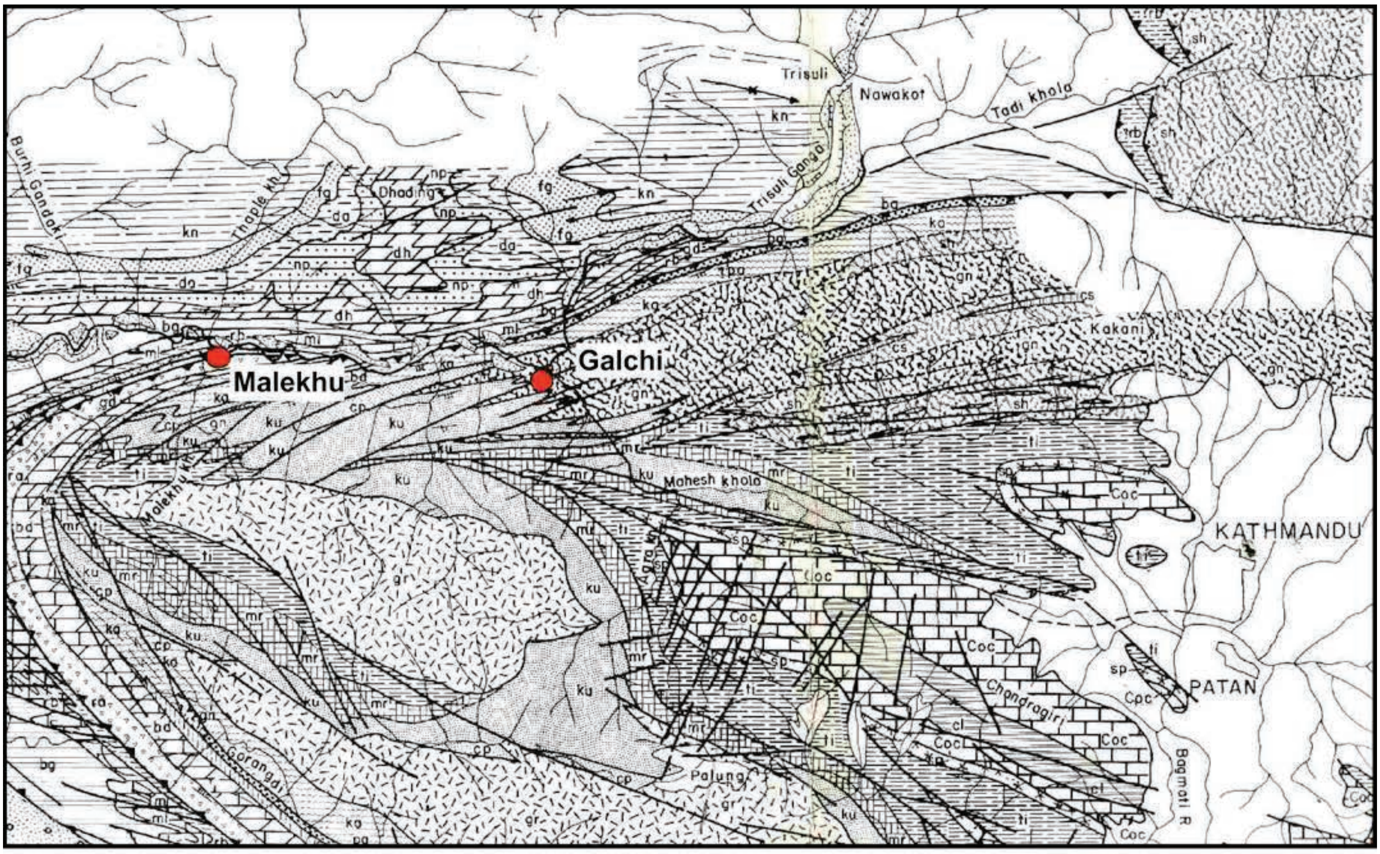
Crystalline complex, and the Tethyan Himalayan Sequence). Next, we outline the geology to be observed throughout the field trip.

Himalayan tectonic models vs. the lesser Himalayan Crystalline Nappes

Early models for the construction of the Himalayan orogen suggested that tectonic units were juxtaposed by in situ thrusting of Indian basement and cover sequences (Argand, 1924; Heim and Gansser, 1939; Dewey and Bird, 1970; Le Fort, 1975). However, top-north shear structures recognized along the gently north-dipping Greater Himalayan Crystalline complex – Tethyan Himalayan Sequence contact at the range crest (e.g., Caby et al., 1983; Burg et al., 1984) have been interpreted by most workers as evidence for major normal faulting during Himalayan orogenesis. The contact is now generally structurally defined as the South Tibet detachment, and is commonly interpreted as a top-north low-angle normal fault system with 10s or even 100s of km of slip (e.g., Searle, 1986; Burchfiel et al., 1992). Current models for the assembly of the Himalayan units focus on the emplacement of the Greater Himalayan Crystalline complex along the South Tibet detachment and the Main Central thrust. These models exclude consideration of the Lesser Himalayan Crystalline Nappes, perhaps because (1) these are a volumetrically modest component of the range, and (2) as discussed above, the Nappes are commonly interpreted as contiguous with one of the three major tectonic units (Upreti and Le Fort, 1999; Webb et al., 2011). In this section, the three major models for the emplacement of the Greater Himalayan Crystalline complex are reviewed and then discussed in the context of the Lesser Himalayan Crystalline Nappes.

Tectonic Models

The first kinematic model proposed after the discovery of the South Tibet detachment is wedge extrusion. In this model, the Greater Himalayan Crystalline complex extruded southwards be-



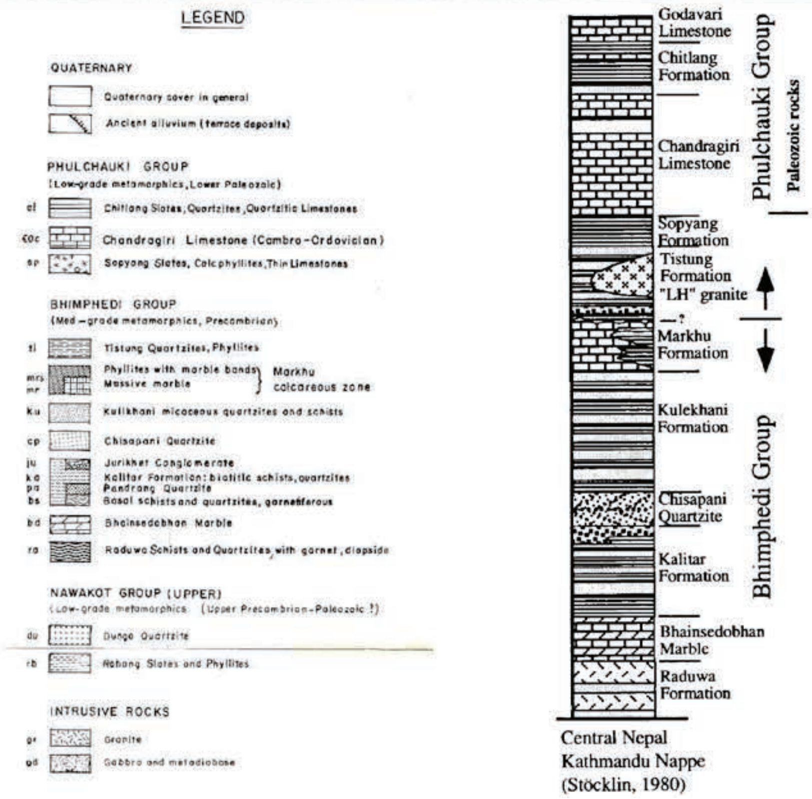


Figure 2
Geological map of the northwestern Kathmandu Nappe modified from Stöcklin and Bhattarai (1982), with stratigraphic column from Stöcklin (1980) as modified by Upreti (1999). The Phulchauki Group-Bhimphedi group contact has been interpreted alternatively along an unconformity within the Tistung Formation by Gehrels et al. (2006).

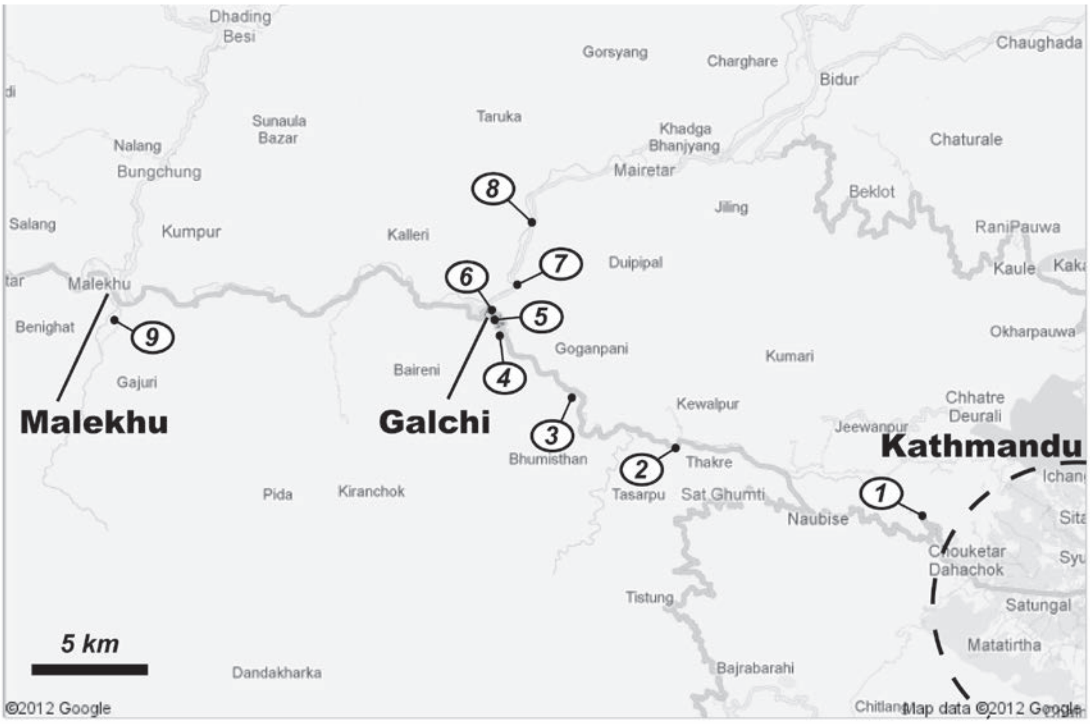


Figure 3
Google Road Map.

tween the other two units as a northward-tapering wedge (Figure 5A) (Burchfiel and Royden, 1985). Recently, these kinematics have been understood in the context of critical taper – Coulomb wedge theory (e.g., Robinson et al., 2006; Kohn, 2008; Zhang et al., 2011), which suggests that normal faulting may occur during collapse of over-thickened thrust wedges (e.g., Davis et al., 1983; Dahlen, 1990).

The second kinematic model is channel flow – focused denudation. The Greater Himalayan Crystalline complex represents partially molten lower/middle crust that tunnels southwards during the Eocene-Oligocene (Figure 5B) (e.g., Beaumont et al., 2001; 2004; Godin et al., 2006). Subsequently, the channel is exhumed by enhanced erosion across a narrow zone where precipitation is focused along the topographic front of the orogen (e.g., Beaumont et al., 2001; Hodges et al., 2001). In both wedge extrusion and channel flow – focused denudation models, the Main Central thrust and South Tibet detachment are active, surface-breaching faults during Early-Middle Miocene emplacement of the Greater Himalayan Crystalline complex.

The third kinematic model is tectonic wedging. The South Tibet detachment is interpreted as a backthrust splaying off of the Main Central thrust (Figure 5C) (Yin, 2006; Webb et al., 2007). Motion along these thrusts accommodated Greater Himalayan Crystalline complex emplacement below the Earth surface, with exhumation resulting from subsequent footwall duplex development (Yin, 2006; Webb et al., 2007). Kinematic models of channel flow – focused denudation and tectonic wedging are distinguished by two criteria: timing and extrusion. In the first model, channel tunneling occurs in the Eocene-Oligocene, preceding Miocene surface emplacement of the Greater Himalayan Crystalline complex via channel flow coupled to extrusion (e.g., Beaumont et al., 2001; Hodges et al., 2001; Godin et al., 2006). In contrast, proposed tectonic wedging occurs in the Miocene and accomplishes emplacement of the Greater Himalayan Crystalline complex at depth, without extrusion.

Structural Geometry of the Lesser Himalayan Crystalline Nappes

Four interpretations are advanced to explain the structural geometry of the Lesser Himalayan Crystalline Nappes (Figure 6): A. The three layer-two fault Himalayan tectonic pattern of the Himalaya is maintained across the Lesser Himalayan Crystalline Nappes. The South Tibet detachment contact occurs between the Bhimphedi Group and the Phulchauki Group, but has yet to

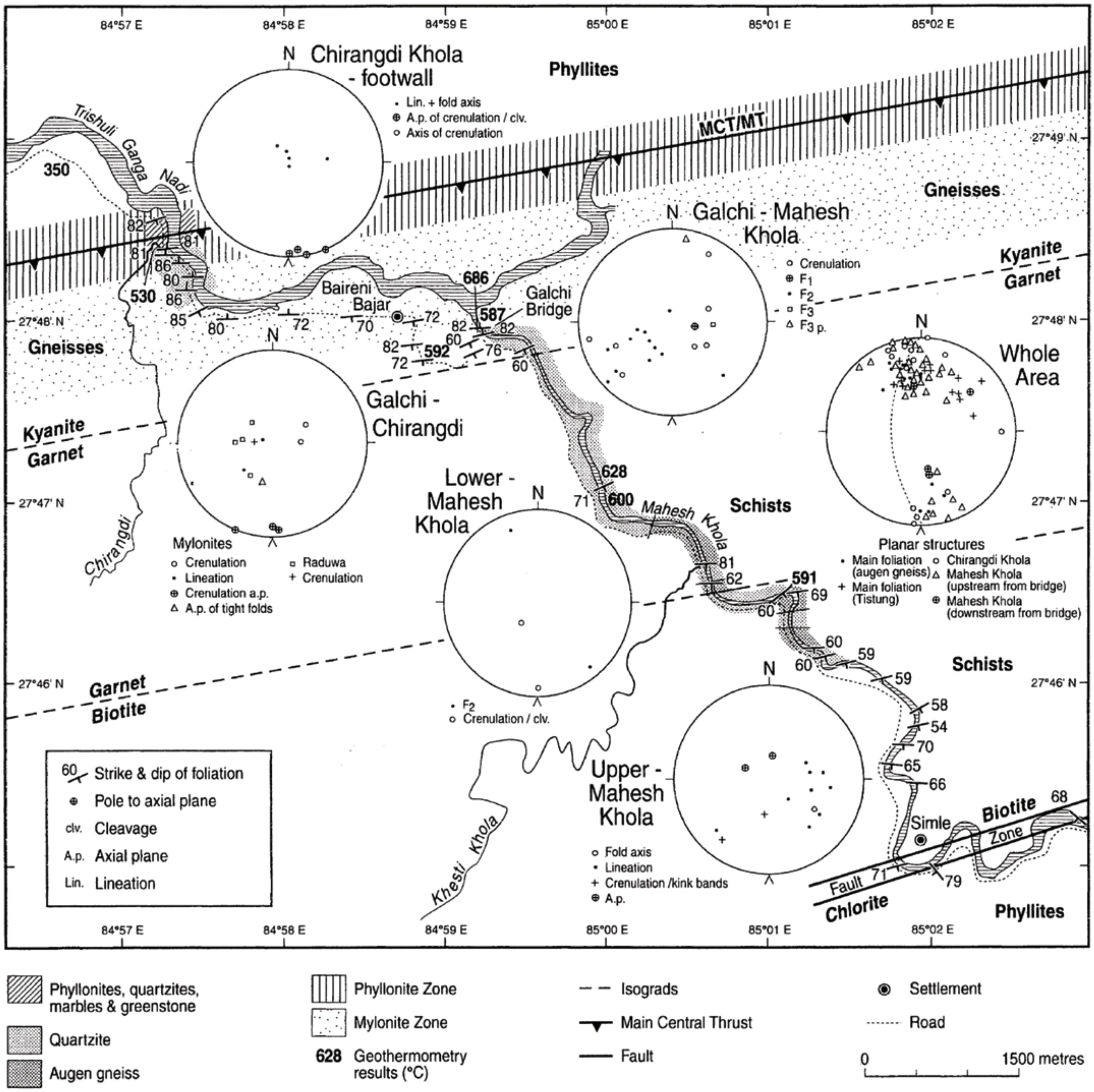


Figure 4
Geological map of the lower Mahesh Khola from Johnson et al. (2001). MCT/MT = Main Central thrust / Mahabharat thrust..

be identified because of poor exposure (e.g., Yin, 2006). The Sheopuri gneiss and Bhimphedi Group are contiguous. B. The South Tibet detachment cuts upsection to the north of the Lesser Himalayan Crystalline Nappes. The Phulchauki Group was deposited on the southerly Greater Himalayan Crystalline complex rocks (e.g., Gehrels et al., 2003; Johnson, 2005). The Sheopuri gneiss and Bhimphedi Group are contiguous. C. The Main Central thrust cuts upsection along the northern margin of the Lesser Himalayan Crystalline Nappes. The Sheopuri gneiss forms the Main Central thrust hanging wall; the Bhimphedi and Phulchauki Groups are restricted to the footwall (e.g., Rai et al., 1998; Upreti and Le Fort, 1999; Hodges, 2000). The Mahabharat thrust at the base of the Bhimphedi Group is not interpreted as the Main Central thrust, but rather as a relatively minor synchronous thrust deforming the Lesser Himalayan Sequence. The Bhimphedi Group rocks

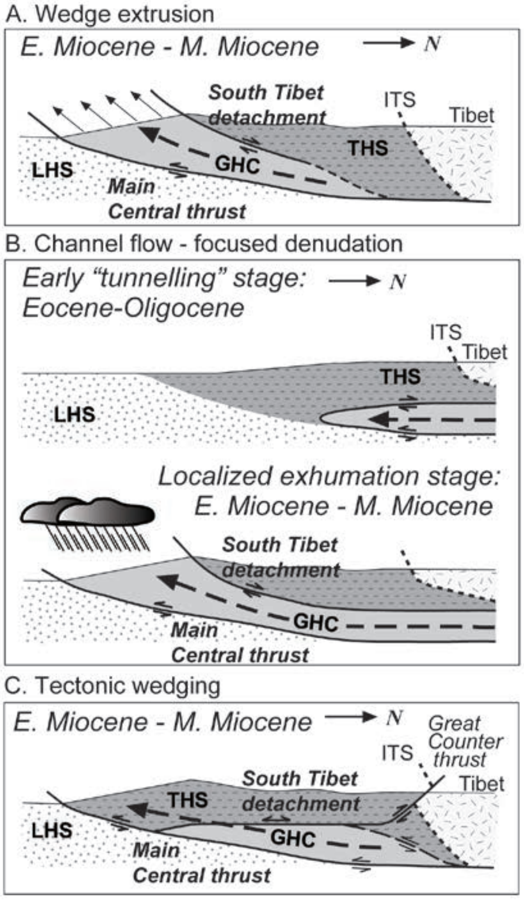


Figure 5
Tectonic models for the emplacement of the Greater Himalayan Crystalline Complex (GHC) modified from Webb et al. (2013). A. Wedge extrusion (e.g., Burchfiel and Royden, 1985). B. Channel flow – focused denudation (e.g., Beaumont et al., 2001). C. Tectonic wedging (e.g., Webb et al., 2007). ITS = Indus-Tsangpo suture; THS = Tethyan Himalayan Sequence; LHS = Lesser Himalayan Sequence

are likewise interpreted as Lesser Himalayan Sequence rocks. The Phulchauki Group rocks are interpreted to represent the southernmost extent of the Tethyan basin, deposited south of the Cenozoic Main Central thrust. D. The South Tibet detachment merges with the Main Central thrust along the northern margin of the Lesser Himalayan Crystalline Nappes. The Sheopuri gneiss forms the South Tibet detachment footwall; the Bhimphedi and Phulchauki Groups are the hanging wall (Webb et al., 2011).

The first three interpretations are generally compatible with all models for Greater Himalayan Crystalline complex emplacement, although model A requires these rocks to taper to the south, contrary to predictions of wedge extrusion models, and model B requires them to taper to the north, contrary to predictions of tectonic wedging models. However, model D limits the leading edge of the Greater Himalayan Crystalline complex to the northern margins of the Lesser Himalayan Crystalline Nappes, where it is locally preserved. This precludes extrusion models.

FIELD TRIP

The trip takes us from the core of the Kathmandu synform northwestwards to the Main Central thrust / Mahabharat thrust, largely following National Highway 4 (Prithivi Highway). The principal focus is deformation across the contact between Sheopuri gneiss and schists of the Bhimphedi Group exposed in the Galchi area. Previous work here states that the contact is (1) indistinct, separating lateral equivalents (e.g., Stöcklin and Bhattarai, 1982); (2) the top-to-the-south Main Central thrust (e.g., Rai et al., 1998); (3) contained within the top-to-the-south Main Central thrust shear zone, with the schists overlying the gneisses (Johnson et al., 2001); or (4) the top-to-the-north South Tibet detachment (Webb et al., 2011). Observations along this transect allow us to test predictions of Lesser Himalayan Crystalline Nappe models for this contact; given the authorship it may be no surprise that the proposed stops display evidence in support of the fourth model. In turn, this structural framework is consistent with the tectonic wedging model discussed above (see section 3.1).

It is worth noting at this point that outcrop quality is generally poor throughout the Kathmandu Nappe region, so the first few stops may be quite discouraging. The rocks will typically be exposed in road-side outcrops of middling to terrible quality, with variable degrees of in-place alteration. But do not lose heart: the erosive power of the Mahesh Khola (Mahesh River) ensures that Stops 5 and 6 alone are worth the price of admission, with spectacular continuous outcrop along the stream bank.

STOPS 1 & 2: Phulchauki Group immediately west of Kathmandu; chlorite-bearing Bhimphedi Group.

Tracking the initial increase in metamorphic grade with structural depth: chlorite zone.

Make one or two quick stops early in the day to establish the lack of high grade rocks in the core of the Kathmandu synform. Outcrops are poor and traffic can be too difficult for road-side observation (you'll still be in the Kathmandu city area), so play this portion of the trip by ear. The road quickly passes through the Chandragiri Limestone and Sopyang Slates of the Phulchauki Group and the Tistung Formation of the Bhimphedi Group be-

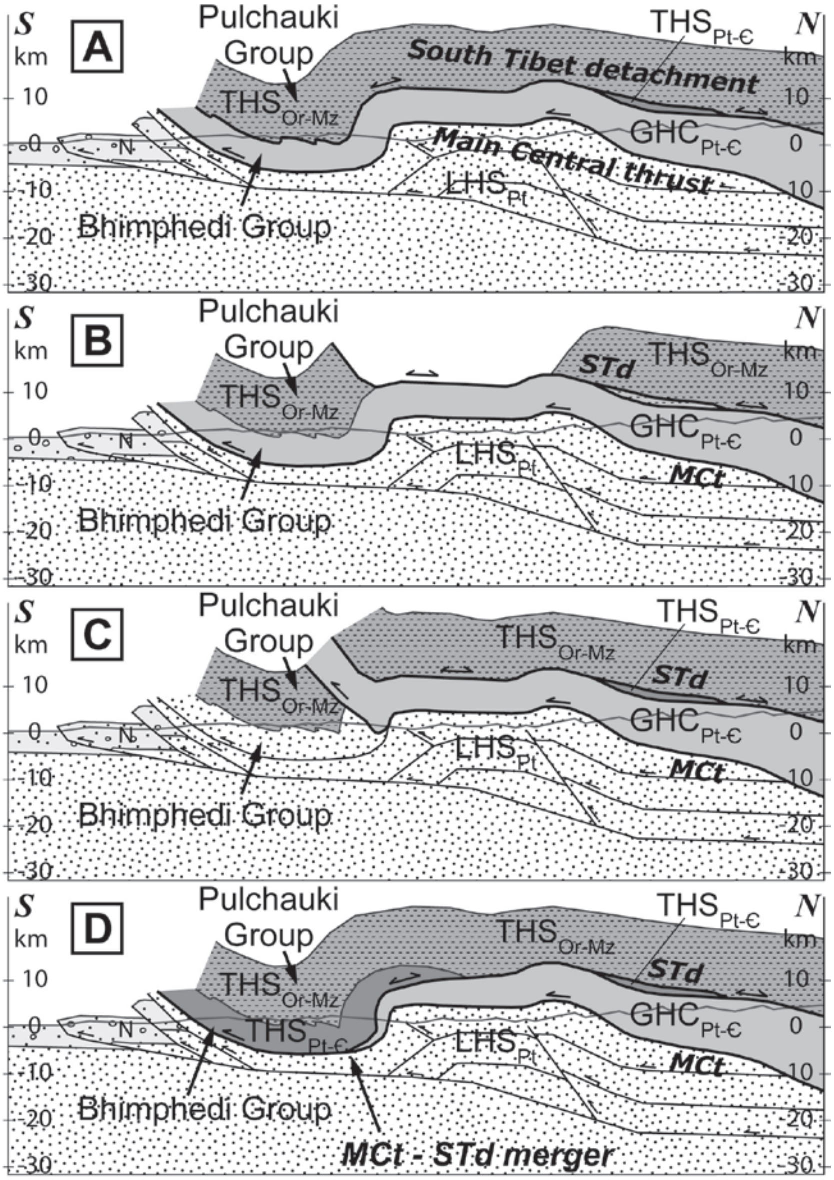


Figure 6
Cross-sections with different interpretations of the Lesser Himalayan Crystalline Nappes (the Bhimphedi and Pulchauki Groups) taken from Webb et al. (2011). THS = Tethyan Himalayan Sequence; GHC = Greater Himalayan Crystalline complex; LHS = Lesser Himalayan Sequence.

fore largely following the Mahesh Khola (Mahesh River) through Kulikhani quartzites, phyllites, and schists (Bhimphedi Group) (Figure 2).

STOP 3: Biotite-bearing Bhimphedi Group (Kulikhani Formation). Location: N27°45.982', E85°02.527'.

Tracking the gradual increase in metamorphic grade with structural depth: biotite zone.

This road-side stop is in the Kulikhani member Formation of the Bhimphedi Group as mapped by Stöcklin and Bhattarai (1982) and the biotite zone as mapped by Johnson et al. (2001) (Figures 2, 3). Main lithologies are biotite schists and quartzites, with foliation dipping steeply to moderately to the south-southeast. The foliation features a crenulation lineation plunging shallowly to the east-southeast. Thin (~50 m) sills of augen granite gneiss also outcrop near this stop; one such sill ~1.5 km down section (near the garnet-in isograd) yielded a ~470 Ma U-Pb zircon crystallization age (Johnson et al., 2001).

STOP 4: Garnet-bearing Bhimphedi Group (Kulikhani Formation). Location: N27°47.832', E85°00.731'.

Tracking the gradual increase in metamorphic grade with structural depth: garnet zone

The structural position of this road-side stop is somewhat debated: it is in the mixed zone of Sheopuri gneiss and the Kulikhani member Formation (Bhimphedi Group) as mapped by Stöcklin and Bhattarai (1982), and the garnet zone of the Bhimphedi Group as mapped by Johnson et al. (2001) and Webb et al. (2011) (Figures 2, 3). The main lithology is garnet – biotite schist, with garnets up to 3 mm in diameter, with foliation dipping steeply to moderately to the south-southeast. The schists are crenulated, with the crenulation fold axis plunging moderately to the southwest. Outcrop quality is generally poor.

STOP 5: Galchi shear zone on the southwestern bank of the Mahesh Khola. Location: N27°47.901', E85°00.213'.

Shear zone developed across quartzites and gneisses.

This stop is a highlight of the trip: here we may explore deformation along the contact between Sheopuri gneiss and schists of the Bhimphedi Group. Park vehicles at the southeastern limits of the village Galchi, walk down a steep path to the southwestern bank of the Mahesh Khola, walk ~400 m upstream, and then work your way back this route making observations (Figure 7). The working area is roughly coincident with the kyanite-in isograd as mapped by Johnson et al. (2001) (Figure 4), and observations outlined herein largely follow Webb et al. (2011). Note: the path down to the Mahesh Khola is not long, but it is *very* steep and so must only be attempted with great care in good weather.

Foliation here generally dips steeply / sub-vertically to the south-southeast. At the farthest southeast, upstream point of this stop, quartzites with meter-scale tight asymmetric cylindrical folds of parallel bedding and micaceous foliation occur (Figure 8). The fold asymmetry suggests an oblique (south block up, left-lateral) shear sense in present orientation.

To the northwest, the quartzites are underlain by a ~200 m thick section of psammitic and pelitic gneiss with minor leucogranitic lenses. These rocks represent the uppermost Sheopuri gneiss. They are strongly deformed, forming a shear zone that Webb et al. (2011) termed the Galchi shear zone after the local village. The remainder of this stop (back towards the parking spot) extends across the upper (southeastern) half of the Galchi shear zone. The upper half of the shear zone features sheath folds, mineral stretching lineations defined by biotite, feldspar, and tourmaline which are parallel to the long axes of the sheath folds (plunging moderately to the west-southwest), S-C fabric, S-C' fabric, sigma-type porphyroclasts, and meter-scale asymmetric boudinage. Leucogranitic lenses are foliated and deformed by asymmetric boudinage, indicating that they are pre- and/or syn-kinematic. Excepting decimeter-scale antithetic thrust faults, all structures have a consistent sense of shear: the Galchi shear zone appears to be an east-northeast striking steep oblique fault with left-lateral, south-block-up motion. Interpretation of the kinematics is discussed in the context of Stop 6, see below.

STOP 6: From the Galchi shear zone to the Main Central thrust / Mahabharat thrust on the northeastern bank of the Mahesh Khola. Location: N27°47.916', E85°00.158'.

Shear zone developed across gneisses, succeeded to the north, i.e., down structural section, by (first) relatively undeformed metasedimentary rocks and (second) a shear zone with opposite shear sense.

Stop 6 continues exploration of the Galchi shear zone, starting where Stop 5 left off, but on the northeast bank of the river (Figure 9). To get to this point, get back in the vehicles and travel a short distance along the road heading north from Galchi along the Trishuli River. At the bridge that crosses the Mahesh Khola, disembark and walk a little farther east (<100 m) along the road, then head up a trail to the right. The trail will wind steeply up a hill, then steeply down to the Mahesh Khola. Walk upstream along the Mahesh Khola until you are opposite from the end-point of Stop 6. At this point, start making observations and work back to the base of the bridge over the Mahesh Khola.

At the starting point of the Stop 6 work, again observe psammitic and pelitic gneiss with minor leucogranitic lenses, strongly deformed in the Galchi shear zone. Structural fabrics match Stop 5 in type, orientation, and shear sense. Sheath folds dominate the basal ~30 meters of the shear zone (Figure 10A). A pre- and/or syn-kinematic leucogranitic lense here (deformed by asymmetric boudinage) yields a U-Pb zircon crystallization age of ~30-20 Ma, consistent with a latest Oligocene / earliest Miocene oldest age limit for some shearing here (Figure 10B) (Webb et al., 2011). Sparse late structures observed here include decimeter-scale bookshelf normal fault systems and meter-scale thrust faults with associated cylindrical folds, again sharing the left-lateral, south-block-up motion (Figure 10C).

To the north (downsection), the Galchi shear zone is underlain by a ~300 m thick section of quartz-rich garnet mica schists. These rocks are differentiated from the Galchi shear zone by the amount of felsic / mafic segregation (i.e., they're schists, not gneiss) and because the dominant structural fabric is mica foliation, with S-C fabric occurring in only a ~10 m thick layer. This layer occurs in the middle of the section and has opposite shear sense vs. the Galchi shear zone. That is, shear sense in the ~10 m thick layer is oblique with right-lateral, south-block-down motion.

The foliation-dominated schists persist to the base of the Galchi bridge, which cuts off the transect. Back at the road (just ~10 meters farther downsection to the north), garnet-mica schists display S-C and S-C' fabric with right-lateral, south-block-down sense of shear. These schists represent the top of a ~1 km thick shear zone dominated by similar fabrics, i.e., the Main Central thrust / Mahabharat thrust.

Timing of shearing along the Main Central thrust / Mahabharat thrust and the Galchi shear zone. Regional timing constraints suggest that deformation along the Galchi shear zone and Main Central thrust / Mahabharat thrust occurred simultaneously or in close succession. The date of the deformed Galchi shear zone leucogranite requires that at least some shearing here occurred at or after the latest Oligocene / earliest Miocene, which is consistent with regional oldest limits for shearing along the Main Central thrust (e.g., Kohn et al., 2004; see summary by Godin et al.,

Figure 7
Stop 5 extends along the southwest (right) bank of the stream here; the south end of Stop 6 is at the left, foreground.

Figure 8
Top-to-the-northeast asymmetric folds in quartzite immediately above the gneiss of the Galchi shear zone, at Stop 5 (from Webb et al., 2011). Brunton compass for scale, view to southeast looking down ~40°.

2006). Ductile shear in both faults must cease by the middle Miocene, since a wealth of 40Ar/39Ar muscovite ages across the Lesser Himalayan Sequence and Kathmandu synform in this region yield middle Miocene dates (Arita et al., 1997; Herman et al., 2010).

Interpretation of shear sense along the Main Central thrust / Mahabharat thrust and the Galchi shear zone. The Main Central thrust / Mahabharat thrust appears as a sub-vertical, east-northeast striking shear zone with right-lateral, south-block-down sense of shear in the vicinity of Galchi village. The Galchi shear zone has the same orientation, with opposing shear sense. However, the regional map pattern (Figures 1, 2) demonstrates that the faults are folded within the Kathmandu synform here, so the synform deformation must be removed if we are to consider the direction of shearing during motion along the faults.

The "unfolding" of the Kathmandu synform requires assumptions because the Kathmandu synform is non-cylindrical. Webb et al. (2011)

Figure 9
View looking north-north-west (downstream) along the Mahesh Khola near Galchi, with the Trishuli River in the background (modified from Webb et al., 2011). Stop 6 extends along the northeast (right) bank of the stream here.

performed this exercise by assuming (1) that the active orientation and shear sense along the Main Central thrust / Mahabharat thrust were sub-horizontal / shallowly north-northeast dipping and top-to-the-south-southwest, respectively, and (2) the same rotations required to restore the Main Central thrust / Mahabharat thrust to this orientation could reasonably be applied to the Galchi shear zone to constrain its orientation and shear sense during fault motion. The details of their approach are described in Inset 1. The results are consistent with top-to-the-north-northeast motion along the sub-horizontal Galchi shear zone.

STOP 7: The Main Central thrust / Mahabharat thrust along the Trishuli River. Location: N27°48.542', E85°00.892'.

Top-S S-C fabric developed across garnet schist.

This road-side stop is in the Main Central thrust / Mahabharat thrust zone along the Trishuli River (Johnson et al., 2001; Pearson and DeCelles, 2005; Webb et al., 2011) (Figures 2, 3). The main lithology is garnet – mica schist, with garnets up to 8 mm in diameter. The schists display S-C fabric with main (C) foliation dipping steeply to the south-southeast (Figure 11). Shear sense is right-lateral, south-block-down in present coordinates.

Time-permitting, there is a very good opportunity to see these rocks well exposed just a little off the main road. This stop is near a bridge crossing a tributary of the Trishuli. A ~40 meter walk from this bridge along the south bank of the tributary, there is fresh exposure in a small waterfall to the right.

STOP 8: Lesser Himalayan quartzites along the Trishuli River. Location: N27°50.475', E85°01.397'.

Confirmation of the basal limit of the Kathmandu Nappe.

This stop extends north of the Main Central thrust / Mahabharat thrust zone to confirm the thickness of the shear zone and the presence of Lesser Himalayan Sequence rocks down-section. This road-side stop is in the Main Central thrust / Mahabharat thrust footwall along the Trishuli River (Johnson et al., 2001; Pearson and DeCelles, 2005; Webb et al., 2011) (Figures 2, 3). Here, fine-grained, grey, partially recrystallized quartzite layers dip steeply to the south-southeast.

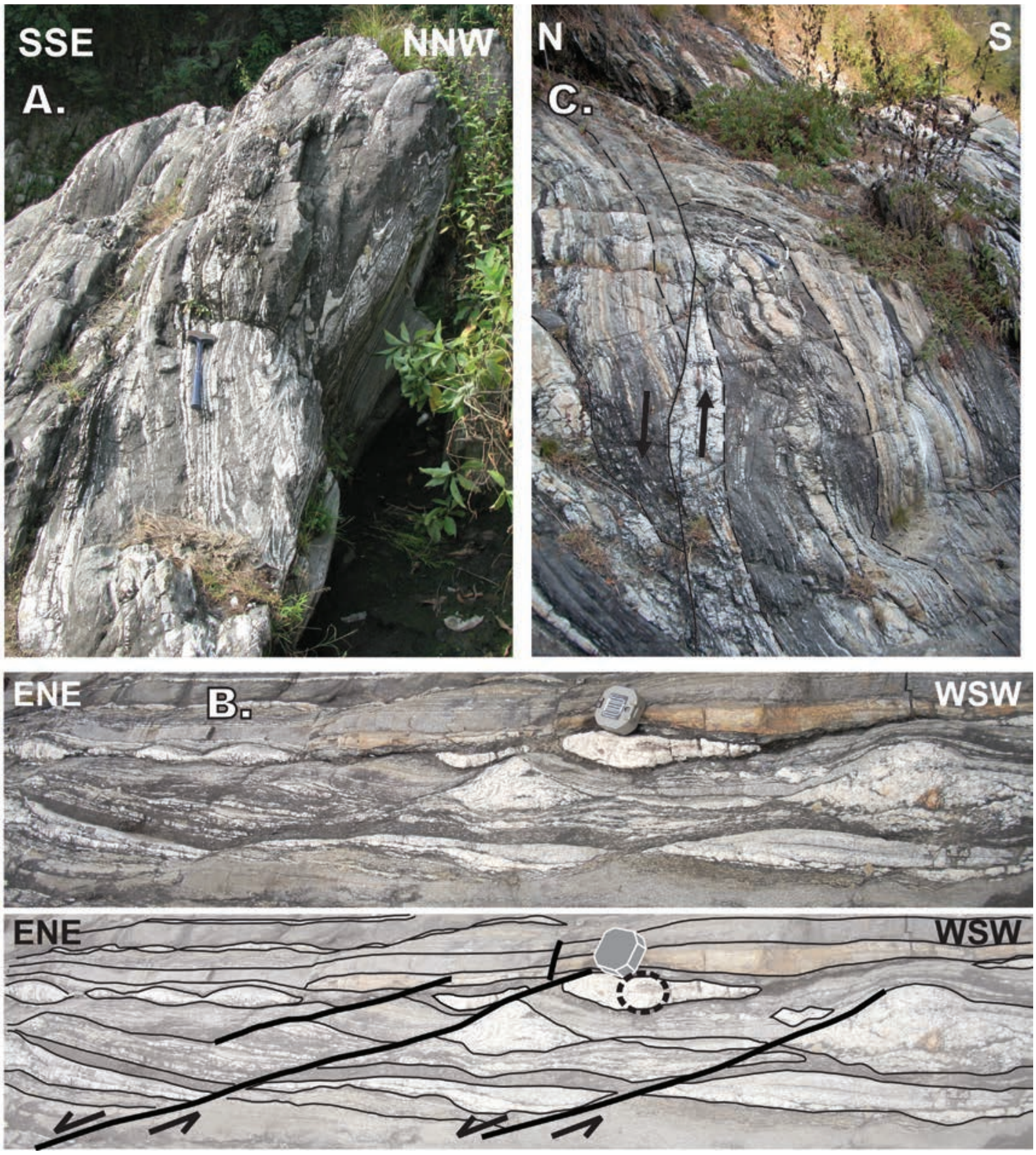


Figure 10
Photographs of deformation in the Galchi shear zone at Stop 6 (modified from Webb et al., 2011). A. Sheath fold, looking down the long axis. View looks to the west-southwest and down ~10°, hammer for scale. B. Composite photograph and line diagram of top-northeast asymmetric boudinage, including shear bands that cross-cut gneissic foliation and leucogranitic lenses. Dashed oval marks a dated leucogranite sample (U-Pb zircon crystallization age of ~30-20 Ma). View looking east-southeast and down ~50°, brunton compass for scale. C. Meter-scale thrust fault, view looking east and down ~10°, hammer for scale (circled).

If Time Permits STOP 9: The Main Central thrust / Mahabharat thrust along the Malekhu Khola. Location: N27°47.861', E84°50.135'.

Confirmation of the basal limit of the Kathmandu Nappe.

Given sufficient time, drive to Malekhu and walk ~1 km south along the Malekhu Khola (Figure 2). This walk leads upsection through Lesser Himalayan Sequence rocks to the Main Central thrust / Mahabharat thrust. Malekhu Khola geology is similar to that of the Mahesh Khola, with rocks and structures again dipping steeply to the south-southeast and structural elevation increasing to the south. However, the Galchi shear zone gneiss and fabrics and the underlying foliated quartz-rich garnet mica schists (above the Main Central thrust / Mahabharat thrust) do not appear here.

The Main Central thrust here is a ~600 m thick shear zone dominated by S-C fabric; sense of motion is oblique (right-lateral with the south-block moving down). Quartzite and phyllonite of the Lesser Himalayan Sequence portion of the Main Central thrust / Mahabharat thrust display asymmetric boudinage and tension gashes (Figure 12). The southern portion of the Main Central thrust zone is dominated by garnet mica schist with S-C fabric. A <100 m thick layer of marble (Bhainse-

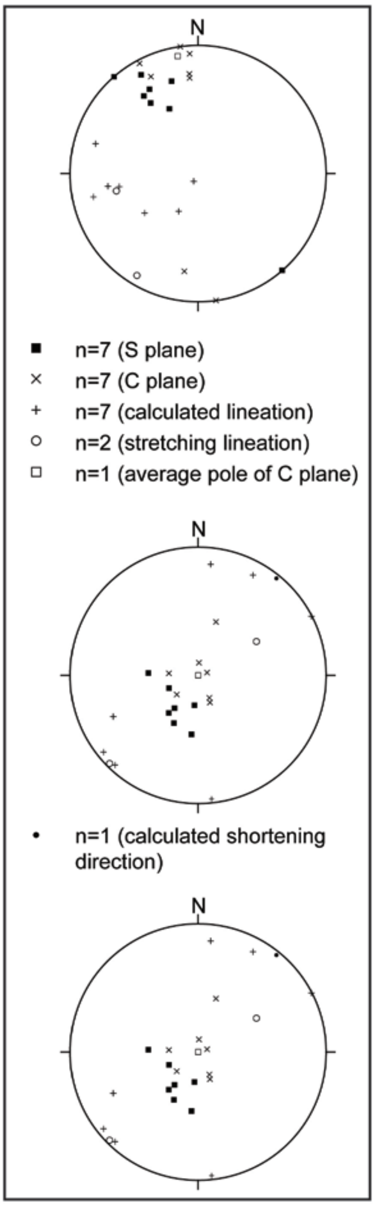
Inset 1.

To evaluate the kinematics of the Main Central thrust / Mahabharat thrust and Galchi shear zone, it is useful to rotate them into the orientation in which they were active. Since the two faults may have synchronous motion and the Main Central thrust / Mahabharat thrust is known to be folded within the Kathmandu synform (e.g., Stocklin, 1980; Johnson et al., 2001), this folding must be "removed" to restore both faults. Because of the non-cylindrical geometry of the Synform, rotation around a single pole cannot restore the folding. At least two poles of rotation are required, but as the strain path is unknown the selection of such poles is non-unique. The approach taken by Webb et al. (2011) is to assume the pre-synform geometry of the Main Central thrust / Mahabharat thrust, restore data from this structure via two rotations, and then use the same rotations to restore the Galchi shear zone structures.

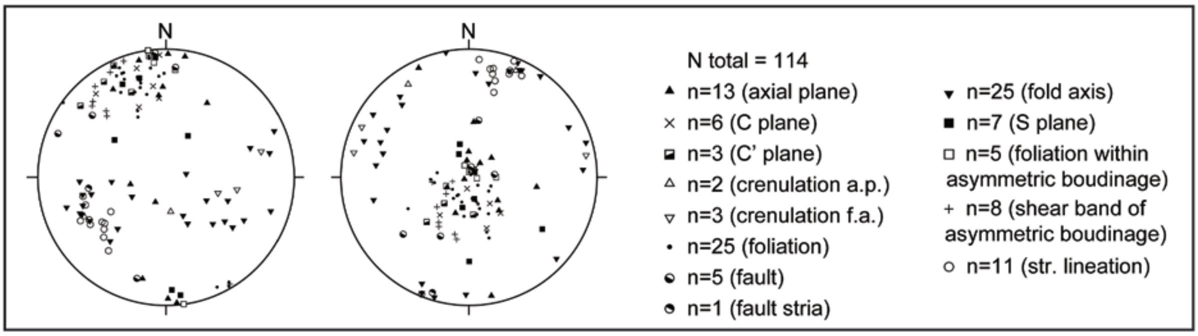
All current models imply a sub-horizontal or shallowly north-northeast dipping Main Central thrust / Mahabharat thrust with a top south-southwest shear direction during activity on this structure in this sector of the orogen (e.g., Burchfiel and Royden, 1985; Beaumont et al., 2001; Yin, 2006). Therefore the Main Central thrust rotation stereoplots (at right) first collects all directional shear data for this structure from the parallel exposures along the Malekhu Khola and Mahesh Khola transects (upper stereoplot). These data are stretching lineations and calculated lines of motion from S-C pairs (calculated lineations). The average pole to C planes is calculated and plotted (trend and plunge of 350.1°, 7.7°). The first rotation restores this pole to a vertical line, thus restoring the Main Central thrust plane to a sub-horizontal orientation (middle stereoplot: the specific rotation is an 82.3 degree rotation around a horizontal pole trending towards 080.1°; the rotation is counter-clockwise if viewed along the horizontal pole looking to the east-northeast). In this new orientation, an average shortening direction is determined from the lineation data (calculated shortening direction; trend and plunge are 39.0°, 3.1° with a top-southwest sense of motion). The front of the range in this sector of the orogen trends ~105°, and it is assumed that this represents the former orientation. The shortening direction should be perpendicular to this trend. The data is therefore rotated 24 degrees counterclockwise around a vertical pole, such that the sense of motion is top towards 195° (lower stereoplot).

The same two rotations to the Galchi shear zone structures (below), such that the restored Galchi shear zone remains parallel to the restored Main Central thrust. The left stereoplot shows the measured data; the right stereoplot shows the restored data. Linear structures that parallel the shear direction are lineations and fold axes along the long axes of sheath folds: after restoration these have a north-northeast trend and shallow plunge. Restored poles to foliation and C planes are sub-vertical, indicating a subhorizontal fault plane; restored cylindrical fold axes cluster shallowly to the west-northwest and to the east. These restored data are all consistent with a top north-northeast sense of motion along a sub-horizontal Galchi shear zone.

Main Central thrust / Mahabharat thrust rotation



Galchi shear zone rotation



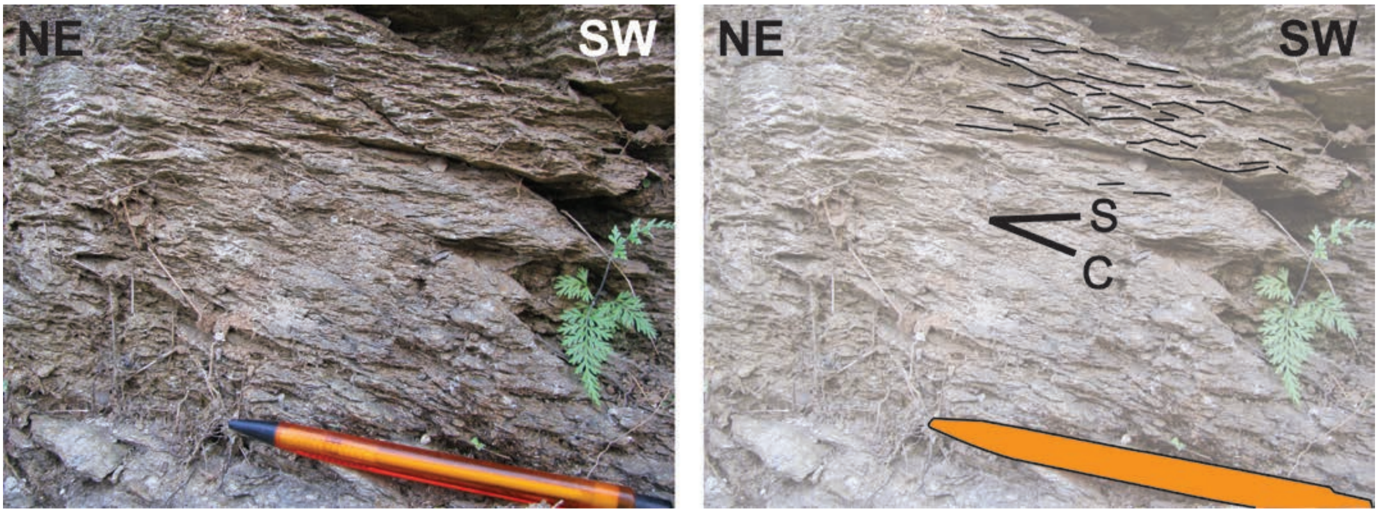


Figure 11
Top-to-the-southwest S-C fabric within the Main Central thrust / Mahabharat thrust shear zone at Stop 7 (from Webb et al., 2011). View looking down ~40° to the southeast, pencil for scale.

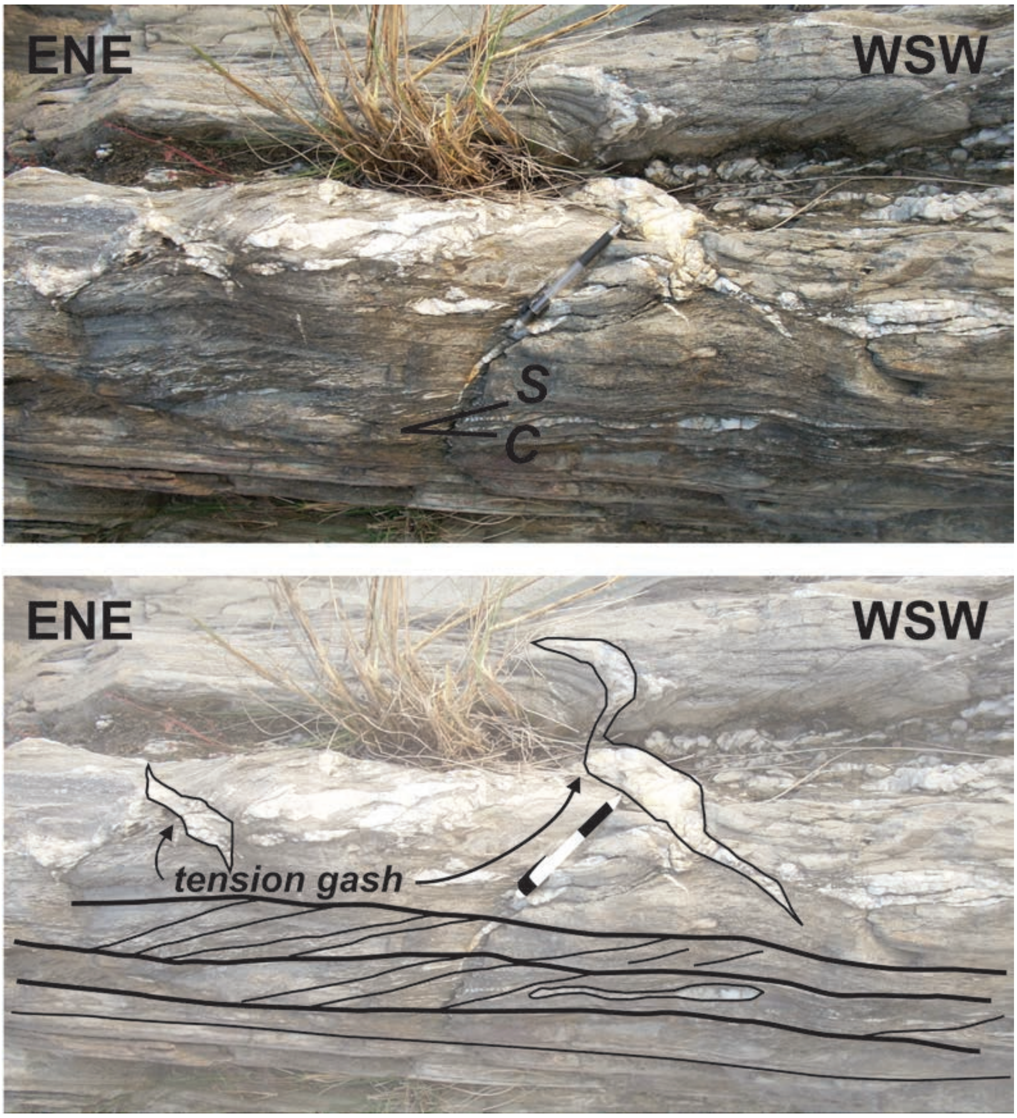


Figure 12
Top-to-the-southwest S-C fabric within the Main Central thrust / Mahabharat thrust shear zone at Stop 7 (from Webb et al., 2011). View looking down ~40° to the southeast, pencil for scale.

dobhan Marble of Bhimphedi Group, Stöcklin and Bhattarai, 1982) occurs immediately above Main Central thrust zone. Farther south, micaceous quartzites, garnet-biotite schist, biotite schist of Kalitar Formation and Chisapani Quartzite (Bhimphedi Group, Stöcklin and Bhattarai, 1982) dominate; a ~200 m thick foliated granitic sill occurs ~1.5 km south of the marble. Metamorphic grade is inverted across the Main Central thrust but right-way-up in its hanging wall. No gneiss or leucogranitic rocks are observed, and the garnet isograd occurs ~2 km above the shear zone. The lithologies, right-way-up metamorphic field gradient, and structural fabrics observed across the Main Central thrust / Mahabharat thrust hanging wall are consistent with the Bhimphedi Group.

SUMMARY

The field trip allows participants to explore the following aspects of Kathmandu Nappe geology: (1) the right-way-up metamorphic field gradient that dominates the Kathmandu synform; (2) the deformation along the Galchi shear zone separating the Sheopuri gneiss from the Bhimphedi Group, which has opposite sense of shear vs. the Main Central thrust / Mahabharat thrust; and (3) the presence of kyanite-bearing gneiss between the Galchi shear zone and the Main Central thrust / Mahabharat thrust near Galchi vs. the absence of both gneiss and the Galchi shear zone in the Main Central thrust / Mahabharat thrust hanging wall near Malekhu. These features are discussed at length in Webb et al. (2011), who use them to support a tectonic wedging model for the emplacement of the Greater Himalayan Crystalline complex (Figure 5D), with the Galchi shear zone interpreted as the South Tibet detachment. In this model, the Sheopuri gneiss is interpreted as Greater Himalayan Crystalline complex rocks, and the Bhimphedi and Phulchauki Groups are interpreted as the lower sections of the Tethyan Himalayan Sequence. We hope that the field trip provides an opportunity for happy, spirited discussion and meaningful insights on questions such as the Lesser Himalayan Crystalline Nappe problem, the development of the South Tibet detachment, and the emplacement of the Greater Himalayan Crystalline complex.

ACKNOWLEDGEMENTS

This work has been supported by grants from the Louisiana Board of Regents (LEQSF(2012-15)-RD-A-12) and the Tectonics program of the U.S. National Science Foundation (EAR-1322033). We thank the Nepal Geological Society for organizing the 27th Himalaya-Karakoram-Tibet Workshop and encouraging us to organize the post-conference field excursion that led to this guide. Similarly, we extend our warm regards and appreciation to the Himalayan geologists and Tribhuvan University geoscience students who accompanied us on the field excursion and provided useful feedback. We thank editor Rodolfo Carosi and an anonymous reviewer for comments that helped to improve this guide.

REFERENCES

Argand, E., 1924, La Tectonique de l'Asie: Proc. Int. Geol. Cong. 7, 171-372.

Arita, K., Dallmeyer, R.D., Takasu, A., 1997. Tectonothermal evolution of the Lesser Himalaya, Nepal: constraints from Ar/Ar ages from the Kathmandu Nappe: The Island Arc 6, 372– 385.

Beaumont, C., Jamieson, R.A., Nguyen, M.H. and Lee, B., 2001, Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation: Nature, v. 414, p. 738-742.

Beaumont, C., Jamieson, R.A., Nguyen, M.H.,Medvedev, S., 2004, Crustal channel flows: 1. Numerical models with applications to the tectonics of the Himalayan-Tibetan orogen: Journal of Geophysical Research 109, B06406, (doi:10.1029/2003JB002809).

Bhargava, O.N., 1995, The Bhutan Himalaya: A Geological Account: Geological Survey of India Special Publication 39, 244 p.

Burchfiel, B.C. and Royden, L.H., 1985, North-south extension within the convergent Himalayan region: Geology, v. 13, p. 679-682.

Burchfiel, B. C., Zhiliang, C., Hodges, K. V., Yuping, L., Royden, L. H., Changrong, D. and Jiene, X., 1992, The South Tibetan Detachment System, Himalayan Orogen: Extension contemporaneous with and parallel to shortening in a collisional mountain belt: GSA Special Paper 269: 1-41.

Burg, J. P., Brunel, M., Gapais, D., Chen, G. M. and

Liu, G. H., 1984, Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China): J Structural Geology 6 (5): 535-542.

Caby, R., Pecher, A., LeFort, P., 1983, Le grande chevauchement central himalayen: nouvelles donnees sur le metamorphisme inverse a la base de la Dalle du Tibet. Revue de Geographie physiqueau et Geologie dynamique 24 89-100.

Dahlen, F. A., Critical taper model of fold-and-thrust belts and accretionary wedges, Ann. Rev. Earth Planet. Sci, 18, 55-90, 1990.

Davis, D., Suppe, J., Dahlen, F.A., 1983, Mechanics of fold-and-thrust belts and accretionary wedges. Journal of Geophysical Research 88(B2), 1153–1178.

Dewey, J.F., Bird, J.M. (1970). "Mountain belts and new global tectonics". Journal of Geophysical Research 75 (14): 2625–2685.

Fuchs, G., 1982, Geologic-tectonical map of the Himalaya at 1:2000000 scale. Geologische Bundesanstalt, Wien.

Gehrels, G.E., DeCelles, P.G., Martin, A., Ojha, T.P., Pinhassi, G., Upreti, B.N., 2003, Initiation of the Himalayan Orogen as an early Paleozoic thin-skinned thrust belt: GSA Today 13 (9), 4-9.

Gehrels, G.E., DeCelles, P.G., Ojha, T.P., Upreti, B.N., 2006, Geologic and U-Th-Pb geochronologic evidence for early Paleozoic tectonism in the Kathmandu thrust sheet, central Nepal Himalaya: Geological Society of America Bulletin 118, 185-198.

Godin, L., Grujic, D., Law, R.D., Searle, M.P. 2006. Channel flow, ductile extrusion and exhumation in continental collision zones: an introduction. Geological Society, London , Special Publications, v. 268, 1-23.

Heim, A., and Gansser, A., 1939, Central Himalaya Geological Observations of the Swiss Expedition 1936: Zurich, Gebrüder Fretz, 246 p.

Herman, F., Copeland, P., Avouac, J.P., Bollinger, L., Maheo, G., Le Fort, P., Rai, S., Foster, D., Pecher, A., Stuwe, K., Henry, P., 2010. Exhumation, crustal deformation, and thermal structure of the Nepal Himalaya derived from the inversion of thermochronological and therobarometric data and modeling of the topography.

Hodges, K.V., 2000, Tectonics of the Himalaya and southern Tibet from two perspectives: Geological Society of America Bulletin, v. 112 (3), p. 324-350.

Hodges, K.V., Hurtado, J.M., and Whipple, K.X., 2001, Southward extrusion of Tibetan crust and its effect on Himalayan tectonics: Tectonics, v. 20, p. 799–809, (doi:10.1029/2001TC001281).

Johnson, M.R.W., Oliver, G.J.H., Parrish, R.R., Johnson, S.P., 2001, Synthrusting metamorphism, cooling, and erosion of the Himalayan Kathmandu complex, Nepal: Tectonics 20, 394–415.

Johnson, M.R.W., 2005, Structural settings for the contrary metamorphic zonal sequences in the internal and external zones of the Himalaya: Journal Asian Earth Sciences 25, 695-706.

Kohn, M.J., Wieland, M.S., Parkinson, C.D., and Upreti, B.N., 2004, Miocene faulting at plate tectonic velocity in the Himalaya of central Nepal: Earth and Planetary Science Letters, v. 228, p. 299–310, (doi:10.1016/j.epsl.2004.10.007).

Kohn, M.J., 2008, P-T-t data from central Nepal support critical taper and repudiate large-scale channel flow of the Greater Himalayan Sequence: Geological Society of America Bulletin, v. 120, p. 259–273, (doi:10.1130/B26252.1).

Le Fort, P., 1975, Himalaya: The collided range. Present knowledge of the continental arc: American Journal of Science 275A (1-44).

Pandey, M.R., Tandukar, R.P., Avouac, J.P., Lave, J., Massot, J., 1995, Interseismic strain accumulation on the Himalayan crustal ramp (Nepal). Geophysical Research Letters 22, 751-754.

Pearson, O.N., DeCelles, P.G., 2005, Structural geology and regional significance of the Ramgarh thrust, Himalayan fold-thrust belt of Nepal: Tectonics, v. 24, no. 4, TC4008, (doi:10.1029/2003TC001617).

Pecher, A., Le Fort, P., 1986. The metamorphism in Central Himalaya its relations with the thrust tectonic. In: Le Fort, P.,Colchen, M., Montenat, C. (Eds.), Evolution des domaines orogeniques d'Asie meÂridionale (de la Turquie a l'Indone Âsie) Volume mem, vol. vol. 47. Science de la Terre, Nancy, pp. 285-309.

Rai, S.M., Guillot, S., LeFort, P., Upreti, B.N., 1998, Pressure-temperature evolution in the Kathmandu and Gosainkund regions, Central Nepal: Journal of Asian Earth Sciences 16, 283-298.

Robinson, D.M., DeCelles, P.G., and Copeland, P., 2006, Tectonic evolution of the Himalayan thrust belt in western Nepal: implications for channel flow models: Geological Society of America Bulletin, v. 118, p. 865-885.

Searle, M.P. 1986. Structural evolution and Sequence of Thrusting in the high Himalayan, Tibetan-Tethys and Indus Suture Zones of Zanskar and ladakh, Western Himalaya. Journal of Structural Geology, vol. 8 923-925,927-936

Searle, M.P., Law, R.D., Godin, L., Larson, K.P., Streule, M.J., Cottle, J.M., Jessup, M.J., 2008, Defining the Himalayan Main Central Thrust in Nepal: Journal of the Geological Society 164, 523-534.

Stöcklin, J., 1980, Geology of Nepal and its regional frame: Journal of the Geological Society 137, 1– 34.

Stöcklin, J., and Bhattarai, K.D., 1982, Photogeological map of part of central Nepal: Kathmandu, Ministry of Industry and Commerce, Department of Mines and Geology, scale 1:100,000.

Upreti, B.N., 1999, An overview of the stratigraphy and tectonics of the Nepal Himalaya: Journal of Asian Earth Sciences 17, 577-606.

Upreti, B.N. and Le Fort, P., 1999, Lesser Himalayan crystalline nappes of Nepal: problems of their origin: Geological Society of America Special Paper 328, 225-238.

Webb, A.A.G., Yin, A., Harrison, T.M., Célérier, J., and Burgess, W.P., 2007, The leading edge of the Greater Himalayan Crystallines revealed in the NW Indian Himalaya: Implications for the evolution of the Himalayan Orogen: Geology, v. 35 (10), p.955-958.

Webb, A.A.G., Schmitt, A.K., He, D., Weigand, E.L., 2011, Structural and geochronological evidence for the leading edge of the Greater Himalayan Crystalline complex in the central Nepal Himalaya. Earth and Planetary Science Letters. v. 304, p. 483-495.

Webb, A.A.G., Yin, A., Dubey, C.S., 2013, U-Pb zircon geochronology of major lithologic units in the eastern Himalaya: Implications for the origin and assembly of Himalayan rocks. Geological Society of America Bulletin, v. 125, p. 499-522.

Windley, B.F., 1988, Tectonic framework of the Himalaya, Karakoram and Tibet, and problems of their evolution. Phil. Trans. R. Soc. Lond. A 326, 3-16.

Yin, A., 2006, Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation: Earth Science Reviews, v. 76, p. 1-131.

Zhang, R., Murphy, M., Lapen, T.J., Sanchez, V., Heizler, M., 2011, Late Eocene crustal thickening followed by Early-Late Oligocene extension along the India-Asia suture zone: Evidence for cyclicity in the Himalayan orogen: Geosphere v.7, 1249-1268.