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Authors
Harvey, Jonathan E
Burbank, Douglas W
Bookhagen, Bodo

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Along-strike changes in Himalayan thrust geometry: Topographic and tectonic discontinuities in western Nepal

Jonathan E. Harvey[1,*], Douglas W. Burbank[1], and Bodo Bookhagen[2]
[1]DEPARTMENT OF EARTH SCIENCE, UNIVERSITY OF CALIFORNIA–SANTA BARBARA, SANTA BARBARA, CALIFORNIA 93106, USA
[2]INSTITUTE OF EARTH AND ENVIRONMENTAL SCIENCE, UNIVERSITY OF POTSDAM, 14476 POTSDAM-GOLM, GERMANY

ABSTRACT

Geodetic and seismologic studies support a tectonic model for the central Himalaya wherein ~2 cm/yr of Indo-Asian convergence is accommodated along the primary décollement under the range, the Main Himalayan thrust. A steeper midcrustal ramp in the Main Himalayan thrust is commonly invoked as driving rapid rock uplift along a range-parallel band in the Greater Himalaya. This tectonic model, developed primarily from studies in central Nepal, is commonly assumed to project along strike with little lateral variation in Main Himalayan thrust geometry or associated rock uplift patterns. Here, we synthesize multiple lines of evidence for a major discontinuity in the Main Himalayan thrust in western Nepal. Analysis of topography and seismicity indicates that west of ~82.5°E, the single band of steep topography and seismicity along the Main Himalayan thrust ramp in central Nepal bifurcates around a high-elevation, low-relief landscape, resulting in a two-step topographic front along an ~150 km segment of the central Himalaya. Although multiple models could explain this bifurcation, the full suite of data appears to be most consistent with a northward bend to the Main Himalayan thrust ramp and activation of a young duplex horse to the south. This poorly documented segmentation of the Main Himalayan thrust has important implications for the seismogenic potential of the western Nepal seismic gap and for models of the ongoing evolution of the orogen.

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INTRODUCTION

Topography within active mountain belts commonly reflects spatial patterns of rock uplift: As rock uplift rates increase, rivers tend to steepen (Snyder et al., 2000), hillslopes increase up to a threshold (Burbank et al., 1996), and overall topographic relief increases (Ahnert, 1970). Analysis of topographic metrics can reveal these spatial patterns of rock uplift, in turn providing information about strain partitioning, fault segmentation, and geometry of subsurface structures (see review in Kirby and Whipple, 2012), and improving our understanding of the earthquake cycle along active faults.

The Nepalese Himalaya are among the classic orogens in which tectonics have been interpreted from topography. Numerous geodetic, geomorphic, and geochronological studies suggest that the Himalayan region of central Nepal is undergoing rapid rock uplift north of a sharp physiographic transition from the foothills to the high Himalaya (e.g., Seeber and Gornitz, 1983; Jackson and Bilham, 1994; Wobus et al., 2003; Grandin et al., 2012). Many of these studies agree that uplift occurs where the orogenic wedge passes over a midcrustal ramp in the basal detachment, the Main Himalayan thrust, (e.g., Cattin and Avouac, 2000), although underplating along the Main Himalayan thrust and potential out-of-sequence thrusting may have shifted the locus of deformation over time (e.g., Bollinger et al., 2004; Hodges et al., 2004). Field efforts supporting these interpretations have been focused heavily on central Nepal, where topography rises abruptly from the Lesser to the Greater Himalaya along a physiographic transition commonly referred to as PT2 (Hodges et al., 2001). This conceptual model is frequently projected along strike with little discussion of lateral variations in structural architecture.

Here, we integrate topographic, geologic, and seismic data to highlight an along-strike discontinuity in range-front topography between central and western Nepal, which we argue is the surface expression of an abrupt change in the geometry and kinematic history of the Main Himalayan thrust. We evaluate multiple hypotheses for the nature of this discontinuity in the context of prevailing models for Himalayan tectonics. Among the plausible explanations, the interpretation most consistent with our observations suggests that in mid-western Nepal, the Main Himalayan thrust ramp splits into two strands that bound a broad duplex horse. This physiographic and tectonic transition represents a poorly described segmentation of the Main Himalayan thrust with important implications both for seismic hazards, as demonstrated most recently by the devastating M 7.8 Gorkha earthquake in central Nepal, and for the ongoing tectonic evolution of the orogen.

*harvey@eri.ucsb.edu; present address: Department of Geosciences, Fort Lewis College, Durango, CO 81301, USA.

GEOLOGIC SETTING

The Himalaya stretch nearly 3000 km along the boundary between the Indian and Asian plates. Since at least the mid-Miocene, a series of south-vergent thrust faults have accommodated shortening across the range and generally define boundaries between the major tectonostratigraphic units (Gansser, 1964). These structures are interpreted to sole into the Main Himalayan thrust at depth. In the central Himalaya, the Main Central thrust placed the high-grade metamorphic core of the Greater Himalayan Series over the low- to medium-grade rocks of the Lesser Himalayan Series in the early Miocene (Hubbard and Harrison, 1989). Farther south, the Main Boundary thrust placed the Lesser Himalayan Series over deformed foreland basin sediments of the Siwaliks/Subhimalaya in the late Miocene–early Pliocene, although in some parts of the Himalaya, it may have been active into the Quaternary (e.g., Huyghe et al., 2005).

Since the early Pleistocene, ~2 cm/yr of convergence between the Indian and Eurasian plates have been absorbed across the central Himalaya (Bilham et al., 1997). Nearly all of this shortening is interpreted to be accommodated along the Main Himalayan thrust, which reaches the surface as the Main Frontal thrust (Lavé and Avouac, 2000). Working models for the behavior of the Main Himalayan thrust generally agree that during the interseismic period, the fault is locked downdip from the surface to a creeping ductile shear zone beneath the High Himalaya (e.g., Avouac, 2003). Recent estimates for the Main Himalayan thrust in central Nepal suggest that this brittle-ductile transition lies at 10–15 km depth, ~100 km downdip from the Main Frontal thrust (Ader et al., 2012), where temperatures approach ~350 °C (Herman et al., 2010). Elastic stress that builds in the locked thrust sheet is released during occasional large (Mw ≈ 8.0) earthquakes that rupture along the Main Himalayan thrust toward the surface at the Main Frontal thrust. This slip style was exhibited most recently by the 2015 M 7.8 Gorkha earthquake in central Nepal, which claimed thousands of lives and caused strong ground shaking over a broad region. These recurrent events present an enormous hazard to rapidly growing populations along the mountain front (e.g., Bilham, 2004).

Integrated over geologic time, rapid transport of the orogenic wedge over the Main Himalayan thrust has generated the highest topography on Earth. In this tectonic setting, the geometry of the Main Himalayan thrust (namely, the dip of the fault and obliquity of transport) should impose a first-order control on rock uplift rates and thus the overall equilibrium topography of the range. As such, the sharp physiographic transition from the Lesser to the Greater Himalaya (Fig. 1), commonly referred to as PT2, has garnered much attention as indicative of a key tectonic change (e.g., Hodges et al., 2001). This informal boundary has been variably attributed to rapid rock uplift over a steeper ramp along the Main Himalayan thrust linking gentler sections beneath the Lesser Himalaya to the south and the Tibetan Plateau to the north (e.g., Cattin and Avouac, 2000), although

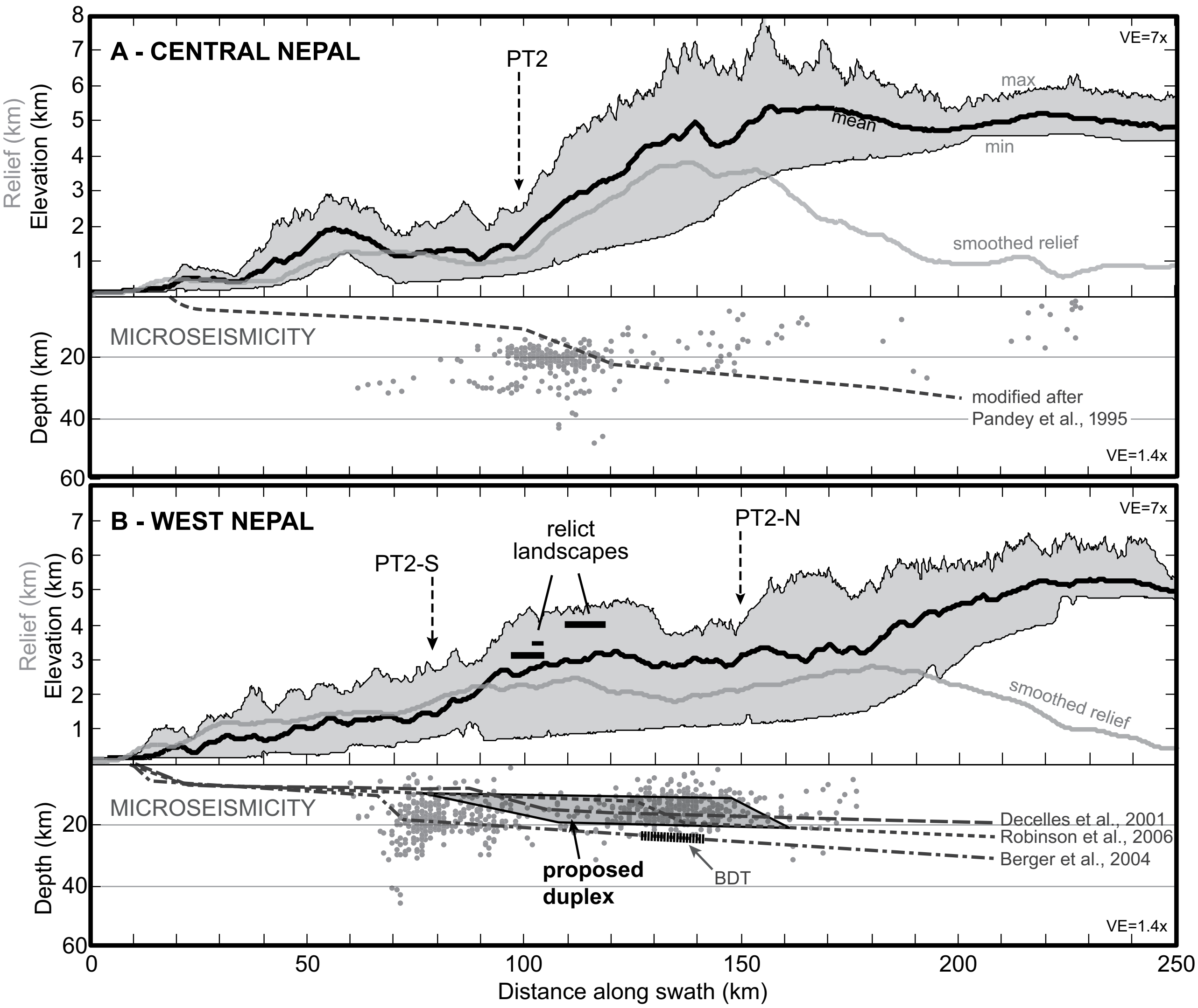

Figure 1. Topographic swath profiles oriented across (A) central Nepal and (B) west Nepal showing maximum, minimum, and mean elevations along the swaths, as well as smoothed 25 km relief (gray line). Lower panels of A and B show earthquake hypocenters from 3 yr of data from the National Seismic Center (1995–1996, 1996–1997, and 1998–1999), relocated by Ader et al. (2012) and projected onto the swath profile centerlines, as well as models of Main Himalayan thrust geometry by various authors (Main Himalayan thrust geometry from Pandey et al. [1995] projected ~100 km along strike from original cross section positioned at the longitude of Katmandu, modified to be consistent with original interpretations). Preferred model presented in this paper calls for duplex with geometry resembling that shown in gray polygon in the lower panel of B. Dark hachures on Berger et al. (2004) Main Himalayan thrust model indicate their inferred location of brittle-ductile transition (BDT). VE—vertical exaggeration.

some argue for out-of-sequence thrusting at the foot of the Greater Himalaya, (e.g., Wobus et al., 2003). Geodetic, geomorphic, and thermochronologic studies confirm that a zone of rapid uplift and exhumation lies immediately north of PT2, in contrast to the relatively low rates within the Lesser Himalaya (Jackson and Bilham, 1994; Lavé and Avouac, 2001; Copeland et al., 1991; Blythe et al., 2007).

Most studies assume an along-strike continuity to the active structures and associated topography found in central Nepal, although this assumption has only been tested on a few occasions. Morell et al. (2015) used physiography and catchment-mean erosion rates to argue for rapid rock uplift north of PT2 in Uttarakhand, India (78°E–81°E), consistent with the prevailing tectonic model for central Nepal. In contrast, Duncan et al. (2003) and Adams et al. (2013) argued that a feature resembling PT2 in Bhutan is likely a relict from Miocene tectonic activity, with more recent deformation focused closer to the foreland. Others have noted along-strike changes in global positioning system (GPS) velocities, (e.g., Jouanne et al., 1999; Berger et al., 2004), seismicity (e.g., Pandey et al., 1999), and in mineral cooling ages (e.g., Robert et al., 2011), each hinting at subtle along-strike changes in structural geometry and uplift history. No studies to date, however, have explored the active tectonics and related physiography of western Nepal in the context of the better-studied areas along strike. This omission is problematic, as documented earthquakes suggest that a broad seismic gap exists in west Nepal, where no large earthquake has been recorded in over 600 yr (Bilham, 2004). This apparent buildup of elastic strain may be recovered by a destructive Mw > 8.0 earthquake. In order to better understand the seismic hazard posed by the plate boundary in west Nepal, it is necessary to develop a more detailed understanding of active structures accommodating slip there than that afforded by simple along-strike projection of models from central Nepal.

APPROACH

Topographic Analysis

A growing body of literature demonstrates that in active orogens, spatial patterns of rock uplift are manifest in the topography (e.g., Kirby and Whipple, 2012). Systematic quantification and exploration of topographic metrics, such as hillslope angle, river channel slope, and local relief, can sometimes reveal first-order patterns of differential rock uplift that are difficult to observe otherwise. Furthermore, unsteady tectonic forcing through time can introduce transient features like knickpoints in river profiles, which can also be identified and analyzed via topographic analysis. We analyze digital topography to highlight along-strike changes in the geomorphology, physiography, and, ultimately, tectonic forcing of the central Himalayan mountain front between ~80°E and 86°E. All analyses were performed with elevation data from the Shuttle Radar Topography Mission (Farr and Kobrick, 2000) reprocessed to fill voids in the original data (Jarvis et al., 2008) and projected into a Lambert azimuthal equal-area projection centered at 35°N, 85°E, with a nominal spatial resolution of 90 m.

Geology and Seismicity

Bedrock geology in western Nepal was compiled from mapping by Fuchs (1977), Arita et al. (1984), DeCelles et al. (1998), DeCelles et al. (2001), Murphy et al. (2002), Murphy and Copeland (2005), and Robinson et al. (2006). Locations of recently active faults were compiled from a combination of data from Taylor and Yin (2009), Murphy et al. (2014), and our own mapping. Earthquake hypocenters from 3 years of data from Nepal's National Seismic Center (1995–1996, 1996–1997, and 1998–1999) relocated and reported by Ader et al. (2012) were projected onto range-perpendicular swath profiles for comparison with the topographic analysis.

RESULTS

First-order observations of topography reveal substantial morphologic differences along the Greater Himalayan mountain front in Nepal. Central Nepal is characterized by a linear, ~500-km-long mountain front rising ~4000 m over a distance of less than 50 km (Figs. 1A and 2). This front coincides with a belt of rapid interseismic uplift rates (Jackson and Bilham, 1994; Grandin et al., 2012) and is the basis for our interpretation of PT2. For an ~150-km-long segment of the range front west of ~82.5°E, the >5-km-high peaks of the Greater Himalaya retreat as far as ~75 km into the hinterland, with only an ~1.5-km-high escarpment in the along-strike projection of PT2 (Figs. 1B and 2). For the sake of discussion, we refer to the northern topographic step as PT2-N and the southern as PT2-S. The latter coincides roughly with the southern margin of the Miocene-aged Main Central thrust sheet, preserved locally as the Dadeldhura (or, to some authors, the Karnali) klippe (Robinson et al., 2006). The escarpment at PT2-N is of a similar magnitude as the southern, with mean elevations rising from ~3 km to ~5 km. These basic topographic observations are illustrated by the slope of mean topography, which shows the escarpments at both PT2-N and PT2-S in western Nepal (Fig. 2B).

In central Nepal, a band of high relief (>3 km) and steep hillslopes (>25°) is also coincident with the belt of rapid interseismic uplift rates and young cooling ages, suggesting that these topographic metrics may indeed be responding to tectonic forcing (Fig. 2C). This well-defined belt of elevated slope and relief appears to bifurcate into two bands west of ~82.5°E before again converging into a single band at ~81°E. In between the bands, there is a broad patch of anomalously low-relief, low-slope topography at midelevations (~3–4 km; Figs. 2C and 3). A closer look at topography reveals three isolated, low-relief, high-elevation plateau remnants aligned along PT2-S (Fig. 3). These plateau-like remnants feature gentle, rolling hills at elevations of 3–4 km perched above an otherwise deeply dissected, rugged landscape (Figs. 3D and 3E). For comparison, these isolated remnants have internal relief of a few hundred meters and mean slopes of ~11°–13°, whereas surrounding canyons are >1.5 km deep with hillslopes at or near threshold angles (>30°). The presence of such subdued landscapes at high elevation in orogenic interiors is commonly interpreted as the result of surface uplift of a landscape previously equilibrated to different tectonic and climatic conditions at lower elevation (e.g., Spotila et al., 1998; Clark et al., 2006). Although features similar in appearance sometimes owe their existence to glacial beveling, exhumation of resistant bedrock, or loss of drainage area due to drainage reorganization (Whipple and Gasparini, 2014; Yang et al., 2015), those in our study area are generally below the glacial limit; are developed in a lithology not unique to the relict surfaces; and do not appear to exhibit any compelling signs of drainage capture that could explain the distribution of remnant surfaces. The persistence of these high-elevation, low-relief remnants above the wet, erosive environment of the Lesser Himalaya serves as a testament to the recency of the forces that brought them to their present elevation. Although high-elevation, low-relief landscapes have been identified in the northwest Himalaya (e.g., van der Beek et al., 2009), they are almost exclusively found north of the Main Central thrust and South Tibetan detachment, whereas the landscape remnants in west Nepal are well to the south of these structures and do not appear to be related.

River steepness (k_{sn}) indices (Fig. 2D) reveal a pattern similar to that of both slope and relief, wherein a well-defined belt of elevated channel steepness in central Nepal coincides with the belt of rapid uplift. West of 82.5°E, elevated k_{sn} values retreat to the north, following the embayment of the Greater Himalaya. Few large rivers cross PT2-S. The Karnali River shows some nar-

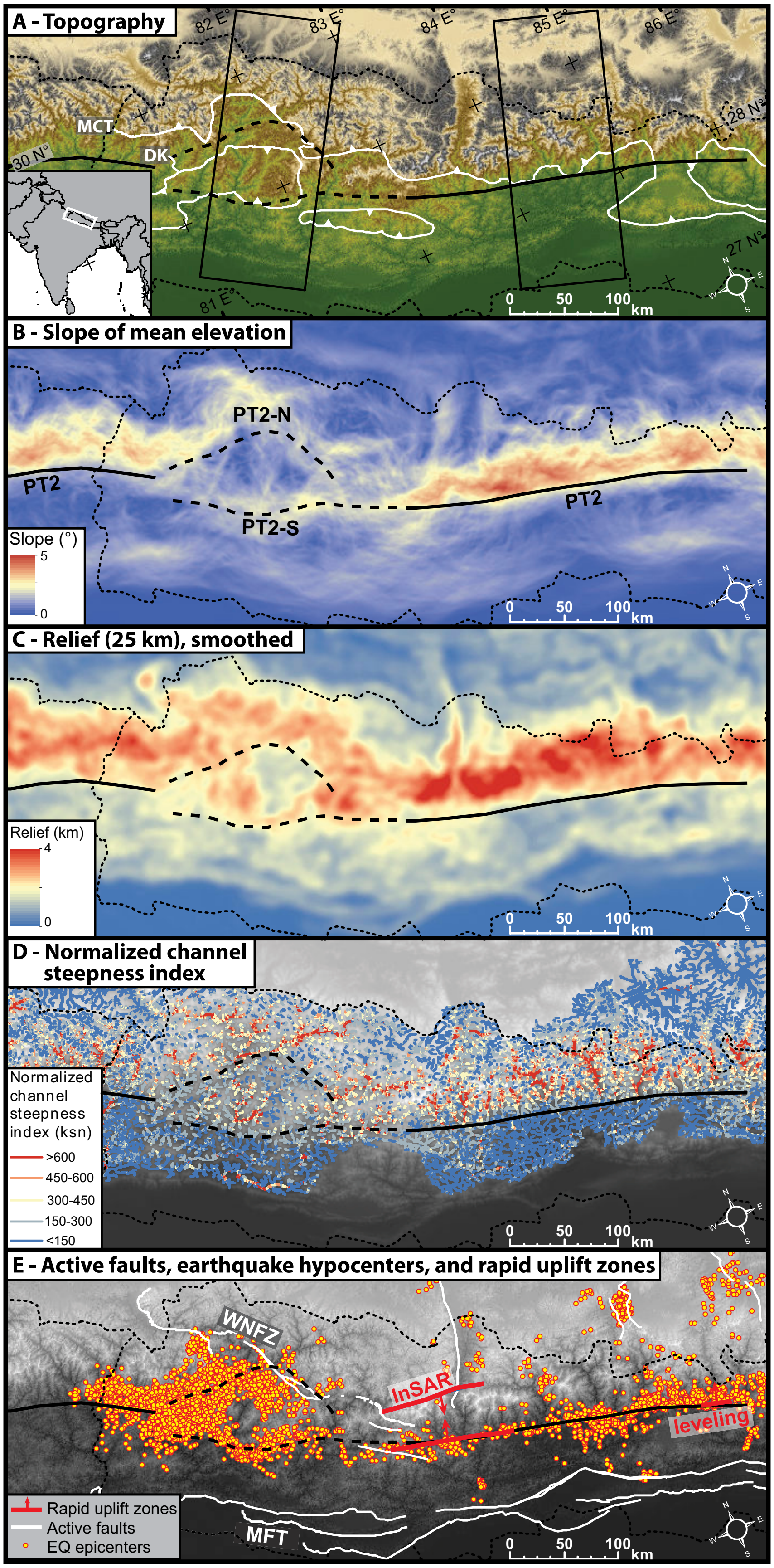

Figure 2. Compilation of data used in analysis. (A) Topography and contact between Lesser Himalayan and Greater Himalayan lithologies (white lines with teeth). Black rectangles depict footprint of swath profiles in Figure 1. MCT—Main Central thrust, DK—Dadeldhura klippe. (B) Slope of mean elevation was calculated by first smoothing the topography by taking the mean within a 25 km moving window and then calculating the slope of the resulting grid. (C) Topographic relief was calculated as the range of elevation values within a circular moving window with a 5 km radius, smoothed by calculating the mean relief within a 5 km radius centered on each cell. (D) Normalized river steepness indices were calculated for all streams with drainage areas over 9 km² using a series of modified scripts for MATLAB and ArcMap (original scripts available at http://geomorphtools.org; methods summarized in Wobus et al., 2006; reference concavity = 0.45). (E) Microseismicity (details in Fig. 1 caption). Red lines show zones of rapid interseismic rock uplift (>3 mm/yr) in the hinterland measured via interferometric synthetic aperture radar (InSAR; Grandin et al., 2012) and repeat leveling (Jackson and Bilham, 1994). WNFZ—Western Nepal fault zone; MFT—Main Frontal thrust; EQ—earthquake.

rowing, but no apparent steepening, across this zone, whereas the Tila River, a large tributary draining the low-relief area, hosts an ~1.5-km-high knick zone just above its confluence with the Karnali River (Figs. 2D and 3A; Fig. DR1[1]). Tributary streams draining the elevated low-relief landscape reach steepness maxima (knickpoints) where they traverse into the steeper, "adjusted" portions of the watershed (Fig. 3A), highlighting the upstream extent of headward incision under the present uplift regime.

Given the rock strength contrast between the Greater Himalayan Series and Lesser Himalayan Series, it is important to evaluate the potential for a lithologic control on channel steepness. To this end, k_{sn} values were explored as a function of both rock type and position within the orogen. Between PT2-N and PT2-S, areas mapped as Greater Himalayan Series appear to exhibit steeper streams than do other lithologies, suggesting that its increased rock strength plays a significant role in maintaining more rugged topography there (Fig. DR3 [see footnote 1]). However, the abrupt increase in Greater Himalayan Series steepness indices at PT2-S implies some contribution beyond lithology, which we interpret as the result of more

[1]GSA Data Repository Item 2015220, Figures DR1–DR4, is available at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

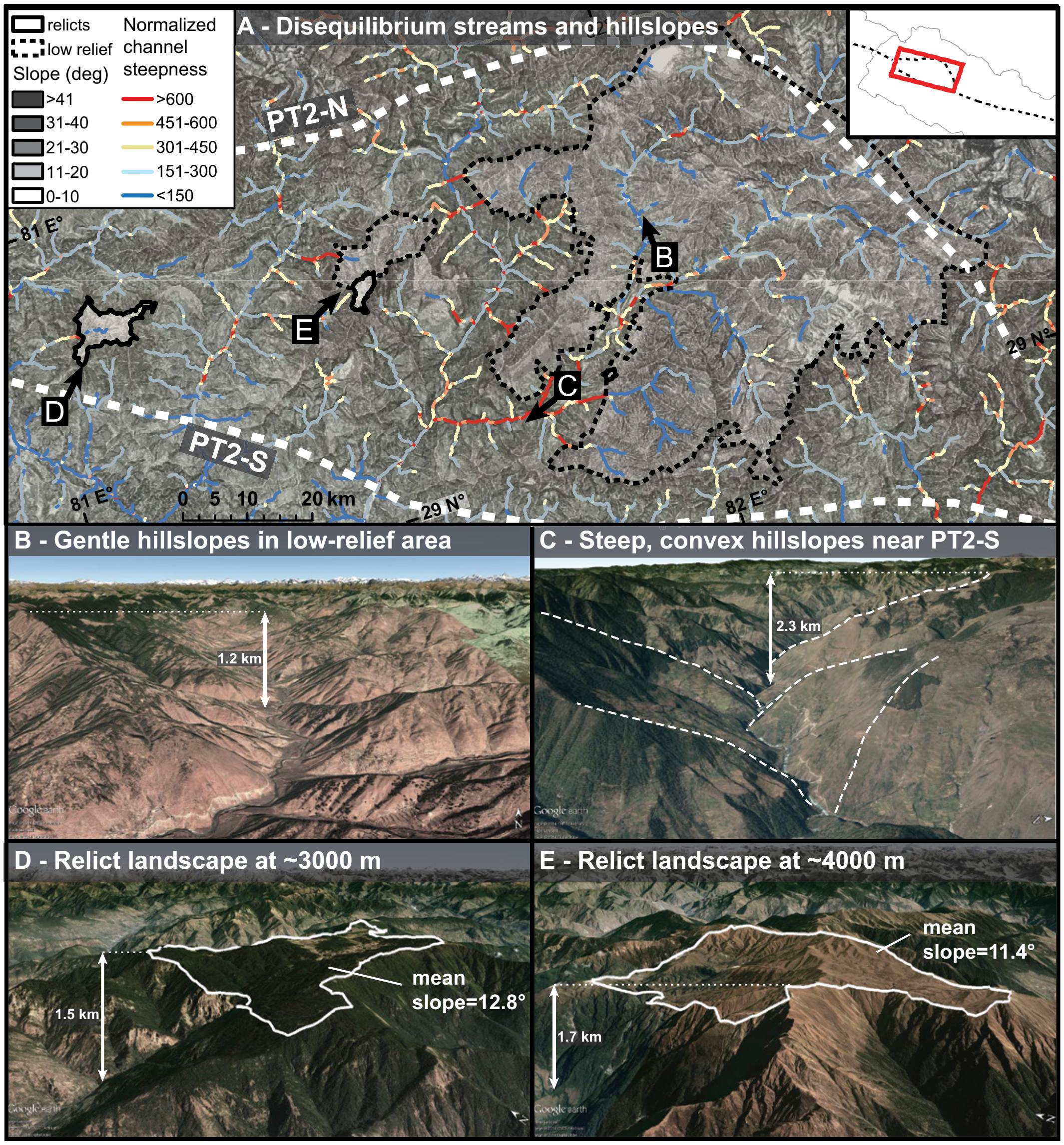

Figure 3. (A) Map showing broader area of low slope/relief (dotted outline) and isolated patches of relict landscape remnants (solid outline). Letters and arrows indicate location of oblique views shown in B–E (DigitalGlobe imagery captured from Google Earth Pro): (B) view upstream at low-slope, low-relief area; (C) view downstream showing more "youthful" topography at southern end of low-relief area; (D and E) low-relief relict landscapes preserved at high elevation above PT2-S. Note the relatively flat surfaces surrounded by deeply incised canyons.

rapid rock uplift. North of PT2-N, steepness values increase irrespective of rock type, again suggesting that uplift rate plays a more important role than does lithology in controlling river profile form in this domain.

Corroborating our topographic analysis, field observations show a marked change in canyon morphology along the Tila River. In its middle reaches, which lie within the low-relief zone, valley walls are relatively gentle (catchment mean slopes ~22°–27°). Downstream, as the river approaches PT2-S and nears its confluence with the Karnali River, the valley walls become increasingly steep (mean slopes ~27°–34°) and convex (Fig. 3). We interpret this morphologic gradient as further evidence for a downstream increase in rock uplift rates as the river approaches PT2-S, as well as the limited upstream propagation of incision in response to the drop in relative base level associated with recent uplift.

Microseismicity data provide an independent perspective on the active tectonic structures in Nepal. In central Nepal, a distinct belt of microseismic epicenters lying at ~15–20 km depth along PT2 (Figs. 1A and 2E) is typically interpreted as the result of strain accumulation near the creeping/locked transition at depth along a ramp in the Main Himalayan thrust (e.g., Jackson and Bilham, 1994; Pandey et al., 1995; Avouac, 2003). The hypocenter of the 2015 Gorkha earthquake was positioned at 15 km depth within this very belt, suggesting that this accumulated strain is indeed released as large earthquakes that rupture the locked zone to the south. For a ~150-km-long segment west of ~82.5°E, the belt of seismicity splits into two diffuse zones that broadly mimic the bifurcated bands of elevated relief, slope, and river steepness. When projected onto a cross section, earthquake hypocenters in west Nepal form two distinct clusters centered around 15–20 km depth (Fig. 1B). The two seismic clusters here have been previously interpreted as tip lines where the aseismic creep displacement on the Main Himalayan thrust is locked (Jouanne et al., 1999), although it remains unclear how one tip line could lie updip from another along the northern flat of the Main Himalayan thrust—the downdip (northern) locking line should absorb the creep that would be required to generate microseismicity farther updip (to the south). Thus, we argue that the bifurcated seismicity in west Nepal remains open to alternative interpretations.

DISCUSSION

The striking ~4 km topographic rise to the Greater Himalaya that characterizes much of the range occurs over two more subtle steps in western Nepal. Both steps exhibit elevated topographic metrics, e.g., hillslope angle, channel steepness, and relief (Fig. 2), which suggest more rapid rock uplift, and they enclose a broad area of high-elevation, low-slope, low-relief topography. Several hypotheses could be promoted to explain the anomalous range-front topography of western Nepal, including, but not limited to (Fig. 4): (1) The topography simply reflects differential incision controlled by spatial patterns of bedrock strength and rainfall; (2) the Main Himalayan thrust in western Nepal lacks a clearly defined ramp; (3) the bifurcation in the seismicity reflects a divergence of the mid-crustal ramp and brittle-ductile transition; or (4) a broad duplex has recently formed along the Main Himalayan thrust, with transport over the roof thrust driving rock uplift at PT2-N and coeval transport over the floor thrust driving rock uplift at PT2-S. Next, we address the viability of each of these hypotheses in the context of the geomorphic observations made earlier.

(1) Although the locations of the northern and southern mountain fronts in western Nepal might be influenced by the outcrop pattern of the crystalline rocks of the Greater Himalayan Series and equivalents in the Dadeldhura klippe (Figs. 2A and 4A; Fig. DR2 [see footnote 1]), several factors suggest that rock strength plays only a partial role. Between PT2-N and PT2-S, streams flowing over Greater Himalayan Series lithologies are decidedly steeper than those on Lesser Himalayan Series units (Fig. DR3 [see footnote 1]). However, north of PT2-N, lithology has no apparent role in controlling channel steepness. This, combined with the observation that lithologically correlative klippen elsewhere in the Himalaya have little topographic expression, suggests that PT2-S cannot be entirely due to the nearby presence of the Dadeldhura klippe. Furthermore, the spatial coincidence of seismicity with the bifurcated mountain front and elevated slope, relief, and channel steepness argues that the topographic discontinuity likely results from the same tectonic forcing as the seismic activity. Although the increased rock strength of the Greater Himalayan Series equivalents in the Dadeldhura klippe may play a role in the preservation of the high-elevation, low-relief landscape between PT2-N and PT2-S, it does not adequately explain the discontinuity in both topographic metrics and microseismicity.

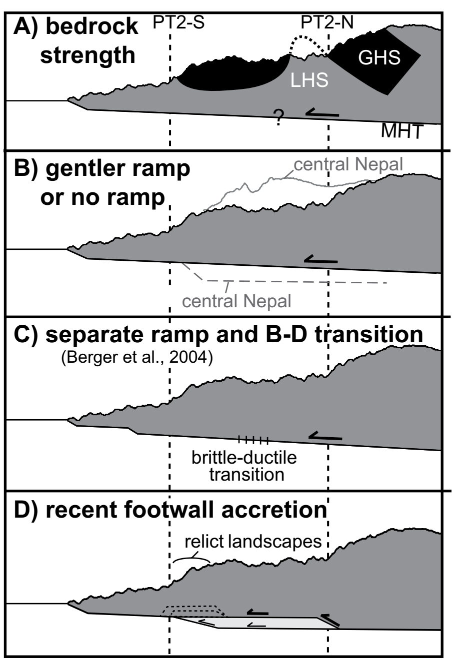

Figure 4. Schematic depiction of possible hypotheses for the two-step topography of west Nepal: (A) outcrop pattern of resistant Greater Himalayan Series (GHS) rocks; (B) gentler Main Himalayan thrust (no discrete "ramp"); (C) downdip separation of brittle-ductile (B-D) transition and Main Himalayan thrust ramp; and (D) recent accretion of footwall material into hanging wall via duplexing, depicted as lighter-gray block along Main Himalayan thrust (MHT). LHS—Lesser Himalayan Series.

One could also argue that the topographic discontinuity in west Nepal is the result of variations in precipitation and erosional efficiency. Satellite-derived mean annual rainfall (Fig. DR4 [see footnote 1]) shows that the low-relief area of west Nepal is indeed drier (~0.5–2 m/yr) than along PT2 in central Nepal (~3–5 m/yr). However, drier still is the area north of PT2-N (~0–1.5 m/yr), which is characterized by high relief, steep slopes, and deep canyons, thus ruling precipitation out as a dominant control on landscape morphology. Recent work by Godard et al. (2014) confirms that precipitation is secondary to tectonics in controlling landscape form in the central Himalaya.

(2) Inverting a compilation of cooling ages from east, central, and mid-western Nepal, Robert et al. (2011) solved for the best-fit Main Himalayan thrust geometries and rates in each cross section. They argued that along-strike differences in the position and geometry of the Main Himalayan thrust flat-ramp-flat transition best explain the patterns of exhumation, although corresponding changes in physiography are not explicitly discussed. Extending that conceptual model along strike, they posited that the Main Himalayan thrust in western Nepal is characterized by a smaller ramp closer to the Main Frontal thrust and a longer, steeper flat to the north (Fig. 11 *in* Robert et al., 2011). Although this could help explain the overall gentler rise to the Greater Himalaya, this model again fails to explain the focusing of seismicity and rock uplift into two discrete bands.

(3) Berger et al. (2004) used an elastic model and GPS data to determine a best-fit Main Himalayan thrust geometry for western, central, and eastern Nepal. East and central Nepal fit within the standard model, with a single ramp ~75 km from the Main Frontal thrust, and a brittle-ductile transition lying near the foot of the ramp. In contrast, the best-fit model for western Nepal includes a single, smaller ramp at ~45–55 km from the Main Frontal thrust and a broader brittle-ductile transition at 105–125 km from the Main Frontal thrust (Figs. 1B and 4C). A variation of this solution was introduced by Cannon and Murphy (2014), who argued that the northern belt of seismicity indeed marks the south end of a broad brittle-ductile transition, above which a large, strike-parallel fold is growing. These models are intriguing in that they offer an explanation for the northern microseismic band. However, if the Main Himalayan thrust is indeed locked updip of the brittle-ductile transition, areas to the south should be seismically quiet during the interseismic period. Another issue with Berger et al.'s (2004) model is that the inferred ramp and brittle-ductile transition lie ~20 km south of PT2-S and PT2-N, respectively. The variation presented by Cannon and Murphy (2014) recognized that rock uplift must be occurring deep in the hinterland, but their mapped fold is generally well north of the northern seismic belt, and they provided no explanation for the southern microseismic band or topographic step. Although these models appear to satisfy the GPS data, they do not adequately explain the full suite of microseismic and topographic data.

(4) A fourth hypothesis posits that several million years of rock uplift above a ramp in the Main Himalayan thrust built and sustained the high elevations of the Greater Himalaya at PT2-N, just as it continues to along PT2 in central Nepal. If a wedge of footwall material were to have been recently accreted into the hanging wall, with a new ramp forming ~65 km to the south (along PT2-S), rock uplift rates would presumably increase above the new southern ramp and decrease above the northern ramp (Fig. 4D). The modern topography could represent the early stages of that transition. Broad northward tilting of the landscape above the duplex due to greater uplift at its southern margin would help explain the low-relief topography between the ramps and the presence of the isolated relict surfaces sitting above PT2-S (Figs. 1B and 3). In this conceptual model, the seismicity would occur near the foot of each ramp, both of which sit at a depth where one might expect a gradual transition from ductile to brittle behavior. Of the four models discussed, only this addresses the position of the two topographic steps, the similar depth of the two seismic clusters, the broad, high-elevation, low-relief area between PT2-S and PT2-N, and the presence of the isolated rel-

ict landscape remnants over PT2-S. Additional work will be necessary before the duplex model can be confirmed in west Nepal. Geodetic studies utilizing interferometric synthetic aperture radar (e.g., Grandin et al., 2012) could help constrain the present-day deformation field. Low-temperature thermochronology could produce longer-term exhumation histories that could be tested against cooling ages predicted by our model (e.g., Robert et al., 2011).

Recent work by Murphy et al. (2014) identified a system of right-lateral faults (Western Nepal fault zone) that cross the range in northwest Nepal near where we identify PT2-N (Fig. 2E). The authors interpreted the Western Nepal fault zone as the early stages of southeastward propagation of the Karakoram fault across the Himalaya. GPS data (Styron et al., 2011) indeed show that ~5 ± 3 mm/yr of arc-parallel slip occurs across this zone. Therefore, in our discussion of the architecture of the orogenic wedge in western Nepal, the relation between the Western Nepal fault zone and the tectonic discontinuity upon which we are focused must be addressed. In most areas, the mapped strands of the Western Nepal fault zone lie well to the north of the microseismicity. However, it is plausible that the cross structure could be the surface expression of ongoing oblique movement of the orogenic wedge over the northern ramp identified in hypothesis 4 above. The obliquity of plate motion relative to the cross structure would dictate a dextral component to the slip, consistent with young fault scarps along the Western Nepal fault zone (Murphy et al., 2014).

Although improved kinematic reconstructions are still needed, we prefer the hypothesis that the topographic and tectonic discontinuity from central to western Nepal is the result of a recent southward stepping of the midcrustal ramp along the Main Himalayan thrust from a more northerly trend (along PT2-N) to one more consistent with trends to the east and west (along PT2-S). This explanation has important implications for both the seismic hazard presented by the plate boundary in the central Himalaya, and for our understanding of how collisional belts grow and evolve. Present models of the earthquake cycle in Nepal posit that, in the interseismic period, the Main Himalayan thrust is locked from the surface to the brittle-ductile transition along a midcrustal ramp in the Main Himalayan thrust (Avouac, 2003). Accumulated elastic strain is largely released during Mw > 8.0 earthquakes that rupture 200- to 300-km-wide segments updip toward the Main Frontal thrust (e.g., Lavé et al., 2005). The interpreted ~50° northward bend in the trend of the Main Himalayan thrust ramp at ~82.5°E and the ~30° bend at ~81°E (Fig. 2) may serve as segment boundaries, limiting the potential rupture length of megathrust earthquakes in the western Nepal seismic gap. However, if the northern topographic step in western Nepal indeed marks the downdip "locking line" of the plate boundary, ruptures generated there must propagate ~50–70 km farther in western Nepal than they do in central Nepal in order to break the surface at the Main Frontal thrust. Coupled with the additional ramp that we infer to the south of PT2-N, the overall increase in width of the orogenic wedge sitting above the locked zone in west Nepal may decrease the likelihood of ruptures originating at the northern locking line reaching the surface trace of the Main Frontal thrust, leading instead to more focused deformation within the currently locked zone and thereby rendering the paleoseismic record at the Main Frontal thrust less complete. This scenario is consistent with the expectation that a relatively thinned orogenic wedge (relative to central Nepal) must thicken to maintain critical taper (Davis et al., 1983). An alternative interpretation is that the greater width of the locked zone would lead to more energetic ruptures in west Nepal (Jouanne et al., 1999). More detailed modeling of rupture mechanics is necessary to tease out the effect of the more complicated local structural geometry on possible rupture extent and earthquake magnitude.

In addition to posing a challenge to the continuity of Main Himalayan thrust geometry as is commonly assumed for the central Himalaya, our interpretations suggest that significant midcrustal deformation continues within the Himalayan hinterland. Footwall accretion has been invoked to explain the present structural geometry of the orogen (e.g., DeCelles et al., 1998; Robinson et al., 2006; Cannon and Murphy, 2014) and the distribution of cooling ages across the range (e.g., Herman et al., 2010). The Himalaya of western Nepal may be an example where footwall accretion is actively participating in mountain building and causing the locus of internal deformation to shift ~65 km toward the tip of the orogenic wedge. This behavior could represent internal adjustments to maintain a critical taper, or it may be a response to the frictional dynamics of the lithologic architecture in the Main Himalayan thrust footwall.

CONCLUSIONS

Clarification of the geometry and architecture of the plate-boundary fault underlying the Himalayan orogen can help to constrain the likely locations and style of future ruptures like the ~M 8.0 Bihar and M 7.8 Gorkha earthquakes that devastated Nepal in 1934 and 2015, respectively. Through straightforward analysis of topography in central and western Nepal, we delineated a clear discontinuity west of 82.5°E, where the prominent, well-studied central Himalayan mountain front bifurcates into two, less abrupt topographic steps that continue northwestward for ~100 km before rejoining into a single band in northern India. Although the observed topography could be generated multiple ways, spatial patterns of microseismicity, topographic indices associated with rapid rock uplift, and high-altitude landscape remnants circumscribed by the bifurcation suggest that the topographic discontinuity indeed has a tectonic origin.

Such tectonic segmentation requires a deviation from the standard model of active tectonics and mountain building in the Nepalese Himalaya. The model most consistent with our observations posits that the Main Himalayan thrust ramp makes an ~50° northward bend in western Nepal, while recent duplexing accommodates some fraction of convergence over a younger midcrustal ramp beneath the southern topographic step. The unusual relict landscapes above the southern step suggest that uplift there is quite recent, such that the fluvial network remains out of equilibrium in its new tectonic context.

Our model warrants further testing, ideally with a combination of geodetic observation of the interseismic period and thermochronology-derived exhumation histories to compare with analogous data collected in adjacent segments of the range. Our preferred model represents a significant deviation from what would be predicted by projecting structural geometries along strike from central Nepal and should be incorporated in future attempts to simulate the earthquake cycle in the central Himalaya.

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Jonathan E. Harvey, Douglas W. Burbank and Bodo Bookhagen

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Notes