Interplay between faulting and base level in the development of Himalayan frontal fold topography

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[1] Fold topography preserves a potentially accessible record of the structure and evolution of an underlying thrust fault system, provided we understand the factors that shape that topography. Here we examine the morphology and fault geometry of two active folds at the northwest Himalayan front. The Chandigarh and Mohand anticlines show the following patterns: (1) most (~60%–70%) growth in catchment size and relief (across multiple scales) is accomplished within ~5 km of the fault tips, (2) range-scale relief is divided unevenly between the fold flanks because of base level contrasts, (3) mean gradients of the uplifting catchments correspond to different flank-averaged rock uplift rates, (4) high hillslope-scale relief coincides with areas of fast rock uplift and stronger lithologies, and (5) existing relief represents only ~15% of the total rock eroded since faulting began, implying significant erosion. The first-order fold topography is developed quickly and asymmetrically as a result of fault-generated rock uplift (which sets the space available for the fold and the distribution of rock uplift rates) with some modulation by base level (which affects the erosional response of the landscape to the uplift). A linear rate of growth in catchment relief with range half-width correlates with catchment-averaged rock uplift rate, suggesting that this metric may be used to infer variations in fault dip at depth. In these frontal fold settings, high slip rates, weak uplifting rocks, and rapid erosion may combine to quickly limit the topographic growth of emerging folds and disconnect their morphology from the displacement field.


I. Introduction

[2] Quantifying the topographic response to tectonic uplift and erosion is vital for understanding a variety of phenomena, such as the coupling of climate and tectonics in orogenesis, sediment delivery to basins, the first-order controls on relief generation, and reconstructions of regional tectonic history. One way to assess the interplay between deformation and erosion in the generation of topography is to observe the geomorphic form and processes associated with emerging landscapes driven by the earliest stages of uplift on active faults. Because topography is at least a partial record of deformation, efforts have been made to invert for the tectonic history from quantitative landform measures (see review by Wobus et al. [2006]). The advantage of this approach is that observations of the Earth surface are easy to make and may be used to constrain parameters that are more difficult to measure, like fault geometry at depth [e.g., Champel et al., 2002] or the distribution of deformation [Kirby et al., 2003; Boulton and Whittaker, 2009]. Unfortunately, the direct translation from topography to tectonics is confounded by a variety of factors, such as spatial variations in rock erodibility, erosional process, and precipitation, and the difficulty of independently validating the geometry and evolution of the tectonic displacement field. As a result, the most effective studies to date are limited to sites where fault structure and slip history are abnormally well constrained [Keller et al., 1998; Snyder et al., 2000; Kirby and Whipple, 2001; Scharer et al., 2006; Cowie et al., 2008; Whittaker et al., 2008].

[3] A convenient framework for examining the topographic response to actively deforming areas is provided by our combined knowledge of (1) how crustal-scale faults grow and (2) how rivers respond to uplift [e.g., Leeder and Jackson, 1993; Burbank et al., 1996; Densmore et al., 2004; Hetzel et al., 2004; Ramsey et al., 2008]. The consistent scaling between fault length and displacement, and predictable three-dimensional variations in fault slip and slip rate [Cowie and Roberts, 2001], can be used to comprehend the concomitant development of topography above active
Figure 1. Interplay between faulting and flanking base level in controlling range width. (a) Tectonic and base level controls on the width of normal fault-bounded ranges (modified from Densmore et al. [2005]). Normal fault dip and spacing sets the footwall width (solid lines are tectonic topography). Base level contrasts (gray basins) modify the tectonic topography, leading to two scenarios: similar (left) or different (right) flanking base levels result in a range width (dashed lines) that is similar (left) and reduced (right) relative to the tectonic topography. (b) Fault dip and spacing sets the thrust fault-bounded hanging wall width (solid lines). Base level contrasts (gray basins) modify hanging wall topography leading to the same two scenarios, with range width (dashed lines) (modified from Ellis and Densmore [2006]) that is similar or reduced relative to the tectonic topography. (c) Mismatch between predicted topographic profile in steady state above a 30° fault ramp (solid line, 5X VE) [from Miller and Slingerland, 2006] and observed swath-averaged minimum profiles (dashed lines, 10X VE) from the Chandigarh and Mohand anticlines in northwest India. Observed profiles are scaled in the horizontal so that the divide position lies above the idealized fault ramp as it does in reality.

The purpose of this paper is to test the hypothesis that, as in extensional settings, both fault geometry and flanking base levels control the early stages of uplift at the fault tips (meaning that relief reflects fault displacement), but is largely decoupled thereafter in the range interiors (meaning that relief no longer reflects fault displacement) [Densmore et al., 2007, 2009].

Topographic growth in response to thrust faulting in forelands should differ from that associated with normal faults for several reasons. First, because thrust faults typically have gentle dips or are even horizontal, their displacement causes more significant rock advection toward, rather than away from, the adjacent base level. Two-dimensional steady state models of fault-bend folds suggest that lateral rock advection plays an essential role in mountain range asymmetry, even without flanking base level contrasts [Miller et al., 2007], and may result in the concomitant advection of topography [Miller and Slingerland, 2006]. Second, the uplift pattern may be spatially variable, and transient, because fault dip often changes as the fault propagates up section. Third, fault imbrication in the direction of transport in thrust belts facilitates piggyback basin development, such that opposing base levels can be very different (Figure 1b). Range asymmetry for folds with identical flank gradients formed above simple blind thrust ramps may be controlled by contrasts in flanking base level [Ellis and Densmore, 2006]. Furthermore, infilling and excavation of piggyback basins may result in flanking base level change with time. Perhaps because of the spatiotemporal variability in both uplift and base levels, real fold topography (that represents the surface response to rock uplift rate relative to the rate of base level change) appears to be more complicated than that predicted by simplified topographic models. For example, observed drainage divide positions can be more recessed toward the hinterland relative to the fold axis than those produced in simulations (Figure 1c) [Gupta and Ellis, 2004; Ellis and Densmore, 2006; Miller and Slingerland, 2006]. In summary, range asymmetry with similar flank slopes may be explained by base level contrasts, whereas asymmetry with different flank slopes may be due to lateral advection and/or nonuniform rates of rock uplift/base level change.

Previous work on the growth of topography above active thrusts has focused on identifying the effects of lateral fold propagation, using along-strike gradients in fluvial dissection, distinctive patterns of channel deflections, and the sequential formation of water and wind gaps [Jackson et al., 1996; Delcaillau et al., 2007]. Unfortunately, many of these observations are consistent with, but do not prove, lateral propagation [Keller et al., 1999]. Perhaps as a result, conflicting interpretations of development and propagation direction can arise, even on the same fold [cf. Delcaillau et al., 2006; Singh and Tandon, 2010]. Comparatively less attention has been devoted to considering the topographic development above folds within the context of the underlying fault growth and flanking base levels. The expectation is that there are potentially large spatial variations in (1) slip rate and thus rate of rock uplift above a growing fault and (2) base level adjacent to the emergent topography, both of which may affect the landscape response to the uplift. Thus, it is perhaps premature to suggest geomorphic criteria for determining propagation direction until more detailed relationships between fold topography, fault geometry, and base level variations are properly explored.
base levels exert important controls on the topography above a growing thrust fault (Figure 1). We test this by exploring the relationships between the uplifting range relief and mean gradients, base level elevations, and relative rock uplift rates determined by fault dip at depth across two active thrust faults at the Himalayan front in northwest India. This work complements previous investigations of the regional tectonic geomorphology [Malik and Nakata, 2003; Gupta and Ellis, 2004; Delcaillau et al., 2006; Thakur et al., 2007; Singh and Jain, 2009; Singh and Tandon, 2010] by evaluating variations in frontal fold morphology within a more detailed structural and theoretical framework.

2. Geologic and Geomorphic Setting

The Himalayan chain is a zone of deformation that has accommodated a significant portion of the convergence between India and Eurasia since the early Paleogene to Eocene (~65–45 Ma) [Molnar and Tapponnier, 1975] (see reviews by Hodges [2000] and Yin and Harrison [2000]). The southernmost tectonostratigraphic zones within the chain include the Lesser (medium-grade metamorphics) and sub-Himalaya (Neogene to present sediments) (Figure 2) [e.g., Le Fort, 1975; Brunel, 1986; Kumar et al., 2006]. The Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT) bound these zones on their southern sides, respectively. By the mid-Miocene (~18 Ma), Himalayan deformation had produced an outboard, subsiding foreland [e.g., DeCelles and Giles, 1996]: the Siwalik basin was the locus of sedimentation sourced from the uplifting Lesser Himalaya [Burbank, 1992; Valdiya, 2002]. Quaternary migration of deformation southward to the HFT created the sub-Himalaya, which incorporated Siwalik sediments into the orogenic wedge and has resulted in active foothill uplift and trapping of Quaternary sediments within intermontane valleys (Duns) (Figure 2) [Nakata, 1984, 1989; Yeats and Lillie, 1991; Wesnousky et al., 1999; Kumar et al., 2001; Malik and Nakata, 2003; Thakur et al., 2007].

The Siwalik Hills in northwest India vary in width from ~10–80 km and consist of folds and faults that exhibit a large range in shortening (~10–60 km or ~20–70%) between the...
2.1. The Chandigarh Anticline

The Chandigarh anticline measures ~40 km long and ~10–12 km wide between the Sutlej and Ghaggar Rivers (Figure 4). The Sirsa and Jhajara Rivers set flanking base levels to the northeast (Figure 3a) and the foreland sets them to the southwest. The range is interpreted to result from uplift associated with slip on the blind HFT above a simple ramp-flat geometry, producing a composite fold with two axes (the Tandi and Masol anticlines) (Figure 4) [Mukhopadhyay and Mishra, 2004, 2005]. The mean drainage divide is positioned above the HFT ramp and offset ~1.5 km toward the hinterland relative to the nearest fold axis (Figure 4b). Only the Upper Siwaliks have been exposed as a result of HFT uplift.

Several observations provide first-order constraints on the timing and rates of Chandigarh anticline formation. Magnetostratigraphic ages of deformed Upper Siwalik rocks in the hanging wall are 2.47–0.63 Ma [Rao, 1993] and suggest that uplift began post 0.63 Ma. At the Ghaggar River mountain front exit, fluvial terrace ages and fault zone trenching suggest ~4–6 mm/yr of uplift and a minimum fault slip rate of 6.3 ± 2 mm/yr [Malik and Nakata, 2003]. Assuming 10.5 km of HFT slip estimated by section balancing [Mukhopadhyay and Mishra, 2004], the minimum fault slip rate implies that the fold is no older than 1.22–2.44 Ma. Assuming maximum regional slip rates of 18 mm/yr [Powers et al., 1998], the fold began to form no later than 0.58 Ma.

2.2. The Mohand Anticline

The Mohand anticline measures ~80 km long and ~15 km wide between the Yamuna and Ganges Rivers (Figure 5) [Rao et al., 1974; Karunakaran and Rao, 1979; Thakur, 1995]. The Asan-Tons and Suswa-Song river systems to the northeast and the foreland to the southwest set flanking base levels. The topography is interpreted to result from slip on an HFT ramp that varies in dip in the transport direction (Figures 3 and 5b) [Mishra and Mukhopadhyay, 2002]. Both Upper and Middle Siwalik rocks have been exposed as a result of the uplift. At the southeastern end, the back-breaking Bhimgoda Thrust dips ~25°SW and locally brings up Lower to Upper Siwalik rocks over Upper Siwaliks [Rao et al., 1974; Thakur, 1995]. Apart from this complication, HFT slip has produced a single-axis fold with a mean drainage divide position that is above the lowest-dipping portion of the HFT ramp and recessed ~7 km toward the hinterland relative to the fold axis.
Figure 4. The Chandigarh anticline. (a) Fold topography (ASTER GDEM; color scale stretched to 0.5 standard deviation to emphasize fold relief), drainage divide (thick black line), hanging wall catchments (white outlines; shaded catchments define the divide), fold axes (thin dashed lines) (from Mukhopadhyay and Mishra [2005]; interpolation along strike from Singh and Tandon [2008]), and sub-ridgeline (hillslope-scale) relief (inset). Faults are modified from Raiverman et al. [1990] and Wesnousky et al. [1999]. Note the Pinjaur Dun drainage divide (thick dashed line) between the Sirsa and Jhajara Rivers. HFT is Himalayan Frontal Thrust. (b) Thirteen kilometer wide swath-averaged minimum, mean, and maximum elevation profiles (SRTM DEM) above the balanced section of Mukhopadhyay and Mishra [2004]. Shading between the profiles is fold relief. The eroded values are the rock area from the balanced section above the present topographic surface (dashed line) and the shaded area between the maximum and minimum swath profiles. Location is in Figure 4a.
Figure 5. The Mohand anticline. (a) Fold topography (ASTER GDEM; color scale stretched to 0.5 standard deviation to emphasize fold relief), drainage divide (thick black line), hanging wall catchments (white outlines; shaded catchments define the divide), fold axis (thin dashed line [from Mishra and Mukhopadhyay, 2002]), and sub-ridgeline (hillslope-scale) relief (inset). Faults and geologic units are modified from Raiverman et al. [1990] and Wesnousky et al. [1999]. Note the Dehra Dun drainage divide (dashed line) between the Asan-Tons and Suswa-Song rivers. HFT is Himalayan Frontal Thrust, Mid is Middle, and Lwr is Lower. (b) Thirteen kilometer wide swath-averaged minimum, mean, and maximum elevation profiles (SRTM DEM) above the balanced section of Mukhopadhyay and Mishra [2004]. Shading between profiles is the fold relief. Kinks in the HFT at depth divide the fault into several segments: flat (1), steep ramp (2 and 3), shallow ramp (4), and decollement slope (5). The eroded values are the rock area from the balanced section above the present topographic surface (dashed line) and the shaded area between the maximum and minimum swath profiles. Location is in Figure 5a.
Densmore et al., 2003; Sangode and Kumar, 2003]. This suggests that anticline uplift began post 0.78 Ma [Sangode et al., 1996, 1999]. Near Mohand (Figure 5), the HFT dips ~30°NE and fluvial terrace ages and fault zone trenching suggest ~6.9 ± 1.8 mm/yr of uplift and a fault slip rate of ≥13.8 ± 3.16 mm/yr [Powers et al., 1998; Wensoulsky et al., 1999]. Assuming 4–5 km of total HFT slip estimated by section balancing [Powers et al., 1998; Mishra and Mukhopadhyay, 2002] and the minimum slip rate, the Mohand anticline began to form no earlier than 0.24–0.47 Ma. Assuming maximum regional slip rates of 18 mm/yr [Powers et al., 1998], the fold began no later than 0.22–0.28 Ma.

2.3. Erosional Processes, Rock Strength and Climate

Field observations of the erosional processes active within these folds provide insight into the mechanisms responsible for relief development [e.g., after Densmore et al., 2007]. Hillslopes throughout the southern Mohand catchments have steep, planar slopes and thin regolith cover (Figure 3e). This suggests that hillslopes are near failure and that landsliding is the dominant hillslope sediment transport mechanism. Amphitheater-shaped headwaters and evidence of slumping and mass movements at the ridgeline suggest that mass movements are also the leading process in the shaping of the divide. Lithofacies analyses describe the uplifting Siwaliks rocks as generally weak and poorly lithified, but suggest that the Middle-to-Lower Siwaliks are more competent than the Upper Siwaliks [e.g., Kumar and Tandon, 1985; Kumar and Nanda, 1989]. Rainfall is a primary historical trigger for the detachment of hillslope material and fluvial transport of sediment and debris into adjacent basins, as well as Siwaliks bedrock incision. Mean annual precipitation is significant (~1–3 m/yr) and highly seasonal in nature (due to the Asian monsoon system) on the Siwalik Hills [Bookhagen and Burbank, 2006], implying that fold erosion is rapid, but episodic.

3. Methods

We used two different digital elevation models (DEMs) to measure topography and catchment morphology in and adjacent to the Chandigarh and Mohand ranges: (1) the hydrologically conditioned HydroSHEDS SRTM DEM (90 m resolution, http://hydrosheds.cr.usgs.gov/) and (2) the ASTER GDEM V001 (30 m resolution, http://asterweb.jpl.nasa.gov/gdem-wist.asp). We first extracted swath-averaged topographic profiles of both ranges. Figures 4b and 5b show across-strike swath profiles from the SRTM DEM that were also used to estimate the cross-sectional area of relief (shaded gray regions) contained within them. We used the higher resolution GDEM data set to generate all other profiles, plots and analyses in this paper. We next extracted boundaries of catchments draining the folds, validated by satellite images and 1:50,000 and 1:250,000 scale topographic maps. Overall, the extracted catchments matched those defined from the maps very well. One exception is marked 1 in the inset of Figure 5a where flow routing was incorrect and hence the map-view catchment relief patterns for two basins were truncated to avoid defining false catchment metrics. All metrics derived from these two catchments were manually measured from the DEM at the real outlet location to reflect the true values.

We focused only on catchments with developed channels visible from Indian Remote Sensing (IRS) LISS-III data (23.5 m resolution) with detailed analysis further limited to those that define the drainage divide (shaded catchments in Figures 4a and 5a). We chose catchment outlet positions at the sharp break in slope determined by DEM-derived slope maps in order to limit analysis to the topography most directly related to HFT uplift. For Chandigarh, the slope break coincides with the change from steep, bedrock-controlled slopes to (1) the flat terraces and floodplains of the Sirsa and Jhajara Rivers on the northeastern flank and (2) the gentle alluvial foreland slope on the southwestern flank (Figure 4) [e.g., Suresh et al., 2007]. For Mohand, the break in slope coincides with the change from steep, bedrock-controlled slopes to (1) the gentle slopes of the onlapping Dun gravels on the upper portion of the northeastern flank (Figure 3c) and (2) the foreland slope on the southwestern flank (Figure 5a).

Quantifying relief is important for characterizing fold morphology. Relief is a scale-dependant measure and thus different measures of relief [e.g., Whipple et al., 1999] can provide insight into relevant phenomena (e.g., trunk river elevation profiles, lithologic variations, and hillslope processes) that vary at different spatial scales. First, we estimated range-scale relief using swath-averaged profiles normal to the HFT strike from several different subdivided regions. Second, we determined catchment relief defined by the difference between maximum (ridgeline) and outlet elevations for each catchment. Third, we quantified relief at the hillslope scale using a modified version of sub-ridgeline relief [after Brocklehurst and Whipple, 2002]. We calculated sub-ridgeline relief by subtracting the modern catchment topography from an envelope surface that was first interpolated across catchment ridgelines, then interpolated to include any peaks that projected above the initial surface. We used a distance-weighted method for the interpolation with a search radius equal to the mean catchment dimension in map view. Although using the 30 m resolution GDEM data set underestimates true meter-scale gradients and hence true relief, our sub-ridgeline relief estimates are averaged over approximately hundreds to thousands of meters (the range of mean catchment lengths), which is also the scale for hillslopes in the study area.

We measured geomorphic variables (mean elevation, range flank-to-hillslope relief, drainage area, range halfwidth (strike-perpendicular distance between mountain front and divide) and outlet elevation) as a function of distance along and across HFT strike because variations in these principal structural directions are the most important. We also measured across-strike range asymmetry to assess differences in fold flank gradients and to separate the effects of base level from other controls on flank gradient. If drainage divide position is set by the erosional competition between flanks with the same mean gradients, then the equilibrium fractional divide position ($D_e$) can be estimated as [Ellis and Densmore, 2006]:

$$D_e = F / (F + R),$$

\[1\]
Figure 6. Topographic variations across the Chandigarh anticline. Five fold regions are highlighted: tip, northwest (NW), center northwest (CNW), center, and southeast (SE). (a) Along-strike profiles of swath-averaged maximum (Max) and minimum (Min) elevations and relief (maximum minus minimum). Difference in relief between fold flanks increases gradually from northwest to southeast toward a maximum at km 35. (b) Extents of the profiles in Figure 6a. The dashed line shows the division between north and south flanks for the calculation of the minimum elevation curve in Figure 6a. (c) Across-strike profiles of swath-averaged mean elevations and relief from the five regions (extents in Figure 6d). A schematic HFT fault plane highlighting the flat versus ramp segments (separated by tick) is located below for comparison with reduced vertical exaggeration (VE) (from Figure 4b). The tip region across-strike topography is plotted from north to south, assuming the HFT locally trends west to east as shown in Figure 2. Inset shows the parameters associated with measuring range asymmetry and several possible predicted configurations [from Ellis and Densmore, 2006]. (d) Map-view extents of the five highlighted fold regions.
where $F$ and $R$ are the elevations of the divide above the flanking foreland and hinterland base levels, respectively. The simplest case is a centered divide position ($D_r = 0.5$) due to equal elevation of base levels on both flanks, whereas a higher base level will pull the divide position toward it (Figure 6c inset). If mean flank gradients are not equal, the predicted $D_r$ will be different than what is observed. We report both observed and predicted values of $D_r$ from the various fold regions, calculated from the mean swath profiles, to evaluate range asymmetry and the contrasts in gradient between fold flanks. We also estimated mean fold flank gradients looking at the relationship between catchment relief and range half-width [after Densmore et al., 2005]. Because our focus is on large-scale relationships between fold form, rock uplift patterns, and base level, we do not employ more detailed measures of hillslope or channel steepness (e.g., hillslope gradients, steepness indices). However, prior work on normal fault footwalls has shown that those more detailed metrics have similar along-strike variations to the more generalized metrics used here [Densmore et al., 2007].

4. Observations

[18] We present our topographic analysis results in increasing order of tectonic and geomorphic complexity, starting with the Chandigarh anticline. We first describe the large-scale, along-strike variations in fold morphology, modern flanking base levels and how they relate to the underlying thrust fault. We focus on modern base levels because we know them best, but specifically address the fact that they can change through time later in the discussion. Next, we look at across-strike variations in morphology and range asymmetry. We then examine catchment-to-hillslope scale variations in relief, drainage area, outlet elevation, and range half-width. We use the following terminology: base level is the lowest elevation to which fluvial processes can erode the land surface, with flanking base level referring to the range-scale measure (axial river position in the hinterland and ~5 km from the mountain front in the foreland), and local base level referring to catchment outlet elevation. Flank refers to topography (e.g., one side of the fold delimited by the drainage divide), limb refers to geologic structure (e.g., one side of the fold delimited by the fold axis), fault tip refers to the along-strike termination of the HFT segment directly associated with each fold, and fold tip refers to the along-strike termination of the topography associated with the fault tip. For brevity, we refer to areas to the northeast of the fold divides as north(ern) and areas to the southwest as south(ern).

4.1. Chandigarh Anticline: Topography, Base Level, and Fault Geometry

4.1.1. Range-Scale Along-Strike Variations

[19] The Chandigarh anticline exhibits systematic along-strike variations in topography and flanking base levels (Figure 6a). Most (>60–80%) elevation and relief are reached over distances of ~7 and ~3 km from the northwestern and southeastern fold tips, respectively. The difference in relief between the fold flanks increases toward the southeast, reaching up to ~4.1 (~200 m on the southern flank versus ~50 m on the northern flank). This difference in relief coincides with an increasing difference between flanking base levels on the two flanks, as indicated by the minimum swath elevations (Figure 6a). The greatest relief difference occurs at the Pinjaur Dun drainage divide between the Sirsa and Jhajara Rivers (Figure 4a).

[20] The Chandigarh anticline mountain front is very linear (Figure 4a). Therefore, in the absence of other observations, we assume that neither the geometry nor the orientation of the HFT varies along strike. The only exception is the region near the northwest fault tip where the HFT appears to bend to strike east-west.

4.1.2. Across-Strike Variations and Range Asymmetry

[21] The across-strike fold relief gradually increases from south to north (Figure 6c). Swath profiles of 4 subregions show the same pattern: a rapid increase in elevation and relief at the mountain front over the first 1–2 km, followed by a more gradual increase over the remaining length. Relief averages ~100 m and peaks at ~200 m near the drainage divide. These overall trends are similar in the tip region to the northwest where the HFT bends east-west, although the relief values are reduced with averages of ~50 m and a peak of ~100 m.

[22] The across-strike correlations between fold topography and fault geometry are straightforward. The sharp mountain front rise occurs on the southern limb of the frontal Tandi fold, which dips ~20–25°SW (Figure 4b) [Mukhopadhyay and Mishra, 2004]. The zone of steady relief increase spans both the HFT ramp and flat (Figure 6c). The drainage divide position above the HFT ramp indicates that both fold flanks are experiencing the same maximum vertical component of uplift, but flank-averaged rock uplift rate and base level are higher on the north flank.

[23] The Chandigarh range asymmetry is large (Figure 6). Mean divide positions are 0.72 for the CNW region, 0.74 for the Center region, and 0.85 for the SE region (Figure 6d). The predicted fractional divide position ($D_r$) is 0.49 for the CNW region, 0.68 for the Center region, and 0.86 for the SE region. This indicates that the divide positions are recessed toward the hinterland relative to predictions. Although the SE region predicted and actual values are similar, in reality the divide is pinned to the northern edge where only a few catchments have channels that are visible in the satellite images, suggesting a value closer to 1 (Figure 4a). The fact that observed fractional divide positions are greater than predicted indicates that the mean gradient is greater on north flank compared to the south flank.

4.1.3. Variations in Catchment Morphology, Sub-Ridgeline Relief, and Local Base Level

[24] Along-strike variations in the morphology of catchments that define the fold divide more specifically illustrate the relief patterns and how they relate to local base level (Figure 7). Southern-flank catchments increase to ~15 km$^2$ from the northwest fold tip toward the southeast over a distance of ~5 km, then gradually increase to ~20–23 km$^2$. Outlet elevations rise steadily from ~300 to 360 m. Six northwest-draining catchments starting from the northwestern fold tip have the lowest outlet elevations because the Sirsa River is adjusted to the lower base level of the nearby Sutlej River (Figure 4a). The catchments culminate in one of similar size to that reached by the largest southern-flank catchments. This large northwest-draining catchment causes the main drainage divide to locally split into two segments. The northeast-draining catchments increase in size to a maximum of ~5 km$^2$ from the northwest tip toward the southeast.
over a distance of ~5 km (e.g., 7–12 km; Figure 7b). Over this stretch, their outlet elevations remain lower than their southern counterparts. Overall, northeast-draining catchment outlet elevations rise steadily from ~275 to 475 m over a 35 km distance. In general, catchment size on opposing fold flanks corresponds inversely with relative outlet elevation, although equal values of outlet elevation are associated with larger catchment sizes on the southern flank.

[25] Catchment relief varies somewhat systematically across the range from ~30–240 m (Figure 7). South-flank relief values up to ~150 m are gained over a lateral distance of ~5 km, followed by a gradual increase to the maximum at the southeastern fold tip over the remaining 30 km. On the northern flank, maximum relief values are also reached over a lateral distance of 5–6 km. Sub-ridgeline relief is also gained rapidly from the fold tips over ~5 km (Figure 4a inset). Sub-ridgeline relief reaches a maximum of ~100 m (~42% of total catchment relief) throughout most of the southern catchments. Catchment-averaged values of sub-ridgeline relief are up to ~40–45 m on both flanks where outlet elevations remain equal, despite the fact that the northern catchments are comparatively small in size (Figure 7b). This ~40 m value is achieved on both flanks within the first ~5 km from the tips before holding steady on the southern flank and gradually declining throughout the rest of the northern flank. Finally, in the southern catchments, maximum values of the catchment-averaged sub-ridgeline relief are obtained once most (~60–70%) of the catchment size (16 out of 23 km²) and relief (150 out of 240 m) is reached. In contrast, maximum mean sub-ridgeline relief in the north-draining catchments is obtained only once catchments reach their maximum size (~5 km²) and relief (~150 m). These patterns indicate that obtaining maximum mean hillslope-scale relief requires a minimum catchment size of ~5–10 km² and total catchment relief of ~150 m (Figure 7). However, further increase in catchment size does not translate into further increase in mean hillslope-scale relief.

[26] There is a strong correlation between catchment relief and range half-width (Figure 7c). The growth in relief for a given increase in range half-width is faster on the north flank relative to the south flank. In other words, this illustrates that the mean gradient of the north flank is higher than the south flank.

4.2. Mohand Anticline: Topography, Base Level, and Fault Geometry

4.2.1. Range-Scale Along-Strike Variations

[27] The Mohand anticline exhibits rather symmetric along-strike variations in topography and base levels (Figure 8a). Most (~65%) of the maximum elevation and relief is reached over distances of ~5 km from both fold tips. The difference in relief is significant between the flanks, reaching a maximum ratio of ~2:1 in the fold center. This difference occurs because the north-flank base level rises from ~350 m elevation to ~600 m, while the south-flank base level remains uniform. The position of maximum base level contrast across the flanks, and the largest difference in flank relief, occurs at the Dehra Dun drainage divide between the Asan–Tons and Suswa–Song rivers (Figure 5a).

[28] The Mohand anticline mountain front is not linear; instead the range appears to be divided into ~5 regions with distinct orientations (Figure 8). Furthermore, the back-
breaking Bhimgoda Thrust is a second structural component to the southeastern portion of the fold (Figure 5a). These features imply some along-strike variability in the geometry of the HFT and of fault-generated uplift within the fold.

4.2.2. Across-Strike Variations and Range Asymmetry

The across-strike mean elevation profiles of the Mohand anticline are mostly bimodal in shape (Figure 8c). The central subregions show approximately the same general...
relief pattern from southwest to northeast that can be broken into several zones. Zone A is the initial increase in elevation over 2–3 km from the mountain front (near the HFT trace), characterized by moderate relief of 100–200 m. Zone B is the maximum relief zone (350–500 m) extending over a distance of ~4 km. The Center region maximum elevation is also reached here (Figure 5b). Zone C exhibits more moderate relief of ≤~200 m and spans the drainage divide. Peak elevations for all regions except the Center lie within zone C and within ~1 km of each other at the divide. Zone D exhibits a reduced, uniform relief of ~<150 m and is restricted to the north flank between a slope break (see also Figure 5c) and the range margin. The northwest fold tip region profiles are unimodal with maximum values of mean elevation and relief in the center (8–11 km; Figure 8c). The southeast region exhibits a bimodal profile in mean elevation but the across-strike relief zones C and D are less distinctive and offset relative to the more central subregions.

The across-strike relief zones correlate with the geologic structure of the fold (Figure 8c). Relief zone A occurs primarily within the southern fold limb where rocks dip ~25–35°SW above a flat HFT (fault plane zone 1) [Mishra and Mukhopadhyay, 2002; Mukhopadhyay and Mishra, 2004]. However, our own field observations call into question this southern limb and instead suggest that this area is a large, hanging wall deformation zone with variable dips of the emergent HFT fault zone (M. Mukul and J. B. Barnes, unpublished data, 2009). Measured bedding orientations also suggest the frontal fold axis is located within relief zone A (Figure 5b) [Mishra and Mukhopadhyay, 2002]. The high relief zone B is above the two steepest segments of the HFT ramp that dip ~30° (fault plane zones 2 and 3). Relief zone C is mostly above a reduced-dipping (~20°) segment of the HFT ramp (fault plane zone 4) and spans the divide. Relief zone D lies above the ~4°NE dipping decollement (fault plane zone 5). In the northwest tip region, we found field evidence of imbricate faulting near the HFT (Mukul and Barnes, unpublished data, 2009) that may explain the unimodal mean elevation profile. The bimodal topography of the southeast tip region with disrupted relief zones C and D is probably indicative of the more complicated rock uplift pattern related to both the HFT and Bhimgoda Thrust. Overall, the southern flank is experiencing a larger relative flank-averaged rock uplift rate compared to the north flank, but base level is also always higher on the north flank.

Mohand range asymmetry is as predicted by the equal-flank gradient model given the contrasts in flanking base levels and increased distance to the hinterland axial river system (Figures 5 and 8). Observed divide positions are 0.56 for the NW, CNW and Center regions, 0.53 for the CSE region, and 0.47 for the SE region. The predicted divide position (D_r) is 0.60 for the NW region, 0.56 for the CNW region, 0.69 for the Center region, and 0.53 for the CSE and SE regions. This general agreement indicates that the mean gradients of both fold flanks are more similar compared to Chandigarh.

4.2.3. Variations in Catchment Morphology, Sub-Ridge Line Relief, and Local Base Level

Along-strike variations in catchment morphology and local base level are somewhat symmetric (Figure 9). Southern-flank catchments increase in size to ~18–20 km² (~65–70% of the maximum) from both tips over a distance of

Figure 9. Morphologic variations of catchments draining the Mohand anticline (shaded catchments in Figure 5). Open circles indicate north-flank catchments, and closed squares indicate south-flank catchments. (a) Outlet elevations and drainage areas as a function of distance along strike from the northwestern fold tip. The gray bars designate the start of both the Bhimgoda Thrust (BT) and the two catchments draining the tip to the southeast plotted with the northern flank catchments. (b) Total relief and catchment-averaged sub-ridge line relief as a function of distance along-strike. (c) Correlation between relief and range half-width. Both flanks yield a similar quasi-linear relationship.
~4 km, then gradually increase to ~25 km² in the center. Outlet elevations rise steadily from ~300–350 m to a maximum of 500 m at the intersection of the Bhimgoda Thrust with the HFT (Figure 9a). Northern catchments increase in size to ~8 km² from southeast to northwest over a distance of ~4 km (74–70 km in Figure 9a), then gradually decrease to uniform values of 2–6 km². Their outlet elevations rise from ~400 to 775 m in the fold center. Overall, catchment size on opposing fold flanks negatively correlates with relative outlet elevation, although equal values of outlet elevation are associated with larger catchment sizes on the south flank.

[33] Relief in catchments defining the drainage divide ranges from ~40–575 m (Figure 9b). South-flank catchment relief of ~400 m or more (~60% of the maximum) are gained over a lateral distance of ~4–6 km from both fold tips. On the north flank, maximum catchment relief of 400 m in the northwest region is gained over ~1 km. Growth in sub-ridgeline relief is also rapid from the tips over a ~5 km distance (Figure 5a). Sub-ridgeline relief reaches a maximum value of ~270 m (~47% of total catchment relief) and is mostly high in the southern catchments. The location of concentrated high sub-ridgeline relief shifts from near the mountain front in the HFT hanging wall throughout the fold to closer to the divide in the Bhimgoda Thrust hanging wall (Figure 5a). This pattern shows that high sub-ridgeline relief corresponds with proximity to both faults (and hence to relatively high rock uplift rates) and exposures of Middle-to-Lower Siwalik rocks.

[34] Catchment-averaged sub-ridgeline relief maxima are reached within ~4–8 km from both tips and are ~90 m and ~50 m on the south and north flanks, respectively (Figure 9b). Like catchment relief, the difference in mean sub-ridgeline relief between flanks generally corresponds with the difference in relative outlet elevations. A major exception is near the splay of the Bhimgoda Thrust from the HFT where nearly equal mean sub-ridgeline relief values exist despite outlet elevation contrasts of 100–150 m (48–62 km; Figure 9b). Furthermore, in the southern catchments, maximum mean sub-ridgeline relief is obtained once ~70% of the maximum catchment size (19 out of 28 km²) and catchment relief (400 out of 575 m) is reached. The few north-draining catchments that reach mean sub-ridgeline relief maxima also do so once ~60–70% of the maximum catchment size (4 out of 6 km²) and catchment relief (250 out of 400 m) is established. These patterns, similar to Chandigarh, indicate that obtaining maximum mean hillslope-scale relief requires a minimum catchment size, but a further increase in size does not translate into a further increase in mean hillslope-scale relief (Figure 9). In Mohand, however, the minimum catchment values are different for each fold flank.

[35] There is a strong correlation between catchment relief and range half-width (Figure 9c). The growth in relief for a given increase in range half-width is faster on the north flank relative to the south flank. However, this relationship between relief and range width is much more similar between the Mohand fold flanks compared to Chandigarh, indicating similar flank gradients.

4.3. Summary

[36] Along-strike topographic variations are systematic across the Chandigarh anticline and more irregular across the Mohand anticline. Most (~60–70%) of the growth in catchment size and relief occurs within the first ~5 km from the fold tips. The difference in range-scale relief between fold flanks reaches up to ~4:1 in Chandigarh and ~2:1 in Mohand due to a gradual increase in base level elevation on the north flank controlled by their axial river systems. Catchment size and relief patterns mostly correspond inversely with relative local base level (outlet elevation). Catchment-averaged sub-ridgeline relief values are limited once minimum catchment sizes and relief are reached. The Chandigarh drainage divide lies above a ramp in the HFT (this relationship is inferred along most of the range strike due to the linear mountain front), suggesting that northern flank catchments are responding to a higher rate of flank-averaged rock uplift. The topographic response to this differential uplift is that the northern flank gradients are steeper. In Mohand, correlations between (1) distinct zones of across-strike relief, (2) changes in HFT dip at depth, (3) the presence of the back-breaking Bhimgoda Thrust, and (4) five fold regions with distinct and variable orientations, and by inference lateral variability in fault geometry, combine to show that the catchments are responding to a rock uplift field that varies in 2 dimensions. High hillslope-scale relief in the Mohand corresponds to high rock uplift rates (inferred from steeper fault dips) and Middle-to-Lower Siwalik rocks.

5. Discussion

5.1. Spatial and Temporal Scales of Fold Relief Growth

[37] The growth of topographic relief on both folds is rapidly arrested away from the fold tips. A major, consistent finding of this work is that most (~60–70%) of the total catchment size and relief is gained over a short (~5 km) distance from the fold tips. To further explore this result, we apply well-established fault-scaling relationships for understanding fault growth to our study area because displacement constraints are limited. Studies of normal and thrust fault growth show that despite two possible mechanisms for lateral expansion (fault tip propagation and adjacent segment linkage), the result is an approximately linear along-strike displacement gradient from a central maximum tapering to zero at the fault tips [Elliott, 1976; Cowie and Scholz, 1992a, 1992b; Dawers and Anders, 1995; Burbank et al., 1999; Cooper et al., 2003; Commins et al., 2005]. Therefore, assuming a steady rate of fault tip propagation, the ~5 km length scale is equivalent to the characteristic time scale required to establish most fold relief on both folds [after Densmore et al., 2004].

[38] Fault length-displacement scaling for both folds is broadly consistent with published relationships for large faults (i.e., for length L > 10 km, displacement d = a L where a = ~0.1–0.2 [Cowie and Scholz, 1992a; Davis et al., 2005; Bergen and Shaw, 2010]). For example, the HFT segment uplifting the Mohand anticline is ~80 km long and has an estimated displacement of 4–5 km (a = 4–5/80 = 0.05–0.06; Figure 5). Furthermore, fault tip propagation rates are generally inferred to be proportional to, and ~10 times larger than, slip rates [Cowie and Scholz, 1992c]. We apply these relationships to infer an order of magnitude estimate for fold age in the study area: regional HFT slip rates are ~6–18 mm/yr [Kumar et al., 2006], suggesting ~60–180 mm/yr for fault tip propagation. Thus, the ~5 km length scale over which most fold relief is established represents ~28–83 kyr.
of lateral fault growth. Assuming fault tip propagation is symmetrical from the center, the HFT and resultant fold would elongate ~10 km every ~28–83 kyr. This implies that the 40 km long Chandigarh anticline is ~112–332,000 years old and the 80 km long Mohand is ~224–664,000 years old. These time frames are, to first order, consistent with geologic evidence that brackets the Chandigarh anticline to >0.58 to <0.63 Ma and the Mohand anticline to >0.22 to <0.78 Ma (see section 2). However, we note these fault tip propagation rates are faster than other estimates (~1–30 mm/yr) for thrust faults with similar lengths (~30–100 km) [Keller et al., 1998; Chen et al., 2002; Jackson et al., 2002] and that lateral fault growth need not be an incremental process (e.g., as described by Jackson and Leeder [1994]).

The process of interaction with adjacent fault segments can complicate propagating fault tip zones. This interaction results in a relay zone with enhanced displacement (and hence rock uplift rate) as the linking faults begin to adjust to their new length even prior to physical linkage [e.g., Gupta and Scholz, 2000; Commings et al., 2005; Olson and Cooke, 2005]. Several studies have either described evidence for or inferred transfer (or tear) faults at the tips of the Chandigarh and Mohand folds [e.g., Rao et al., 1974; Raiverman et al., 1983; Thakur, 1995; Delcaillau et al., 2006; Singh and Tandon, 2010]. For example, it has been inferred that the northwest fault tip of the HFT in Chandigarh has been rotated counterclockwise to trend east-west (as is the associated topography) due to interference with the Janauri anticline to the northwest (Figure 2). The northwest fault tip of the Mohand anticline laterally overlaps with an adjacent fault tip west of the Yamuna River (Figure 2), suggesting that segment linkage and the formation of lateral ramps may have been important in the long term structural evolution of the HFT here. These observations and inferences suggest that some fault tip interaction has occurred in both folds that may influence the topography. Therefore, it is possible the observed ~5 km length scale required to reach most relief might be different if fault tip interaction was not a factor.

5.2. Rock Uplift is the Principal Determinant of Fold Flank Gradients

Our analysis of fold flank gradients shows that, despite their first-order geomorphic similarity, the Chandigarh and Mohand anticlines exhibit different relationships between range half-width and relief. Normal fault-generated footwall relief depends quasi-linearly on half-width, a result that (1) yields a range-scale elevation gradient and (2) is most simply interpreted as indicating that relief is a geometric consequence of the available space [Densmore et al., 2005]. Both the Mohand and Chandigarh anticlines show similar linear relationships, but by comparing the flank-scale gradients on both sides, we can better evaluate the effect of relative rock uplift.

The north flank of the Chandigarh anticline is steeper than the south flank by a factor of ~3 (Figure 7c). This difference in flank gradient is consistent with higher, catchment-averaged rock uplift rates on the northern flank, as demonstrated by comparing the topography and the structural cross section (Figure 4b). Because hillslope relief is a relatively small proportion of overall relief in these catchments, higher rock uplift rates should translate directly into a steeper channel network [Whipple et al., 1999; Whipple and Tucker, 1999], and thus a higher flank gradient. It is important to reiterate, however, that channel steepness responds not to absolute rock uplift rate, but to the rate of change relative to local base level. Base level change along either fold flank will therefore perturb, and potentially mask, the effect of spatially varying rock uplift rate. In Chandigarh, sediment fans derived from the Lesser Himalaya impinge on the toe of the northern fold flank [Singh and Tandon, 2010], likely resulting in modulation of the local landscape response to the rock uplift. The magnitude of this effect, while potentially significant, depends upon the sediment accumulation rate within the Pinjaur Dun, which is unknown.

In contrast, the Mohand anticline flanks have similar overall gradients (Figure 9c), although direct comparison is difficult because of large differences in catchment size. The structural cross section reveals that the south-flank catchments overlie both the steepest portions of the HFT ramp (segments 2–3, Figure 5b) and the flat segment 1. North-flank catchments are underlain by the moderately-dipping HFT segments 4 and 5 only. Thus, compared with Chandigarh, Mohand catchments are subjected to more nearly equivalent catchment-averaged rock uplift rates between the different fold flanks, which may account for the similarity in overall flank gradients. Base level change is less of a complicating factor for catchments on the north flank of the Mohand, because there is no evidence of Quaternary sedimentation near the catchment outlets and the axial river systems are a significant distance away to the north (Figure 5a).

One implication of our results is that the rate of catchment relief growth with range half-width may be a useful indicator of catchment-averaged rock uplift rate, or at least its spatial variation, in emerging foreland folds. The relief to range half-width ratio (the proportionality constant in Figure 7c) is 0.01 for the north flanks of both folds (Figures 7c and 9c). In these cases, HFT dip is similar (~20–24°NE), the slip rate is likely similar (~6–14 ± 2–3 mm/yr), and the rock type is identical (Upper Siwaliks). Within the same lithology but above a variable fault dip at depth (0°–20°NE), the ratio of catchment relief to range half-width is 0.03 in the south-draining Chandigarh catchments (Figure 7c). In contrast, for the case of more variable rock types (Lower to Upper Siwaliks) and higher fault dip (~30° versus ~20°) below a portion of the southern Mohand catchments, the catchment relief to range half-width ratio is ~0.01 versus 0.01) (Figure 9c). These results hint that the relief to range half-width ratio may reflect variations in catchment-averaged rock uplift rates where decreasing values correspond to higher average fault dip at depth (e.g., 0.01–0.15 for dips of 20–30° versus 0.03 for average dips of ~20°). We note that this ratio is different from the fluvial steepness index, which may also be proportional to rock uplift rate [e.g., Kirby and Whipple, 2001; Wobus et al., 2006], because it represents a convolution of both hillslope and fluvial slopes.

5.3. Sub-Ridgeline Relief Determined by Rock Uplift Rate and Rock Type

Similar patterns in the relative values and distribution of sub-ridgeline relief across both folds suggest some fundamental controls on hillslope-scale morphology. For example, (1) maximum values of sub-ridgeline relief are reached once catchments obtain most (~60–70%) of their
size, (2) maximum values of sub-ridgeline relief are ~40–45% of total catchment relief, and (3) all of these values are reached at ~5 km from the fault tips. We suggest that, while faulting determines regional relief patterns with modulation by base level, rock uplift rate and rock type combine to influence hillslope-scale relief. In Chandigarh, regions of high sub-ridgeline relief are located above or near the HFT ramp where rock uplift rate is high, and regions with low values exist either above the distal part of the flat in the HFT (where rock uplift is zero), or on the north flank (where uplift rate is high but local base level is also high) (Figure 4a). Because maximum rock uplift rate and lithology are uniform everywhere, we might expect the minimum catchment size needed to reach maximum mean sub-ridgeline relief and its absolute value, to be the same on both flanks. Indeed, both flanks reach maximum mean hillslope-scale relief values of ~40 m after a minimum catchment size of ~5–10 km² is reached (Figure 7). Applying this logic to Mohand, we would predict different values of maximum catchment-averaged sub-ridgeline relief and associated minimum values in catchment size, because the fold possesses similar catchment-averaged uplift rates but contrasts in lithology across its flanks. There are differences between the Mohand flanks in the minimum catchment size needed to reach maximum mean sub-ridgeline relief (19 versus 4 km² for south versus north) and its absolute value (~90 versus ~50 m for south versus north) (Figure 9). This suggests that lithology may play a role in hillslope gradients within the uplifting catchments.

Sub-ridgeline relief corresponds with fault dip and lithology in the Mohand anticline. North-flank catchments are within the Upper Siwaliks, whereas the southern catchments are within the (1) Middle and Upper Siwaliks in the northwestern half of the fold, (2) mostly Upper Siwaliks at the HFT-Bhimoda Thrust junction, and (3) Lower-to-Upper Siwaliks in the Bhimgoda Thrust hanging wall (Figure 5a). High sub-ridgeline relief is located (1) above the steep HFT ramp portion and near the Bhimgoda Thrust trace and (2) predominantly within the Lower-to-Middle Siwalik rocks (Figure 5a). These relationships suggest that high rock uplift rate and Lower-to-Middle Siwaliks result in high hillslope-scale relief. In contrast, Upper Siwaliks rocks and reduced uplift rate result in low hillslope-scale relief. Finally, the north flanks of both folds are experiencing similar rock uplift rates (ramps below them dip ~20–24°NE) and exposing identical Upper Siwaliks rocks. Perhaps as a consequence, the north flanks possess similar values of maximum mean sub-ridgeline relief. These observations imply that rock uplift rate and rock type combine to set the patterns and limits to hillslope-scale relief within the uplifting catchments.

5.4. Erosion and Implications for Interpreting Fold Growth

The erosion history of these folds is important for interpreting their development. Erosion has been significant because the existing fold topographies represent a small fraction of the total rock mass eroded. The across-strike area encompassed by the swath-averaged maximum to minimum profiles represents only ~15% of the total rock area estimated to have been removed by erosion from the balanced sections (Figures 4b and 5b). Furthermore, this study has documented that fold relief over multiple scales is rapidly limited from the fold tips. This implies that the preservation of inherited surface features from the pre-uplifted landscape may be difficult. For example, wind gaps may not be preserved following several kilometers of fault slip and associated erosion in this type of setting. Instead, wind gaps may be low-elevation areas advected from the hinterland flank due to the horizontal component of fault displacement [Miller and Slingerland, 2006]. Substantial erosion also implies that the emerging topography will quickly become set by the rock uplift field with modulation by base level(s) and the strength of the exhuming rock(s). The implication here is that topographic growth may cease long before faulting does, if erosion is efficient enough, because slip rates are high and the uplifting rock is weak. Thus, the morphology may quickly become decoupled from fault slip. As a consequence, inferring fold growth kinematics (e.g., fault propagation direction) based on the topography is likely to be hard, unless unambiguous evidence of the prefaulted landscape can be identified (such as a wind-to-water gap transition successively occupied by the same river [Keller et al., 1999]). We caution that there is a danger in translating idealized examples of fault tip propagation from areas like Wheeler Ridge [e.g., Mueller and Talling, 1997; Keller et al., 1998] to these thrust front-foreland settings, where rock uplift rates are higher (~4–7 mm/yr versus ~1.5–3 mm/yr) and erosion rates may be significantly higher (10–15 mm/yr in the Siwaliks of central Nepal versus 0.04 mm/yr in California) [e.g., Keller et al., 1998; Lavé and Avouac, 2001].

5.5. Quaternary Base Level Fall in the Duns

The hinterland fold flank base level that is set by the piggyback basin axial river system is susceptible to variations in elevation and position with time. Mechanisms that can cause this base level to fluctuate include episodes of enhanced sedimentation, uplift, and/or incision. In Pinjaun Dar, Quaternary fan aggradation has caused the Sirsa and Jhajara Rivers to impinge upon the northern flank of the Chandigarh anticline, leading to base level rise. Since ~20 ka, there has been 10–30 m of incision in the distal portions of the Duns fans near the Sirsa River (Figure 4a) [Suresh et al., 2007]. This implies a flanking base level drop of ~10–30 m, or an increase in mean north flank relief from 60 to 80 m to 90 m today in the CNW region of the Chandigarh fold (Figure 6d). In Dehra Dun, the Yamuna River (NW base level for the Mohand anticline) has incised by at most ~30 m since ~10 ka (Figure 5a) [Singh et al., 2001]. This 30 m base level drop since ~10 ka would cause a small increase in mean north flank relief in the NW region of the Mohand anticline (Figure 8c). Assuming the equilibrium divide position model, these base level falls of ≤30 m in the Duns since ≤20 ka would result in a ~0.5–1 km shift in divide position toward the foreland. This shift would be difficult to demonstrate from present-day topography alone and suggests that only larger base level changes may leave any definitively measurable adjustment in fold topography.

5.6. Conceptual Model for Topographic Growth of Foreland Folds

Our observations show that fault geometry and base levels vary across the folds in two dimensions. This spatial variability has yet to be incorporated into a conceptual understanding of how rock uplift rates, modulated by base
Conceptual model for the evolution of topography not only rock uplift but also relative base level rise due to rivers on the hinterland position is probably recessed toward the hinterland, because ramp location determines range position and size. Divide results in systematic fold topography (Figure 10b). Fault 5.6.2. Case 1: Early or Simple Folding toward higher base level on the hinterland of the future uplift. set the stage prior to faulting. These factors can impart a bias (Figure 10a). The main mountain front position and associ-

Figure 10. Conceptual model for the evolution of topography on emerging Himalayan frontal folds. (a) Case 0 \((C_0)\), before propagation of deformation, shows prefaulted, foreland-sloping topography and future thrust fault (dashed line). (b) Case 1 \((C_1)\) shows the geometrically simple or early stages of fault displacement. High relief is associated with the lowest base level determined by relative proximity to the main mountain front and associated fan sedimentation as well as the river systems. (c) Case 2 \((C_2)\) shows the more complicated or later stage of displacement that results in multifaceted relief modulated by the same factors influencing base levels. Highest across-strike and sub-ridgetline relief is associated with steep fault dip and/or exposures of more resistant rocks. (d) Case 3 \((C_3)\) shows how transient factors such as (1) base level changes due to incision/river avulsion/deflection (big arrows near rivers and small arrows on north flank), (2) fault tip interaction (small arrows on tip), or (3) secondary faulting (dashed fault with question mark) could cause further topo-

level, influence emerging fold topographies in forelands. Here we summarize faulting and base level interactions in several schematic cases that can be temporally related (Figure 10).

5.6.1. Case 0: Prefaulted Foreland
[40] Prior to thrusting, some landscape features may pre-

condition the setting of the future emergent topography (Figure 10a). The main mountain front position and associ-

ated fan sedimentation, location of major transverse rivers [e.g., Gupta, 1997], and the gradual slope of the foreland all set the stage prior to faulting. These factors can impart a bias toward higher base level on the hinterland of the future uplift.

5.6.2. Case 1: Early or Simple Folding
[50] Simple fault geometry or the earliest stage of uplift results in systematic fold topography (Figure 10b). Fault ramp location determines range position and size. Divide position is probably recessed toward the hinterland, because rivers on the hinterland-facing flank of the fold may experience not only rock uplift but also relative base level rise due to piggyback basin aggradation, thus retarding their ability to incise. The across-strike difference in fold relief is dictated by proximity of the piggyback basin axial rivers, the position of drainage divides within that basin, and the location of major transverse rivers that may be deflected. Fold topography is characterized by (1) across-strike range asymmetry, (2) rapid relief gain from the propagating fault tips, and (3) higher hinterland-flank gradients on the actively uplifting region. Hillslope-scale relief patterns and catchment-averaged values are set by uplift rate and rock type. The Chandigarh anticline could represent this case because the fault geometry is simple and does not appear to vary much along strike.

[51] During this stage, fold topography may reach steady state [e.g., Campel et al., 2002; Willett and Brandon, 2002; Miller et al., 2007]. Given typical high rates of fault slip and lateral propagation in active thrust belt settings, fold relief is likely to grow and reach limiting values rapidly (within \(~10–100s\ of kyr\) following initial uplift. Fold topography may rapidly decouple from fault slip, but may be further compi-

cated by base level variations. This suggests an important point: if base level is set by axial rivers and thus varies only gradually along strike, then fold topography is also likely to vary little along strike, being set only by the available space and the channel network steepness [Whipple et al., 1999; Densmore et al., 2005]. The implication is that the topog-

raphy may give the illusion of cylindrical folding, almost regardless of the geometry of the underlying displacement field. Furthermore, pervasive denudation, facilitated by intense precipitation and/or weak rock, may make it difficult to preserve inherited fluvial features from the prefaulted topography.

5.6.3. Case 2: Later or More Complex Folding
[52] Fold topography will be more complex in response to either a more spatially variable fault geometry or a later stage of displacement, particularly if fault dip changes up section and/or fault orientation changes along strike (Figure 10c). Here, the factors influencing base level have not changed, only the tectonic forcing has. The resulting fold topography retains the previous patterns with the following complicat-

ions: (1) different zones of across-strike relief and (2) more variability in mountain front position and orientation. Across-strike relief will be high in zones coincident with steeper dipping portions of the fault. Hillslope-scale relief patterns are set by the relative rate of rock uplift and may vary further if multiple geologic units of varying strength become exposed. The Mohand anticline could represent this case because the HFT geometry is more complicated and several geologic units are exposed.

5.6.4. Case 3: Transient Forcing
[53] Transient processes may result in adjustments by the fold topography (Figure 10d). For example, flanking base level can fall as a result of piggyback basin incision perhaps due to climate change and/or disruption of sediment input from the main mountain front. This could result in drainage divide migration toward the foreland and may reduce hin-

terland-flank gradients. Transverse river channel avulsion near the main mountain front may affect base level contrasts between fold flanks by changing the location of the hinter-

land-flank axial river (and hence base level) and cause readjustment of fold relief as a consequence. Transient tec-

tonic changes could occur, such as fault tip interaction and secondary faulting within the fold. We view the Chandigarh
and Mohand anticlines as best representing this case combined with cases 1 and 2, respectively, because of episodic Quaternary fan sedimentation and incision within the Duns [e.g., Singh et al., 2001; Suresh et al., 2007; Sinha et al., 2010].

6. Summary and Conclusions

[54] The form of an emerging landscape is the result of the combined effects of rock uplift rate and the erosional response to that uplift. We hypothesized that, as previously shown for normal fault-bounded footwalls, faulting and base level are the principal controls on topography generated by folding. We observed that the rock uplift pattern dictated by the fault geometry principally determined the morphology (relief across various scales, range asymmetry, mean flank gradients) of two growing fault-bend folds at the Himalayan front in northwest India. Even though base level and its spatiotemporal variations theoretically establishes an important boundary condition for the erosional response to fault-generated uplift, its modulation of the rock uplift pattern appears less significant in these two cases. In particular, the rate of catchment relief growth with range half-width is approximately linear, but different across the fold flanks most likely due to differences in flank-averaged rock uplift rates. We speculate that this metric may be used to infer catchment-averaged rock uplift rates and hence variations in fault dip at depth. At the hillslope (sub-ridgetline) scale, both rock uplift rate and rock strength (lithology) coincide to influence the relief patterns. Finally, we suggest that in these thrust front-foreland settings, the combination of high slip rates (~6–18 mm/yr), high rock uplift rates (~4–8 mm/yr), uplift of weak rocks, and fast but episodic erosion during monsoon rainfall implies that topographic growth can become decoupled from fault slip over very short time scales (perhaps as little as ten to hundreds of kiloyears). As a result, we caution against the use of established criteria for inferring fold growth kinematics (e.g., wind and water gaps) developed from more idealized settings that may be less applicable in these rapidly evolving areas.

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