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Channel Width Response to Differential Uplift

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[1] The role of channel width and slope adjustments to differential uplift in rivers within actively deforming terrains remains contentious. Here high-resolution topographic surveying of formerly antecedent outwash channels demonstrates marked changes in channel width as a primary response to differential uplift. For five Late Quaternary alluvial paleochannels crossing small folds along the active Ostler fault zone of southern New Zealand, nearly continuous measurements of paleochannel width and concomitant incision reveal abrupt narrowing of widths toward minimum values at channel positions coincident with the initial uplift. When the magnitude of differential uplift is sufficiently small, narrowing alone permits these channels to remain antecedent. In the context of a unit stream power model for fluvial erosion, observed limits on the magnitude of channel narrowing suggest that above some threshold amount of differential uplift, continued incision requires concomitant changes in channel gradient. Thus when crossing small growing folds, alluvial rivers simply narrow their channels, whereas larger folds that demand greater incision prompt an initial narrowing followed by channel steepening.

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1. Introduction

[2] Increasing recognition that channel width serves as a primary adjustable feature of both alluvial and bedrock rivers has refined traditional views that changes in channel slope dominate fluvial response to variable tectonic, climatic, and lithologic conditions [*Whipple*, 2004; *Stark*, 2006; *Wobus et al.*, 2006]. As such, recent work on width response to varying rock uplift rates [*Harbor*, 1998; *Snyder et al.*, 2000; *Lavé and Avouac*, 2001; *Snyder et al.*, 2003; *Duvall et al.*, 2004; *Montgomery*, 2004; *Pearce et al.*, 2004; *Turowski et al.*, 2006; *Wobus et al.*, 2006] and bedrock erodibility [*Montgomery and Gran*, 2001] makes clear the potential importance of adjustments in channel width that are driven by external forcing. In addition to emphasizing the need for explicit consideration of channel width in characterizing active deformation from attributes of the fluvial network [e.g., *Kirby and Whipple*, 2001; *Lavé and Avouac*, 2001; *Kirby et al.*, 2003; *Carretier et al.*, 2006], such work highlights inherent linkages between channel slope and width adjustments in modulating fluvial incision [e.g., *Finnegan et al.*, 2005]. Less clear, however, is the relative order in which slope and width adjust to spatial gradients in rock uplift and the degree to which such responses are coupled [*Duvall et al.*, 2004], given that both are observed in rivers [*Lavé and Avouac*, 2001], ephemeral streams [*Pearce et al.*, 2004], and submarine channels [*Mitchell*, 2006] responding to differential uplift.

[3] Here we present the results of channel width measurements from deformed outwash channels preserved as wind gaps along the Ostler fault zone, a Quaternary thrust fault located in the east central Southern Alps of New Zealand (Figure 1). Through analysis of differential rock uplift and incision profiles along these formerly antecedent channels we document systematic changes in channel width as a function of and as a first response to uplift over the fault zone. Evaluation of observed width adjustments with a simple unit stream power incision model suggests that the relative magnitude of differential uplift determines whether channel narrowing is sufficient to erode through a growing fold or whether subsequent channel steepening is necessary as incision increases across some threshold. In contrast with previous work that relies on remotely sensed width measurements [e.g., *Lavé and Avouac*, 2001] or qualitative estimates of relative rock uplift rates [e.g., *Duvall et al.*, 2004; *Pearce et al.*, 2004], deformation over simple, small-scale folds along intact and well-exposed outwash surfaces is readily characterized at a nearly continuous spatial scale. As such, the Ostler fault provides an illuminating example of fluvial response to differential uplift outside the influence of climatic or lithologic effects.

2. Study Area

[4] Located in the intermontane Mackenzie Basin in the Southern Alps of New Zealand (Figure 1a), the Ostler fault represents an east directed zone of active thrusting in a broad area of distributed deformation east of the Pacific-Australian plate boundary. Of the ~38 mm/yr of relative plate motion involved in this oblique collision [*DeMets et*

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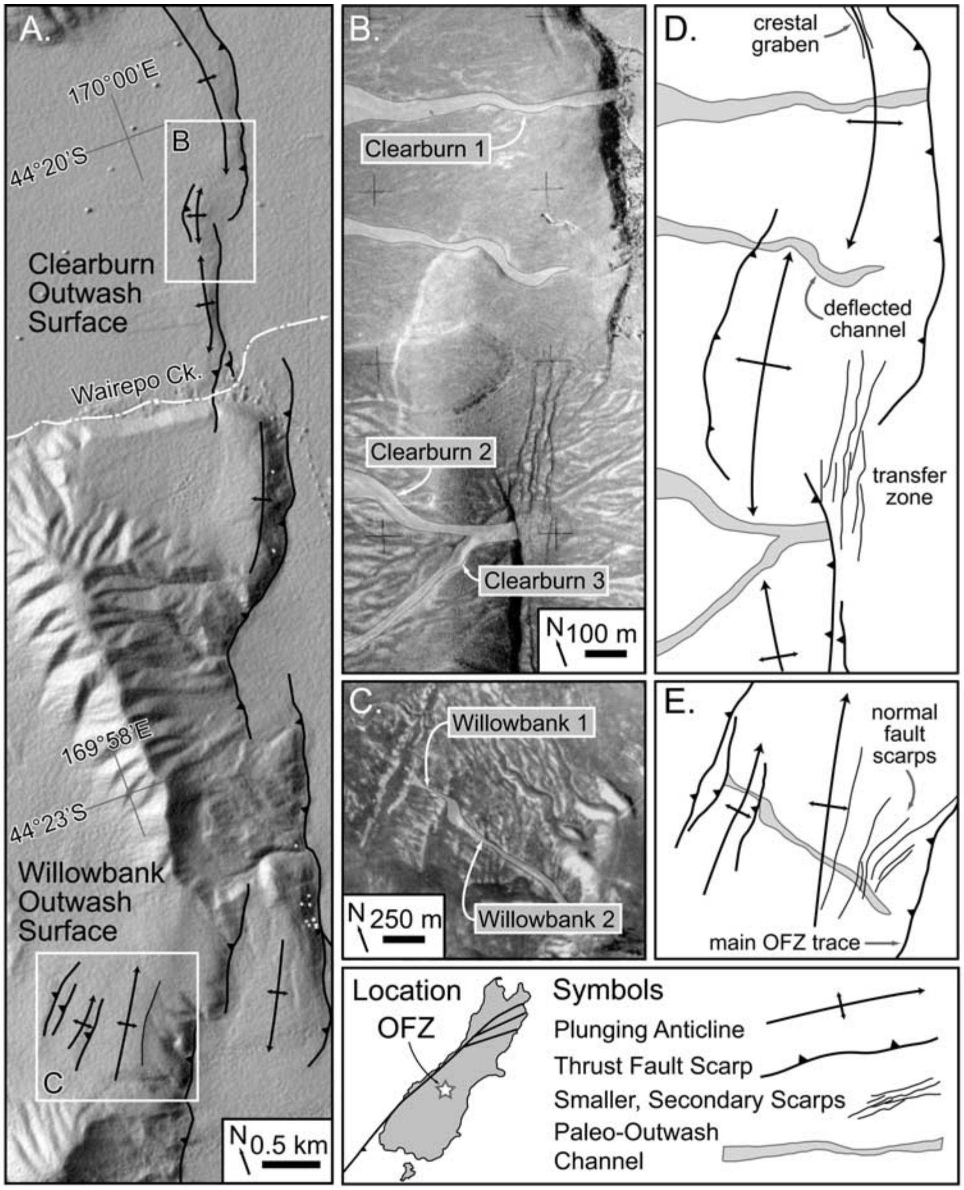

Figure 1. Ostler fault zone, South Island, New Zealand. (a) Hillshade image of central segments of the Ostler fault generated from a TOPSAR 10 m DEM is shown. (b and c) Aerial photographs of both Clearburn and Willowbank sites show surveyed paleochannels. (d and e) Photo interpretations of Figures 1b and 1c, respectively, highlight the major geomorphic and neotectonic elements in each location.

al., 1994], approximately two thirds is absorbed by the plate-bounding Alpine fault [*Norris and Cooper*, 2001] with the remainder distributed among structures, such as the Ostler fault, east of the Southern Alps [*Pearson et al.*, 1995; *Tippett and Hovius*, 2000]. Slip rate estimates based on deformed geomorphic features along the fault zone suggest that central segments of the Ostler fault accommodate ∼1–2 mm/yr of this slip [*Blick et al.*, 1989; *Read and Blick*, 1991; *Davis et al.*, 2005; *Amos et al.*, 2007]. As evidenced by a lack of laterally offset geomorphic markers, the Ostler fault is a pure thrust fault, and displacement occurs without any significant component of oblique slip [*Read*, 1984; *Davis et al.*, 2005].

[5] The surficial geology of the Mackenzie Basin is dominated by multiple generations of outwash surfaces and fluvial terraces spanning at least three Late Pleistocene glaciations [*Read*, 1984; *Blick et al.*, 1989]. Although only loosely constrained by regional climatic correlations and optically stimulated luminescence dating [*Amos et al.*, 2007], major outwash valleys along the Ostler fault become systematically younger to the north from Willowbank saddle (>120 ka) [*Read*, 1984] to the outwash surface at Clearburn of last glacial age (15–25 ka) [*Davis et al.*, 2005] (Figure 1a). Terraces and outwash surfaces throughout the Mackenzie Basin are intricately textured with numerous abandoned outwash channels that are cut into coarse,

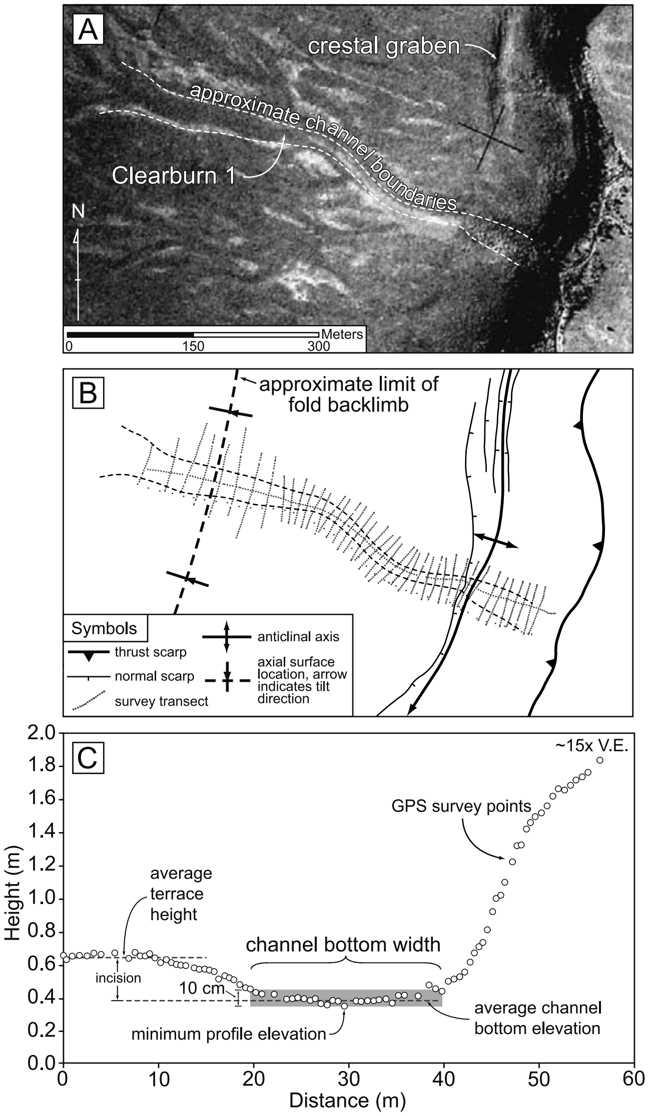

Figure 2. (a and b) Air photo and geomorphic interpretation of Clearburn channel 1 show the location of survey transects both within and outside the area affected by folding. (c) Schematic illustration of channel width measurement from surveyed cross-channel profiles is shown. Width is defined as the length of the flat channel bottom, distinguished automatically through MATLAB scripting as all survey points falling within 0.10 m of the minimum profile elevation. The difference between average bank height and the mean elevation along the channel bottom also yields a measure of incisional depth for each profile considered.

homogeneous fluvial and outwash gravels (Figures 1b and 1c). Vegetative cover on the dry, eastern side of the Southern Alps is minimal, and despite a locally variable cover of loess and soil typically less than a meter in thickness [*Maizels*, 1989], geomorphic surfaces and paleochannels remain relatively pristine, uneroded, and clearly visible.

[6] Geomorphic surfaces along the Ostler fault zone are deformed by numerous fault-related folds with half wavelengths of 0.25–1.0 km that are developed above active, east directed thrusts. Individual ruptures along the fault zone are highly segmented and display complex, sinuous surface traces with predominantly westside-up displacements (Figures 1d and 1e). Secondary faulting is also common as localized normal faulting associated with hanging wall folding and smaller thrust scarps in transfer zones between overlapping fault strands [*Davis et al.*, 2005]. Although fold style varies considerably along strike of the Ostler fault [*Amos et al.*, 2007], the relatively low amplitude, asymmetric hanging wall anticlines analyzed here are common along the fault's entire 50 km length. Lateral deflection (Figure 1d) and differential incision of channels cut into growing folds clearly indicate that deformation was ongoing when the outwash surfaces were active [*Davis et al.*, 2005] and permit evaluation of observed morphologic change as a direct response to differential uplift.

3. Methods

3.1. Channel Surveying

[7] Paleo-outwash channels along the Ostler fault zone were surveyed using a Trimble 4700 differential GPS with centimeter-scale vertical and horizontal precision. Surveying focused on channels traversing small anticlines incised during fold growth. For each channel examined, at least 20 cross-sectional profiles were measured perpendicular to the channel margins (Figure 2). Only relatively straight channels with observed continuity through growing structures were included in our analysis.

[8] In the absence of direct observations of bankfull channel width typically available for channels presently occupied by streams, width was defined geometrically along the flat-bottomed portion of channel cross profiles as a proxy for width of the bed material (Figure 2c). Using an automated MATLAB routine, channel width is measured as the distance along the cross-channel profile of all points that fall within 10 cm of the minimum profile elevation along the channel bottom. This threshold value represents the level of "geomorphic noise," or subtle variation in the ground surface due to local differences in loess, soil, and vegetative cover typical of terrace and outwash surfaces in the Mackenzie Basin. For channels preserved on surfaces deformed by laterally propagating folds, cross sections are rotated about a horizontal axis parallel to the channel to correct for the effects of tilting subsequent to surface abandonment (Figure 3). In each case, topographic profiles along the fold crest were extracted from a TOPSAR 10 m digital elevation model (DEM) and used to calculate the structural slope from a least squares regression through the fold profile in the channel vicinity (Figure 3b). Observed magnitudes of lateral tilting are typically less than a degree, and removal of this gradient from each cross profile rotates the flat channel bottom to horizontal (Figure 3c) before it is input into the channel width measurement routine described above.

[9] For each cross profile the observed difference between the channel bottom and the adjacent terrace surface provides a measure of incisional depth along the paleochannel length (Figure 2c). Terrace height is determined using the average elevation of the lowest adjacent flat terrace surface, and average channel bottom elevations are calculated from the values used in channel width measurements. For con-

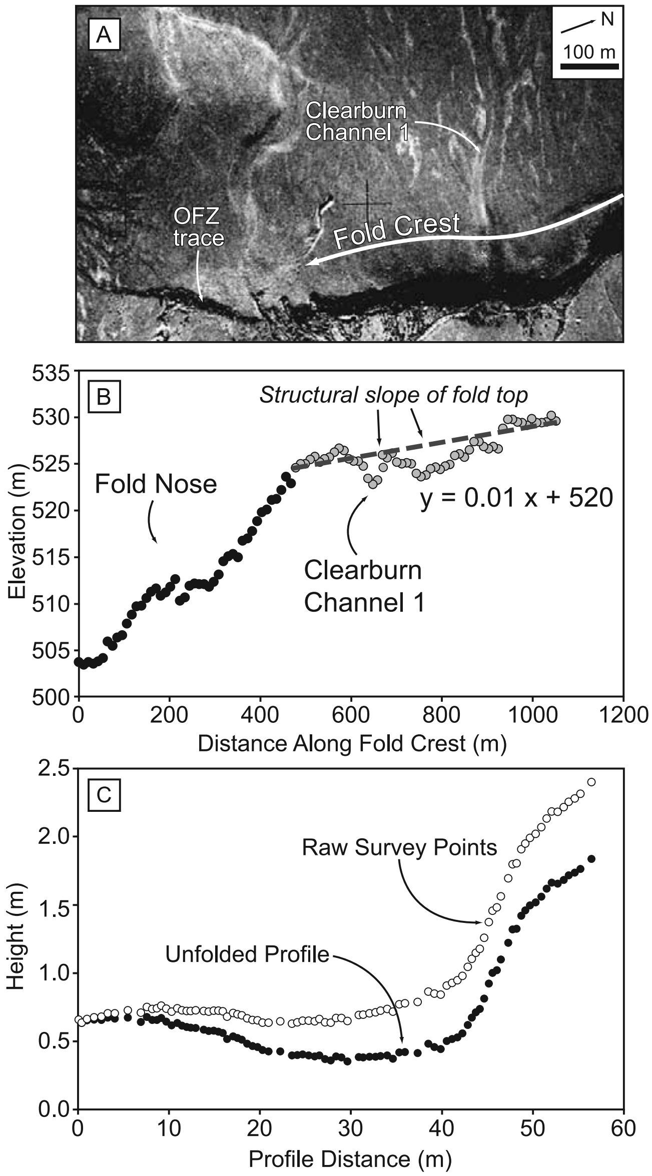

Figure 3. Rotation of cross-channel profiles to remove the effects of postabandonment tilting. (a) Aerial photo of the northern Clearburn fold shows the location of topographic profiling along the anticline axis. (b) TOPSAR 10 m DEM profile along the fold crest at Clearburn illustrates the strong gradient in the direction of southward fold propagation. Linear regression through the fold top (dashed line) yields a slope of 0.01. (c) Unfolding of cross-profile data prior to width measurement removes this local slope to restore the flat channel bottom to its initial horizontal orientation.

sistency, incisional depth is always measured along the same side of the channel. Given the relatively high density of cross-profile measurements for each channel, our surveys provide a nearly continuous measure of incisional depth across the folded hanging wall of the Ostler fault zone.

3.2. Buried Channel Topography

[10] Given the age of both Clearburn (15–25 ka) and Willowbank (>120 ka) outwash surfaces, abandonment of the paleochannels considered here likely predates 10 ka, and erosion of the channel margin may have modified the original preserved channel geometry. As a direct check on the accuracy of our width measurements we measured the buried channel topography along 19 cross profiles for one channel at the Clearburn site (Figure 4) by probing soil and loess depth at 0.5–1.0 m intervals along the channel cross section. Although revealing a slightly more complex bar and braided channel geometry at depth (Figure 4a), buried channel cross profiles show remarkably straight and steep-walled banks, suggesting little diffusion of bank material prior to loess deposition. In particular, channel segments within the core of the growing fold show extremely narrow, slot-like channels that are incised abruptly beneath flat portions of the channel bottom (Figure 4b).

[11] Comparison of measured channel widths and incisional depths between the surface cross sections and the buried profiles allows evaluation of the uncertainties associated with our measurements from the surface topography alone. Given the somewhat irregular nature of the buried channel profiles, we increased the threshold of "geomorphic noise" to 25 cm in the automated width measurement routine. In general, the results of our soil depth profiling suggest that channel width errors are likely to be greater upstream of the fold, where the channel banks are somewhat subdued and less readily distinguished at the surface (Figure 4a). With the exception of buried profiles that lack a distinctly flat bottom (Figure 4b, top and middle), the actual width of the channel bed either agrees well with or is overestimated by surface measurements at channel positions within the zone of active folding. As such, reported errors on width and incision measurements for all profiles nominally reflect average differences between surface measurements and the buried Clearburn channel within each of these distinct zones. Uncertainties on width and incision are ± 6.5 and 0.2 m, respectively, for wider portions of the channel upstream of the active uplift and ± 1.7 and 0.6 m for incised channel segments within the fold. Given that channel width was underestimated for wider portions of the channel upstream of the fold (Figure 4a) the actual magnitude of channel narrowing described in our results is also somewhat underestimated here.

4. Results

4.1. Channel Width Variations

[12] Comparison of observed changes in channel width for abandoned outwash channels along the Ostler fault zone with contemporaneous folding reveals marked width variations in conjunction with increasing differential incision (Figures 5 and 6). Along each channel, incisional depth accurately mimics the surveyed fold profile and thus provides a measure of the incision driven by folding while the channel was still active. Channel width for all measured profiles clearly trends toward minimum values of 2–6 m with only ~1–1.5 m of differential incision, even for those profiles where incisional depth ultimately exceeds 3–5 m (Figure 6).

[13] Although channel width measurements show remarkably consistent behavior for all profiles (Figure 6), the width minimum occurs at different positions with respect to the fold crest for different magnitude uplifts.

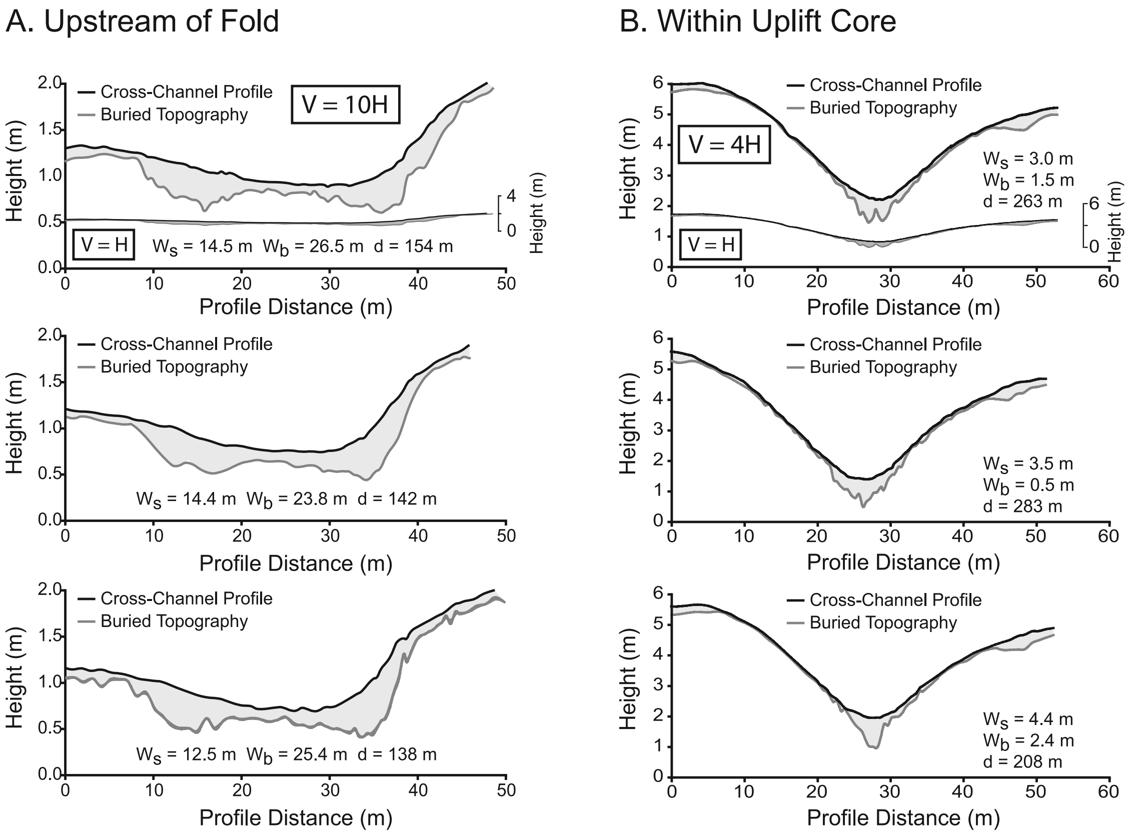

Figure 4. Examples of cross-channel survey profiles and buried channel topography from soil-depth profiling along Clearburn channel 1. W_s denotes width measurements from the surface topography, W_b indicates width measurements from the buried channel, and *d* represents distance along the channel long profile. (a) Comparison of the surface topography and the buried channel profiles upstream of the active uplift suggests that channel width is generally underestimated for the relatively subdued channels outside the area affected by folding. (b) In contrast, buried channel width is well matched or overestimated by the surface topography for channels incised within the fold core. To aid visual comparison, profiles are greatly vertically exaggerated to emphasize topographic variations and are also shown with equal vertical and horizontal scales for the top profiles in Figures 4a and 4b.

For smaller folds with crestal uplift <2 m (e.g., Willowbank 1) the width minimum approximately corresponds with the fold crest (Figure 5d), whereas channels deformed by larger folds (e.g., Clearburn 1) narrow to minimum values as soon as uplift exceeds 1–1.5 m (Figure 5a). In any case, all paleochannels along the Ostler fault appear to approach a minimum in channel width during continued differential incision driven by active folding.

4.2. Unit Stream Power

[14] Theoretical models for fluvial incision often express erosion rate *E* as being either proportional to unit stream power or the shear stress exerted by a volume of water moving downslope along the channel bed [e.g., *Howard and Kerby*, 1983; *Whipple and Tucker*, 1999]. Such equations may take the general form $E \propto \omega = \gamma(Q/w)S$, where γ is the specific weight of water, (Q/w) represents the discharge per unit width, and *S* is channel slope [*Montgomery and Gran*, 2001; *Montgomery*, 2004]. Simple consideration of the variables involved in this expression suggests that both width and channel slope variations should play an important role in modulating the erosive capability of rivers [e.g., *Finnegan et al.*, 2005], if erosion is indeed linearly proportional to unit stream power. Recent theoretical work on dynamic width and slope adjustments in bedrock channels [*Wobus et al.*, 2006] also suggests that the timescales that govern each response may be fundamentally different. Here we distinguish between the relatively instantaneous and transient perturbations to the slope profile during folding that ultimately drive channel width narrowing (see section 5) and sustained channel steepening and knickpoint development in response to continued uplift [e.g., *Seeber and Gornitz*, 1983; *Kirby and Whipple*, 2001; *Lavé and Avouac*, 2001].

[15] Although formulated for detachment-limited erosion characteristic of bedrock rivers [e.g., *Howard et al.*, 1994], application of a unit stream power model to the alluvial channels considered here is justified given that they were clearly incising their beds, often to depths equal to several times their widths. Under this condition, erosional work done along incising reaches is limited by the ability of the available discharge to entrain material in the channel substrate regardless of whether it is bedrock or coarse outwash gravel.

[16] Implementation of a unit stream power model requires implicit knowledge of slope along a given channel

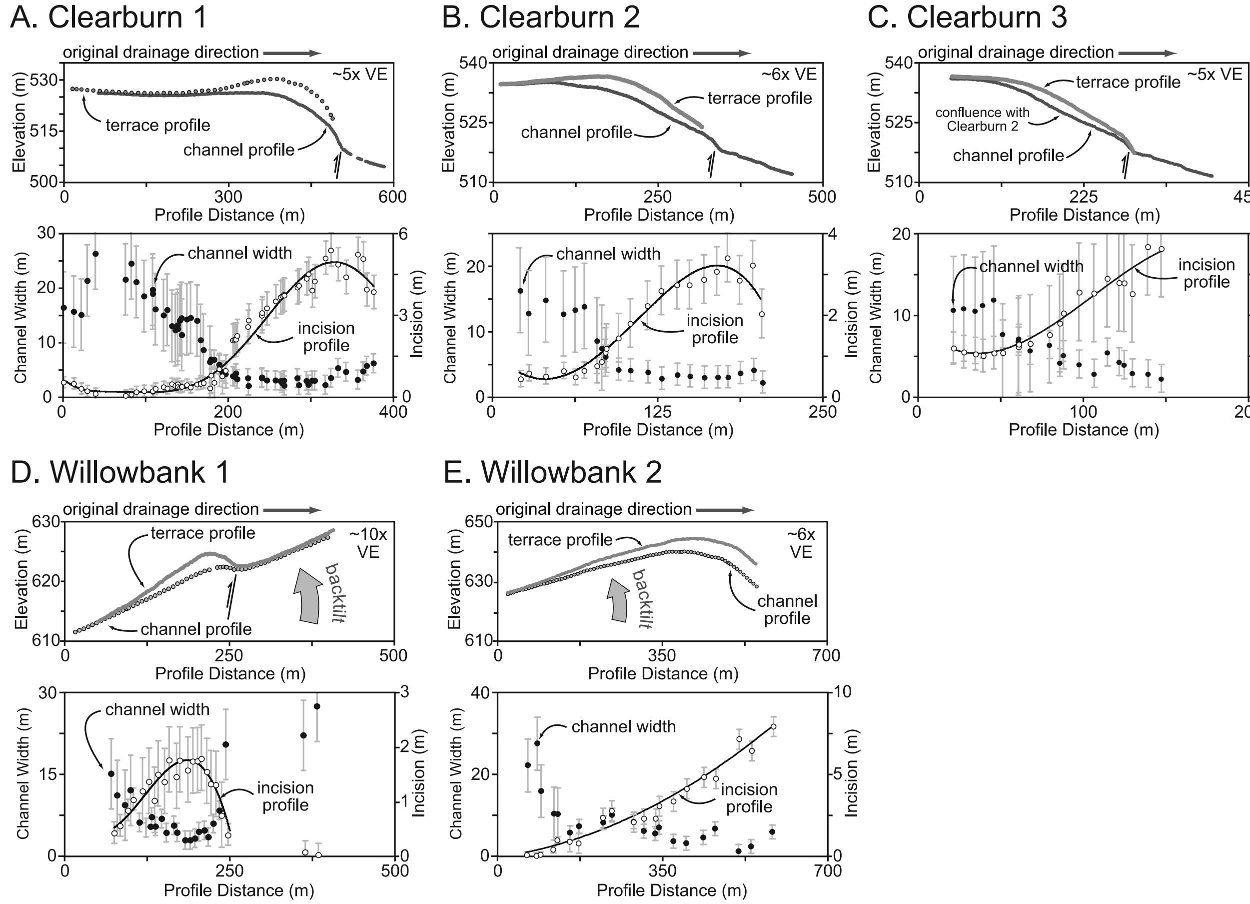

Figure 5. Channel and terrace long profiles and the resulting channel width and incision measurements for each of the considered paleochannels. Although the surveyed long profiles reflect substantial tilting and deformation since surface abandonment, the observed elevation difference between the terrace and channel bottom yields a measure of differential incision that mimics the general fold profile. Polynomial fits to incision measurements are included to emphasize this relationship.

reach. Because surveyed long profiles for the Ostler paleochannels incorporate deformation subsequent to channel abandonment, we cannot directly measure the true slope when the channels were still active. Consequently, we utilize the modern stream profile surveyed along Wairepo Creek at the Clearburn site (Figure 1a) both upstream of and crossing the active hanging wall anticline as model slope inputs (Figure 7a). Slope profiles in each case are projected along the channel length. Channel width measurements for Wairepo Creek were not included in our analysis because the channel there reflects some modification of its natural width through the construction of several small, shallow dams along its course. These dams were installed in the last ∼150 years, however, and do not likely influence measurements of channel slope taken outside the areas affected by damming.

[17] Wairepo Creek displays a prominent steep reach where it traverses the active hanging wall anticline along the Ostler fault zone (Figure 7a). The maximum gradient along this reach is 4 times the background "undisturbed" gradient of 0.005 upstream of the area affected by active folding. Also evident in this slope profile is a slight reduction in channel slope upstream of the active fold. We attribute these gentler gradients to ponding of sediments driven by damming of the modern stream behind the zone of active uplift [e.g., *King and Vita-Finzi*, 1981; *Burbank*

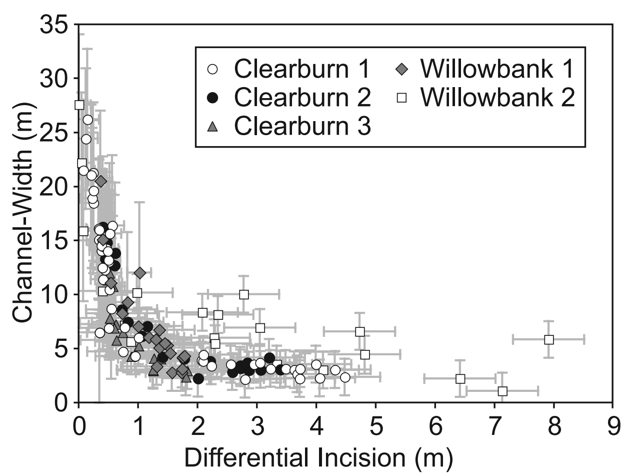

Figure 6. Channel width versus differential incision for all profiles. Note the systematic narrowing of channel widths to an apparent minimum value with only ∼1.5 m of differential incision driven by folding.

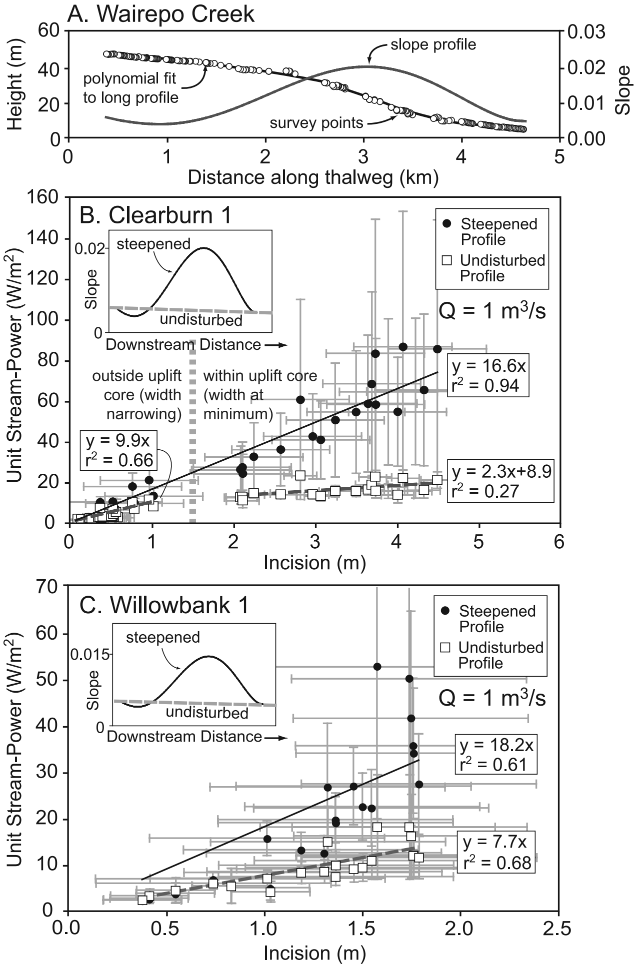

Figure 7. Slope inputs and unit stream power calculations. (a) The modern slope profile along Wairepo Creek is taken from a polynomial fit to the surveyed long profile, which shows a distinct inflection in slope corresponding to a prominent knickpoint over the hanging wall anticline. (b and c) Steepened channel gradients allow continuous increase in stream power with progressive incision through the uplift core for Clearburn 1 (Figure 7b), whereas both steepened and undisturbed profiles allow such increases with observed width changes along Willowbank 1 (Figure 7c). With the exception of the undisturbed profile points within the uplift core of Clearburn 1, linear regressions are fixed through the origin.

et al., 1996]. In the stream power calculations for each paleochannel, steepened slope profiles that mimic the modern knickpoint along Wairepo Creek were scaled lengthwise to the observed fold half wavelength at each site (Figures 7b and 7c, insets). The magnitude of the knickpoint and the amplitude of the associated slope inflection for the modeled steepened slope profiles were scaled to not exceed the maximum incisional depth along each profile (Figure 5).

[18] To simplify our calculations, discharge was held constant at 1 m^3/s along the relatively short span of each paleochannel. Assumption of a constant discharge is reasonable given that no tributaries join the measured paleochannels in the region of our surveys. In this study we are concerned primarily with relative variations in stream power with progressive incision. Although unit stream power and the rate constants associated with our regressions depend on the input discharge (Figures 7b and 7c), their absolute magnitudes are arbitrary and do not affect our analysis.

[19] Analysis of changes in stream power as a function of concomitant variations in the magnitude of erosion across a fold reveals two classes of behavior (Figure 7). In one, channel steepening following width narrowing yields a relatively high correlation between stream power and incision, whereas in the other, width changes alone produce an equivalent or better match. In comparison to relatively uniform channel gradients a steepened slope profile along Clearburn 1 produces a roughly linear and continuous increase in unit stream power with progressive incision through the entire growing fold (Figure 7b), such that stream power and incision are highly correlated (r^2 = 0.94). Such slope increases appear necessary because when channel width attains a minimum value, which happens after only ~1.5 m of incision, only steeper gradients can allow stream power to increase as incision climbs to >4 m (Figures 5a and 6). Without increased slopes the rate of increase in unit stream power diminishes rapidly after only ~1.5 m of uplift along this channel, as illustrated by the separate linear regressions outside and within the uplift core (Figure 7b). Through the zone of active uplift, stream power and incision are poorly correlated when only changes in channel width are considered (r^2 = 0.27). In this case, therefore, channel steepening is required to drive the additional 3–4 m of incision across the fold crest.

[20] Despite substantial deformation of the channel profile since abandonment of the Clearburn outwash surface, comparison with the scaled, folded terrace profile along Clearburn 1 provides some constraint on the initial long profile geometry while the channel was active (Figure 8a). There a pronounced dissimilarity between the terrace profile and the folded channel suggests that deformation of the long profile cannot be reproduced by simple "unfolding" or vertically similar scaling of the present fold geometry. Instead, this discrepancy along the channel profile suggests either a change in the kinematics of fold growth or ~1 m of incision within the uplift core and an equal amount of aggradation upstream of the fold crest (Figure 8a). Although the history of fold growth is often complex and difficult to infer unambiguously [e.g., *Verges et al.*, 1996], this simple reconstruction is consistent with the presence of a knickpoint or a steepened channel reach "frozen" into the long profile of Clearburn 1 prior to surface abandonment and subsequent deformation.

[21] Examination of observed changes in paleochannel width for other channels along the Ostler fault zone, however, suggests that width may adjust prior to or without prolonged changes in channel slope. In contrast to Clearburn 1, stream power for both undisturbed and steepened profiles along Willowbank 1 increases roughly continuously with ongoing erosion (Figure 7c) and is similarly correlated with the magnitude of incision (r^2 = 0.68 and 0.61, respectively). Such a result is consistent with width changes alone being sufficient to permit incision through the relatively smaller fold in this location. Although channel steepening is not ruled out by this analysis, the relatively

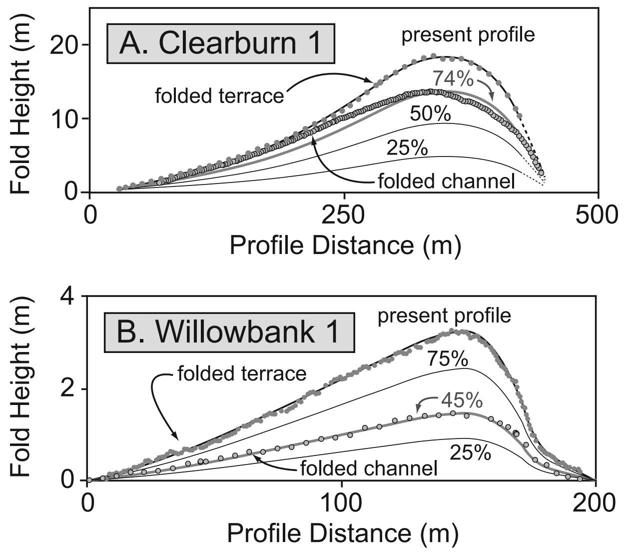

Figure 8. (a) Comparison of the deformed terrace profile scaled to 74% (gray line) with the folded Clearburn channel 1 suggests at least a meter of channel aggradation and incision upstream and downstream of the fold crest, respectively, prior to surface abandonment. (b) Similarity between the deformed terrace profile scaled vertically to 45% (gray line) and the folded channel along Willowbank 1, however, provides little evidence of steepening while the channel was active. Vertically scaled terrace profiles (50 and 25% in Figure 8a, 75 and 25% in Figure 8b are included for visual comparison.

linear and undisturbed long profile along Willowbank 1 (Figures 5d and 8b) shows little evidence of knickpoint development prior to channel abandonment and subsequent deformation. There, similarity between the shape of the deformed channel and the scaled, folded terrace profile suggests that observed steepening at the fold front results solely from postabandonment folding and incremental deformation of a previously linear channel profile (Figure 8b). Along this channel, spatial correspondence between the channel width minimum and the uplift crest (Figure 5d) and the lack of any preserved channel steepening prior to surface abandonment provides clear evidence of width adjustment in the absence of sustained increase in channel slope.

5. Discussion

[22] Even in the absence of changes in planform geometry [e.g., *Burnett and Schumm*, 1983; *Ouchi*, 1985], antecedent rivers may differentially incise through zones of active uplift. Although conceptual models are available to explain channel width adjustment in self-formed alluvial channels [e.g., *Parker*, 1978; *Andrews*, 1982], a theoretical framework to explain dynamic width narrowing for bedrock rivers incising through zones of active rock uplift is only just emerging [e.g., *Wobus et al.*, 2006]. Recent experimental work by *Cantelli et al.* [2004], however, may shed some light on this process in alluvial systems. In flume experiments that simulate erosion after dam removal, *Cantelli et al.* [2004] documented systematic channel narrowing as a river erodes through the deltaic front originally deposited behind the dam. An analogous situation may exist for channels incising through a fold that is asymmetric in the downstream direction where instantaneously steepened gradients over the forelimb during folding concentrate flow velocity and thus shear stress at the channel center, promoting deepening, narrowing, and entrenchment. From a mechanistic perspective this transient increase in forelimb incision creates a knickpoint, which then migrates upstream [e.g., *Gardner*, 1983] but diminishes in height as a function of differential uplift gradients along the fold backlimb [*Burbank et al.*, 1996]. At the upstream limit of folding the knickpoint should then merge with predeformational profile, thus restoring a uniform slope profile along the channel. Through the zone of active uplift, channel entrenchment, narrowing, and deepening further increase fluvial shear stress or unit stream power along the channel [*Snyder et al.*, 2003], thereby establishing a positive feedback [*Cantelli et al.*, 2004]. The ability of channel narrowing to bolster the erosive potential of antecedent rivers should, however, be strongly modulated by a lower limit to the amount a given channel can effectively narrow.

[23] Measured widths for all paleo-outwash channels considered in this study trend toward minimum values of ~2–6 m in response to incision driven by folding (Figure 6). Despite difficulties in accurately reconstructing paleoflow for abandoned channels we speculate that the ubiquity of this response reflects similar discharges while the Ostler channels were still active. Similarly, *Turowski et al.* [2006] reported the presence of a minimum channel width in an experimental simulation of channel response to varying tectonic uplift rates. Rather than differential uplift over an isolated structure, however, rates of uplift in these experiments were held constant along the channel length, and channel adjustments primarily reflect changes in flow velocity and depth that occur as channel slopes increase at higher uplift rates [*Turowski et al.*, 2006].

[24] Stream power considerations for the Ostler paleochannels indicate that when channel width narrows to a minimum value, further incision requires steepened channel gradients and development of a sustained knickpoint. Either increased turbulent shear stresses on the channel walls as width decreases or concomitant reduction in the ability to transport the total upstream bed load flux through the system may ultimately limit the physical magnitude of channel narrowing in response to differential uplift. Alternatively, an increase in lateral erosion rate or sediment transport from the channel walls may serve to reduce vertical incision and promote channel widening once the channels have narrowed to minimum values [*Cantelli et al.*, 2004; *Turowski et al.*, 2006].

[25] On the basis of our Ostler fault data a schematic representation of predicted width variations illustrates the influence of varying magnitudes of fold height and half wavelength on channel response to active deformation (Figure 9). For channels at a similar discharge the maximum incision for different size uplifts occurs at differing downstream positions with respect to where the minimum channel width is achieved. For smaller magnitude uplifts the minimum channel width coincides spatially with the uplift, or incisional maximum and width changes occur without an

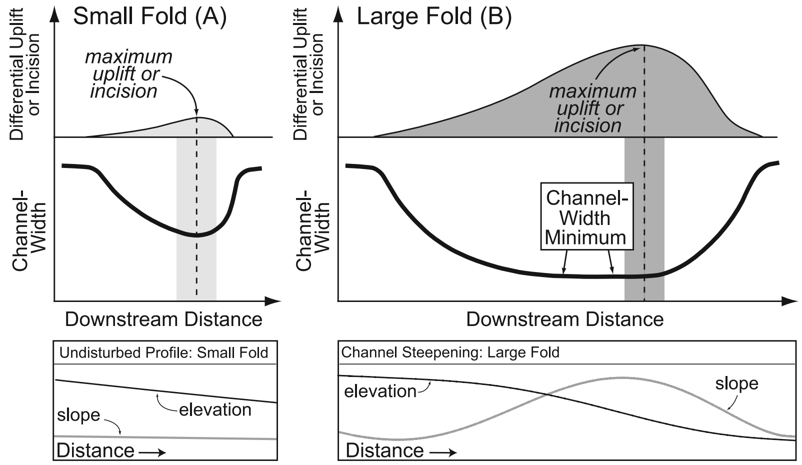

Figure 9. Conceptual illustration of channel width response to active folding. At a given discharge, smaller-magnitude uplifts (fold A) may intersect the narrowing curve before reaching the channel width minimum and thus maintain undisturbed longitudinal profiles. For larger uplifts (fold B), incision, once channel width has reached a minimum value, requires steepening of channel slope.

accompanying increase in slope. Such is the case for Willowbank 1 (Figure 5d), where spatial correspondence between the fold crest and width minimum combines with the relatively linear long profile (Figure 8b) to suggest that channel narrowing was sufficient to erode through the growing fold in this location. In contrast, channels such as Clearburn 1 that are forced to incise through larger folds tend to narrow to a minimum value upstream of the incision/uplift maxima (Figure 5a), thereby requiring slope steepening in order to sustain their courses across the growing structure.

[26] Consistent with this model is the suggestion that the relative role of slope and width adjustments in driving differential incision primarily reflects the magnitude of differential uplift, available discharge, and total bed load flux [*Burbank et al.*, 1996; *Humphrey and Konrad*, 2000]. When increased energy is needed to sustain the channel across a growing fold, the initial response of a river is a decrease in width driven by transient perturbations to the slope profile. These perturbations generate ephemeral knickpoints that migrate across the fold and die out as the differential deformation decreases upstream. If the magnitude of a given uplift requires additional erosive energy downstream, the channel then maintains some of its steepened gradient localized over the region of greatest differential uplift. This conceptualization provides an attractive means to explain the response of channel width to differential uplift along growing folds. Such a model is consistent with observations of modern bedrock rivers crossing much larger, rapidly deforming folds in Nepal, where >80% of the channel narrowing occurs before any channel steepening is observed [e.g., *Lavé and Avouac*, 2001].

[27] Despite the relatively large uncertainties associated with estimating channel width from deformed and buried paleochannels (Figure 4) each of the Ostler wind gaps appears to narrow toward a minimum value as differential uplift increases (Figures 5 and 6) regardless of the absolute magnitude of actual narrowing. The ubiquity of this response coupled with our stream power analysis (Figure 7) suggests that width adjustments may serve as the primary response to differential uplift independent of prolonged changes in channel slope. By incorporating modern long profiles at the Clearburn site (Figure 7a) this result relies on the assumption that both steepened and undisturbed channel gradients along Wairepo Creek provide reasonable constraints on the potential magnitude of uplift-driven slope changes while the outwash channels were still active. Although we lack constraints on the validity of this assumption, the reconstructed long profile and observed width variations along Willowbank 1 (Figures 8b and 5d) make clear the potential for width adjustments alone to drive erosion through sufficiently small growing folds.

[28] The paleochannels considered here are developed in deformed glacial outwash, and each is incised through growing folds to depths 2–3 times greater than its width. If this incision can be considered "detachment limited," then the observed narrowing response to differential uplift may also be applicable to detachment-limited bedrock channels. Additional studies of differential incision, channel width, and slope adjustments for bedrock rivers are needed to confirm that width changes represent the initial response in antecedent channels crossing folds in both alluvial and bedrock settings.

6. Conclusion

[29] In order to sustain its course over a growing fold a river must increase both its ability to erode its bed and its capacity to transport sediment. In the context of energy and work done by a river this increase can occur through narrowing or steepening of the channel or both. Channel width measurements from deformed paleochannels in New Zealand allow us to delineate the morphologic responses of former rivers from differential uplift across growing folds. Through a focus on relatively simple fold geometries, small channels, pristine geomorphic features, and formerly antecedent channels preserved as wind gaps along the Ostler fault make clear the influence of alluvial channel morphology in modulating fluvial incision. Here we show that the

initial response of an antecedent channel to differential uplift is to become narrower, thereby deepening the flow and increasing shear stresses on the bed. Once a minimum in channel width has been achieved, additional incision then requires a sustained increase in channel gradient. Although undoubtedly linked to some degree, our findings indicate that width variations in alluvial systems may occur in the absence of disturbed channel profiles rather than as a direct consequence of prolonged channel steepening [*Finnegan et al.*, 2005; *Turowski et al.*, 2006]. If so, these results highlight the importance of channel narrowing as the initial response of antecedent rivers to differential uplift and emphasize the need for explicit consideration of channel morphology in assessing river networks in actively deforming terrains [*Whipple*, 2004]. Our study also underscores the utility of well-preserved geomorphic markers as an invaluable frame of reference for evaluating fluvial response to external tectonic, climatic, and lithologic variations [e.g., *Whipple et al.*, 2000; *Pazzaglia and Brandon*, 2001; *Oskin and Burbank*, 2007].

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References

Amos, C. B., D. W. Burbank, D. C. Nobes, and S. A. L. Read (2007), Geomorphic constraints on listric thrust faulting: Implications for active deformation in the Mackenzie Basin, South Island, New Zealand, *J. Geophys. Res.*, *112*, B03S11, doi:10.1029/2006JB004291.

Andrews, E. D. (1982), Bank stability and channel width adjustment, East Fork River, Wyoming, *Water Resour. Res.*, *18*, 1184–1192.

Blick, G. H., S. A. L. Read, and P. T. Hall (1989), Deformation monitoring of the Ostler fault zone, South Island, New Zealand, *Tectonophysics*, *167*, 329–339.

Burbank, D., A. Meigs, and N. Brozovic (1996), Interactions of growing folds and coeval depositional systems, *Basin Res.*, *8*, 199–223.

Burnett, A. W., and S. A. Schumm (1983), Alluvial-river response to neotectonic deformation in Louisiana and Mississippi, *Science*, *222*, 49–50.

Cantelli, A., C. Paola, and G. Parker (2004), Experiments on upstream-migrating erosional narrowing and widening of an incisional channel caused by dam removal, *Water Resour. Res.*, *40*, W03304, doi:10.1029/2003WR002940.

Carretier, S., B. Nivière, M. Giamboni, and T. Winter (2006), Do river profiles record along-stream variations of low uplift rate?, *J. Geophys. Res.*, *111*, F02024, doi:10.1029/2005JF000419.

Davis, K., D. W. Burbank, D. Fisher, S. Wallace, and D. Nobes (2005), Thrust-fault growth and segment linkage in the active Ostler fault zone, New Zealand, *J. Struct. Geol.*, *27*, 1528–1546.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein (1994), Effect of recent revisions to the geomagnetic reversal time-scale on estimates of current plate motions, *Geophys. Res. Lett.*, *21*, 2191–2194.

Duvall, A., E. Kirby, and D. Burbank (2004), Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California, *J. Geophys. Res.*, *109*, F03002, doi:10.1029/2003JF000086.

Finnegan, N. J., G. Roe, D. R. Montgomery, and B. Hallet (2005), Controls on the channel width of rivers: Implications for modeling fluvial incision of bedrock, *Geology*, *33*, 229–232, doi:10.1130/G21171.1.

Gardner, T. W. (1983), Experimental-study of knickpoint and longitudinal profile evolution in cohesive, homogeneous material, *Geol. Soc. Am. Bull.*, *94*, 664–672, doi:10.1130/0016-7606(1983)94<664:ESOKAL>2.0.CO;2.

Harbor, D. J. (1998), Dynamic equilibrium between and active uplift and the Sevier River, Utah, *J. Geol.*, *106*, 181–194.

Howard, A. D., and G. Kerby (1983), Channel changes in badlands, *Geol. Soc. Am. Bull.*, *94*, 739–752.

Howard, A. D., W. E. Dietrich, and M. A. Seidl (1994), Modeling fluvial erosion on regional to continental scales, *J. Geophys. Res.*, *99*, 13,971–13,986.

Humphrey, N. F., and S. K. Konrad (2000), River incision or diversion in response to bedrock uplift, *Geology*, *28*, 43–46, doi:10.1130/0091-7613(2000)28<43:RIODIR>2.0.CO;2.

King, G. C. P., and C. Vita-Finzi (1981), Active folding in the Algerian earthquake of 10 October 1980, *Nature*, *292*, 22–26, doi:10.1038/292022a0.

Kirby, E., and K. Whipple (2001), Quantifying differential rock-uplift rates via stream profile analysis, *Geology*, *29*, 415–418, doi:10.1130/0091-7613(2001)029<0415:QDRURV>2.0.CO;2.

Kirby, E., K. X. Whipple, W. Tang, and Z. Chen (2003), Distribution of active rock uplift along the eastern margin of the Tibetan Plateau: Inferences from bedrock channel longitudinal profiles, *J. Geophys. Res.*, *108*(B4), 2217, doi:10.1029/2001JB000861.

Lavé, J., and J. P. Avouac (2001), Fluvial incision and tectonic uplift across the Himalayas of central Nepal, *J. Geophys. Res.*, *106*, 26,561–26,591.

Maizels, J. K. (1989), Differentiation of late Pleistocene terrace outwash deposits using geomorphic criteria—Tekapo Valley, South Island, New Zealand, *N. Z. J. Geol. Geophys.*, *32*, 225–241.

Mitchell, N. C. (2006), Morphologies of knickpoints in submarine canyons, *Geol. Soc. Am. Bull.*, *118*, 589–605, doi:10.1130/B25772.1.

Montgomery, D. R. (2004), Observations on the role of lithology in strath terrace formation and bedrock channel width, *Am. J. Sci.*, *304*, 454–476.

Montgomery, D. R., and K. B. Gran (2001), Downstream variations in the width of bedrock channels, *Water Resour. Res.*, *37*, 1841–1846.

Norris, R. J., and A. F. Cooper (2001), Late Quaternary slip rates and slip partitioning on the Alpine fault, New Zealand, *J. Struct. Geol.*, *23*, 507–520, doi:10.1016/S0191-8141(00)00122-X.

Oskin, M., and D. W. Burbank (2007), Transient landscape evolution of basement-cored uplifts: Example of the Kyrgyz Range, Tien Shan, *J. Geophys. Res.*, doi:10.1029/2006JF000563, in press.

Ouchi, S. (1985), Response of alluvial rivers to slow tectonic movement, *Geol. Soc. Am. Bull.*, *96*, 504–515, doi: 10.1130/0016-7606(1985)96<504:ROARTS>2.0.CO;2.

Parker, G. (1978), Self-formed straight rivers with equilibrium banks and mobile bed. Part 1: Sand-silt river, *J. Fluid Mech.*, *89*, 109–125.

Pazzaglia, F. J., and M. T. Brandon (2001), A fluvial record of long-term steady-state uplift and erosion across the Cascadia forearc high, western Washington State, *Am. J. Sci.*, *301*, 385–431.

Pearce, S. A., F. J. Pazzaglia, and M. C. Eppes (2004), Ephemeral stream response to growing folds, *Geol. Soc. Am. Bull.*, *116*, 1223–1239, doi:10.1130/B25386.1.

Pearson, C. F., J. Beavan, D. J. Darby, G. H. Blick, and R. I. Walcott (1995), Strain distribution across the Australian-Pacific plate boundary in the central South Island, New Zealand, from 1992 GPS and earlier terrestrial observations, *J. Geophys. Res.*, *100*, 22,071–22,082.

Read, S. A. L. (1984), The Ostler fault zone, in *Guidebook to the South Island Scientific Excursions International Symposium on Recent Crustal Movements of the Pacific Region*, edited by P. R. Wood, pp. 121–134, R. Soc. of N. Z., Wellington.

Read, S. A. L., and G. H. Blick (1991), Late Quaternary deformation and geodetic monitoring in the area of "the knot" on the Ostler fault zone, South Island, New Zealand, *N. Z. Geol. Surv. Rec.*, *43*, 85–91.

Seeber, L., and V. Gornitz (1983), River profiles along the Himalayan Arc as indicators of active tectonics, *Tectonophysics*, *92*, 335–367, doi:10.1016/0040-1951(83)90201-9.

Snyder, N. P., K. X. Whipple, G. E. Tucker, and D. J. Merritts (2000), Landscape response to tectonic forcing: Digital elevation model analysis of stream profiles in the Mendocino triple junction region, northern California, *Geol. Soc. Am. Bull.*, *112*, 1250–1263, doi:10.1130/0016-7606(2000)112<1250:LRTTFD>2.0.CO;2.

Snyder, N. P., K. X. Whipple, G. E. Tucker, and D. J. Merritts (2003), Channel response to tectonic forcing: Field analysis of stream morphology and hydrology in the Mendocino triple junction region, northern California, *Geomorphology*, *53*, 97–127, doi:10.1016/S0169-555X(02)00349-5.

Stark, C. P. (2006), A self-regulating model of bedrock river channel geometry, *Geophys. Res. Lett.*, *33*, L04402, doi:10.1029/2005GL023193.

Tippett, J. M., and N. Hovius (2000), Geodynamic processes in the Southern Alps, New Zealand, in *Geomorphology and Global Tectonics*, edited by M. A. Summerfield, pp. 109–134, John Wiley, Hoboken, N. J.

Turowski, J. M., D. Lague, A. Crave, and N. Hovius (2006), Experimental channel response to tectonic uplift, *J. Geophys. Res.*, *111*, F03008, doi:10.1029/2005JF000306.

Verges, J., D. W. Burbank, and A. Meigs (1996), Unfolding: An inverse approach to fold kinematics, *Geology*, *24*, 175–178, doi:10.1130/0091-7613(1996)024<0175:UAIATF>2.3.CO;2.

Whipple, K. X. (2004), Bedrock rivers and the geomorphology of active orogens, *Annu. Rev. Earth Planet. Sci.*, *32*, 151–185, doi:10.1146/annurev.earth.32.101802.120356.

Whipple, K., and G. E. Tucker (1999), Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs, *J. Geophys. Res.*, *104*, 17,661–17,674.

Whipple, K. X., N. P. Snyder, and K. Dollenmayer (2000), Rates and processes of bedrock incision by the Upper Ukak River since the 1912 Novarupta ash flow in the Valley of Ten Thousand Smokes, Alaska, *Geology*, *28*, 835–838, doi:10.1130/0091-7613(2000)28<835:RAPOBI>2.0.CO;2.

Wobus, C. W., G. E. Tucker, and R. S. Anderson (2006), Self-formed bedrock channels, *Geophys. Res. Lett.*, *33*, L18408, doi:10.1029/2006GL027182.

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