Final Technical Report

# RATES OF VERTICAL DEFORMATION ABOVE BLIND AND POORLY EXPOSED FAULTS: DEVELOPING A GEOMORPHIC TOOL FOR HAZARDS ANALYSIS: COLLABORATIVE RESEARCH WITH PENN STATE AND UCSB

NEHRP Award Number: 03HQGR0038

Eric Kirby[1]
Douglas W. Burbank[2]

[1] Department of Geosciences, Penn State University, University Park, PA 16802
ekirby@geosc.psu.edu; (814) 865-0732
[2] Department of Earth Science, University of California, Santa Barbara, CA 93106
brubank@crustal.ucsb.edu; (805) 893-7858

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**Technical Abstract**

Recent theoretical models suggest that topographic characteristics of bedrock channels are products of interactions among tectonics, substrate resistance, and the erosive ability of the river. At present, however, the degree to which these factors influence the form of channel profiles is poorly understood. The Santa Ynez Mountains, California is one of the many compressional ranges formed as a result a large restraining bend in the San Andreas Fault. Relatively uniform lithology and climate coupled with well-defined and variable rates of rock-uplift across the range make this an ideal setting to study river response to tectonic perturbations. Profile form of bedrock channels draining the southern flank of the Santa Ynez Mountains was characterized with both digital and field datasets in terms of channel gradient, concavity, and width. Comparisons between channels experiencing a rock-uplift rate of ~0.75 mm $yr^{-1}$ and channels developed in similar rocks, but where rock-uplift rates are ~5 mm $yr^{-1}$, show that a roughly 6-fold increase in rock-uplift rate induces channels ~2 times as steep and ~3 times as narrow as low-uplift streams. Importantly, and in contrast to previous studies, our channel observations suggest that both stream gradient and width are free to adjust to increases in tectonic rates.

**Project Introduction and Purpose**

This study was inspired by an interest in extracting rates of tectonic deformation directly from stream-channel profiles. Rates and patterns of active deformation constitute the basic framework for understanding the geodynamics of deforming lithosphere, yet characterizing spatially distributed deformation of the upper crust, when possible, is often both complicated and expensive. As a result, developing improved quantitative methods of gathering tectonic information directly from landscape topography motivates this project and much of the current research in tectonic geomorphology. Recent studies show that the bedrock-channel network dictates critical relationships among relief, elevation, and denudation rate (Howard, 1994; Howard et al., 1994; Whipple and Tucker, 1999) in tectonically active settings. Moreover, fluvial profiles are easily generated from readily available and highly accurate digital elevation models (DEMs). A number of studies using systematic behavior of river profiles have been successful in qualitatively determining patterns of active deformation within a mountain belt (Keller, 1986; Lavé and Avouac, 2000; Merritts and Vincent, 1989; Seeber and Gornitz, 1983). Quantitative realizations of this goal however, remain limited to field sites where local calibration of model parameters is possible (Kirby and Whipple, 2001). The ability to successfully extract tectonic information directly from channel profiles requires a quantitative understanding of relationships among such factors as channel gradient, channel width, substrate rock strength, and rock-uplift rate. Characterizing bedrock river response to tectonic variability is therefore necessary in field sites where these parameters can be effectively isolated and investigated.

**Santa Ynez Mountains Field Site**

We undertook a study of the topographic characteristics of bedrock channels in the Santa Ynez Mountains of coastal southern California (figure 1). This portion of the western Transverse Ranges is a topographically rugged south-dipping homocline with a maximum elevation of 1400 m (Dibblee, 1982; Tierney, 2002). The study area includes over 70 bedrock channels (figure 2), which incise the southern flank of the range. The sub-parallel channels are generally steep, narrow, and relatively short (<10 km). The drainage basins exhibit an average drainage area of 6.5 $km^2$ (table 1). The study area has a Mediterranean climate characterized by episodic, cool winter storms and a warm, dry spring, summer and fall.

Flights of marine terraces are present along the length of the study-area coastline. Previous studies in the western (Gurrola et al., 1998; Metcalf, 1994) and eastern part of the range (Trecker et al., 1998) developed an extensive chronology of these well-preserved marine terraces. Terraces within the field site have been dated using a variety of chronologic techniques (Gurrola et al., 1998; Metcalf, 1994; Rockwell et al., 1992, Trecker et al., 1998) and correlated with the most recent eustatic sea-level curve (Lambeck and Chappell, 2001) in order to define the rates and patterns of rock uplift. Thus, in the study, "rock uplift" refers to vertical motion of rock with respect to modern sea level. Pleistocene rock-uplift rates vary considerably along a 125-km transect, from ~0.75 mm $yr^{-1}$ in the western part of the range, to ~5 mm $yr^{-1}$ at Red Mountain near Ventura (figure 1) (Metcalf, 1994; Trecker et al., 1998). Despite these strong lateral gradients in rock-uplift rate, the elevations of multiple terrace levels at a site are

consistent with little temporal variation in rock uplift over the past ~200 k.y. (Metcalf, 1994).

Bedrock exposed in study area channels consists of an assemblage of Eocene through Pliocene sedimentary rocks (Dibblee, 1982). Rock units exposed along the flank of the homocline strike nearly east-west, parallel to the range crest. As a consequence, the pattern of lithologic variations is nearly constant along the strike of the range. In the western study area (rock uplift rates of ~0.75 mm/yr), exposures of resistant (Eocene) sandstone crop out along the range crest and upper-mountain flanks. These resistant beds stand in contrast to the soil-mantled hillslopes developed in the less-resistant (Oligocene-Pliocene) sandstone, conglomerate, and shale along the lower flanks of the range. Of particular utility for this study, a small subset of channels is developed entirely within these less-resistant rocks. In contrast, none of the channels in the eastern (high rock-uplift rate) region cross major transitions in rock strength. In this site, channels erode only the relatively weak Oligocene-Pliocene units.

**Theoretical Framework**

Bedrock channel incision is commonly considered to be a detachment-limited process, whereby incision into bedrock occurs because a stream's capacity to entrain and transport particles of sediment exceeds the locally available sediment supply (Howard, 1994). Using a form of basal shear stress, Howard and Kerby (1983) originally modeled detachment-limited bedrock channel erosion as a power-law function of drainage area ($A$) (a proxy for discharge) and stream gradient ($S$):

$$E = KA^m S^n \tag{1}$$

where $m$ and $n$ are positive constants and $K$ is known as the coefficient of erosion.

The evolution of bedrock channel profiles is commonly written as a competition between rock uplift and erosion (Howard, 1994; Whipple and Tucker, 1999):

$$\partial z / \partial t = U(x,t) - KA^m S^n \tag{2}$$

where ($\partial z/\partial t$) is the time rate of change of bed elevation, $U$ is the rock-uplift rate relative to a fixed base level and erosion rate is modeled as described above (equation 1).

For fluvial landscapes where erosion balances rock uplift everywhere along the channel (i.e. channel equilibrium) and under conditions of spatially uniform uplift, rock strength, and erosion process, the equilibrium channel gradient ($S_e$) decreases as a power function of drainage area according to the relation:

$$S_e = (U/K)^{1/n} A^{-m/n} \tag{3}$$

In equilibrium channels if and only if conditions of uniform $U$ and $K$ exist, then the ratio of $m/n$ sets the rate of change of channel gradient with drainage area and the coefficient $(U/K)^{1/n}$ dictates the equilibrium profile gradient. Equation 3 can then be rewritten as:

$$S = k_s A^{-\theta} \tag{4a}$$

$$k_s = \left(U/K\right)^{1/n} \tag{4b}$$

$$\theta = m/n. \tag{4c}$$

Equations 4b and 4c highlight two important channel indices: the steepness index ($k_s$) and the concavity index ($\theta$). The channel "steepness" index (figure 3) is a relative measure of channel gradient and is useful for comparison of profile gradient among multiple channels. The steepness index has been utilized in several recent studies (Kirby and Whipple, 2001; Kirby et al., 2003; Snyder et al., 2000) and is similar in principle to the stream-gradient index developed by Hack (1973). Stream channel concavity ($\theta$) is the downstream rate of change in slope with respect to drainage area (figure 3). Theoretical predictions indicate that channel concavities should fall within a range of 0.30 – 0.60 given a uniform rock-uplift rate (independent of magnitude), rock erodibility, and climate (Roe et al., 2002; Whipple and Tucker, 1999). Regressions of channel gradient and drainage area data readily provide a direct estimate of both indices from stream profiles (Kirby and Whipple, 2001; Snyder et al., 2000).

## Methodology

*Stream Profile Analysis*

For each of 50 streams along the coast (figure 2), we extract channel profiles from a USGS 30-m DEM generated from 7.5' topographic maps. In order to minimize inherent scatter in elevation points along the stream profile (a consequence of DEM generation and data processing), we filter the elevation data by passing a moving average along the raw channel elevations (window size of 750 m). Local channel slopes are then calculated from the smoothed data using a constant vertical interval of 5 m. This sampling yield a data set evenly distributed in $\log S - \log A$ space.

Power-law regression analysis of river slope against drainage area yields both a channel concavity ($\theta$), and a channel steepness index ($k_s$) (equation 4; figure 3). In general, scaling breaks interpreted to mark the transition between hillslope or colluvial channels and the fluvial channel network can be identified in topographic data by an abrupt decrease in channel slope with increasing drainage area.

Following Snyder et al. (2000), steepness indices ($k_s$) were calculated using a fixed, reference concavity. Use of a reference concavity facilitates comparison of gradients on channels with widely varying drainage area (e.g. Kirby et al., 2003).

*Field Data*

Although private ownership severely restricts access to most of the channels along the Santa Ynez coast, we were able to gain access to the entire El Capitan watershed in the western study area and 3 watersheds in the eastern region: Los Sauces, Madranio, and Padre Juan (figure 2). In each watershed, data were collected on rock strength along the stream length, high-flow channel width, and general channel characteristics, such as size and sorting of sediment and active channel scour.

## Results and Discussion

Most models for bedrock incision consider that erosion rate is in some manner proportional to mean boundary shear stress. It follows intuitively that, in an equilibrium system, higher uplift rates require steeper gradients, narrower channels or some combination of both (for the same discharge) to keep pace with rock uplift (Whipple et al., 1999). Although both modes of adjustment have been observed (Kirby and Whipple, 2001; Lavé and Avouac, 2000), the relative role of each process remains highly uncertain

(Snyder et al., 2000; Snyder et al., 2003). Our results show that, whereas channels from both uplift regions show no adjustment in longitudinal-profile concavity (obeying theoretical model predictions), they do adjust both gradient and width in response to tectonic forcing in the Santa Ynez Mountains.

*Channel Concavity and Steepness Indices*

The 9 western, low-uplift channels that incise only the weaker (Oligocene – Pleistocene) rocks display a mean concavity index of 0.48 +/- 0.04 (table 1 and 2), a value consistent with both the theoretically predicted range (0.30 – 0.60) and results published from other field sites (Kirby and Whipple, 2001; Snyder et al., 2000). Steepness indices for these low-uplift streams range from 8.75 to 19 with a mean of 13.8 +/- 4.0 (table 1 and 2). Within the high-uplift region, 6 channels also developed entirely in weak, Oligocene-Pliocene age units, exhibit a mean channel concavity of 0.6 +/- 0.09 (table 2). This value is similar to channels restricted to similar rocks in the low-uplift region and fits within the theoretically predicted range of 0.3 – 0.6. The mean steepness index for the high-uplift streams is 26.1 +/- 4.9. Mean values of the steepness index between the high- and low-uplift regions are consistent with the proposition that channels are steeper where rock uplift is more rapid (Whipple and Tucker, 1999). An ~6-fold increase in uplift rate, however, appears to engender only an ~2-3-fold increase in channel steepness for channels eroding analogous weak rock units (figure 4).

*Channel Width*

Channel width data were collected along dominantly bedrock reaches within a tributary to El Capitan stream (low uplift) and Madranio creek (high uplift) (figure 5). In order to effectively compare channel widths at specific drainage areas between these two streams, we fit a regression through each data set with an exponent of 0.4, equivalent to that approximated by Montgomery and Gran (2001). The best-fit width coefficient for the fixed regression for the low-uplift tributary is 0.032 and 0.012 for Madranio creek within the high-uplift region (figure 6). These results imply that the high-uplift channel is ~3 times narrower than the low-uplift channel and therefore that channel width freely adjusts to differences in rock-uplift rate. Although adjustments in channel width have been observed in large, gravel-bedded rivers (Lavé and Avouac, 2000; Lavé and Avouac, 2001), the few studies conducted in bedrock channels of similar size to Santa Ynez streams did not observe discernable changes in width with rock-uplift rate (Snyder et al., 2003). Thus, these results directly challenge the widespread assumption in landscape evolution models that stream gradient is the only bedrock channel parameter free to adjust to changes in tectonic forcing. Moreover, these results serve to further highlight a critical need for understanding the controls on channel width in bedrock streams.

The apparent adjustment of channel width to rock-uplift rate in this study area directly impacts the relationship between channel steepness indices and the rate of tectonic forcing (equation 4). The fact that observed gradient indices in the high-uplift channels are only approximately twice that of the low-uplift streams illustrates the dramatic control that channel width can exert on incision rate. Essentially, the effective coefficient of erosion (K equation 1) changes in concert with uplift rate in these channels. This result carries the evident implication that, in order to glean quantitative information about tectonic forcing from channel profiles, we must consider the role of adjustments in channel hydraulic geometry. Until we develop a fuller understanding of how hydraulic

geometry depends on aspects of channel form, incision rate, and sediment flux, we are forced to rely on empiricisms when applying simple incision models.

**Implications for assessing uplift rates**

This study addressed the response of bedrock-channel profiles to variations in rock-uplift rate in a field site where tectonic forcing and climate are well defined. Several important conclusions regarding the potential use of channel profiles as indicators of tectonic forcing are as follows:

- Consistent with the predictions of simple bedrock-incision models, Santa Ynez channels developed under conditions of uniform rock-uplift rate and lithology display channel concavity indices ($\theta$) ranging from 0.3 – 0.6. Thus, our study reinforces the suggestion that there are predictable aspects of channel profile form that appear under spatially-uniform rock uplift, and that changes in channel concavity may be expected in channels adjusted to spatial variations in rock uplift.
- Despite relatively constant concavity, channels are systematically steeper in regions of greater rock uplift rate. In the Santa Ynez, it appears that a 5-6 fold increase in rock uplift engenders a doubling of channel steepness.
- The apparent non-linearity between channel steepness and rock uplift rate appears to result from a concomitant adjustment of channel width. Channels in the high-uplift region are ~3 times as narrow as their low-uplift counterparts. Thus, we conclude that the erosion coefficient ($K$) varies in concert with rock-uplift rate due to a systematic narrowing of channels within the high-uplift region. Before we can export these results to field sites where uplift rate is unknown, we must account for potential variability in this model parameter. This result suggests we must be cautious when drawing quantitative inferences regarding the rates and distribution of tectonic forcing directly from channel profiles in the absence of local calibration.
- When we account for variations in channel width, however, we are able to reproduce the variations in channel profile form between high and low uplift rate sites with model that considers channel incision that is linearly proportional to bed shear stress. This simple result leads us to suggest that analysis of channel profiles, when conducted judiciously, holds promise as a tool to characterize spatial patterns of active rock uplift.

**Non-Technical Summary**

Current studies suggest that pattern and form of mountain rivers is largely dictated by tectonic activity. Active deformation might therefore be assessed directly from the landscape by studying rivers draining active mountain ranges. In this study, we analyzed channels draining the Santa Ynez Mountains of southern California, a tectonically active region where rates of deformation have been previously assessed to test the feasibility of this approach. Comparisons between channels experiencing a 6-fold difference in rock-uplift rate show that channels are both steeper and narrower in response to increased tectonic rates.

**Reports Published**

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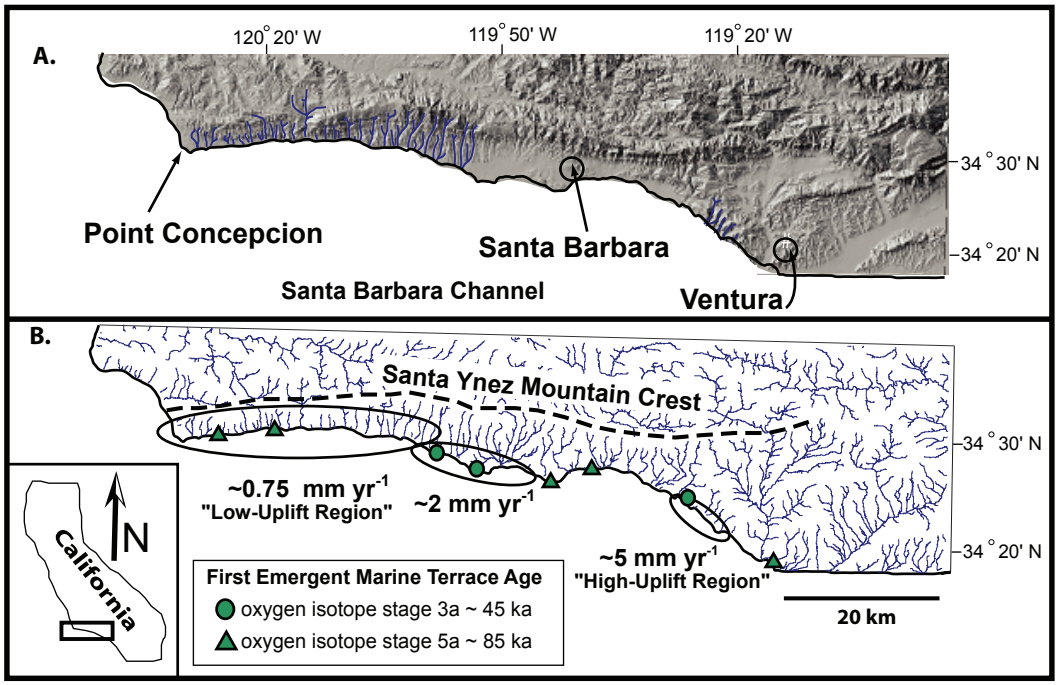


**Figure 1.** Location of study along the Santa Ynez Mountains. (A) Relevant stream channels and geographic landmarks of the field site. (B) Drainage network and crest of the Santa Ynez Mountains. Triangle and circle symbols indicate locations and marine isotopic stage (stage 3a ~45 ka, 5a ~85 ka) of dated first-emergent marine terraces [Metcalf, 1994; Trecker et al., 1998]. Rock-uplift rates derived from marine terrace data are also shown. Note that rock-uplift rates are low (~0.75 mm $yr^{-1}$) in the west ("low-uplift region") relative to the high rate toward the east near Ventura (~5 mm $yr^{-1}$) ("high-uplift region"). Inset shows regional extent of study area.

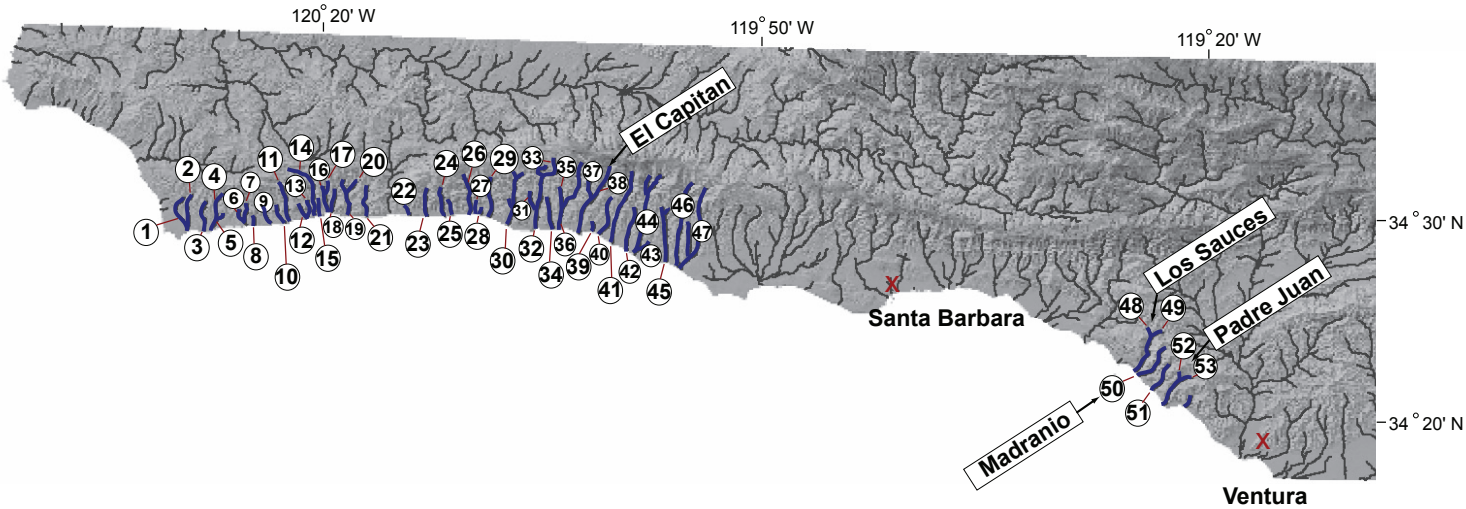


**Figure 2.** Drainage network of the Santa Ynez Mountains. Streams used in study calculations are numbered. Channels observed in the field are labeled by stream name (white box).

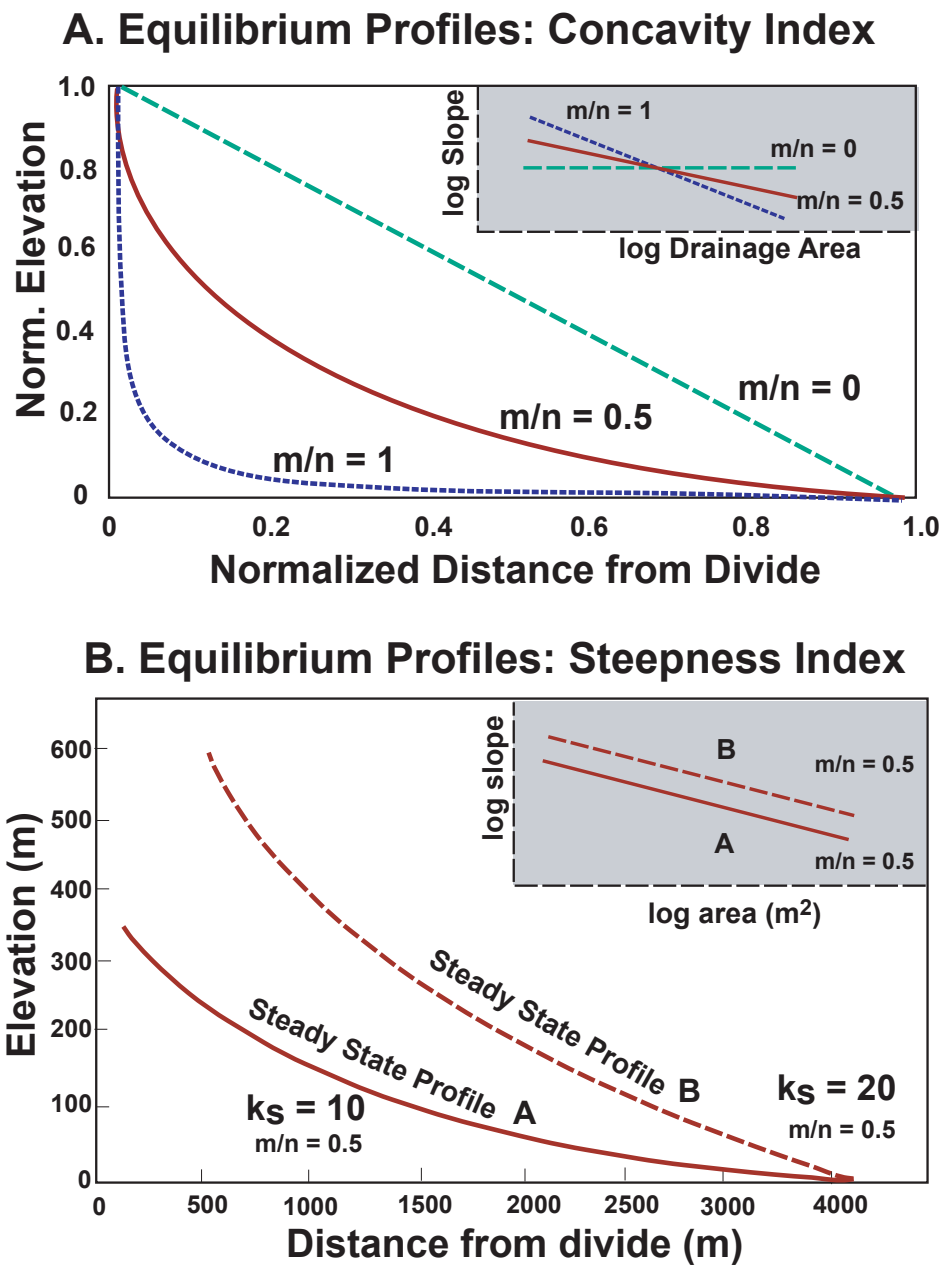


**Figure 3.** Schematic diagrams of key parameters derived from equilibrium longitudinal profiles [modified from Whipple and Tucker, 1999]. (A) Longitudinal stream-profile concavity is set by the m/n ratio (concavity index). Upper inset shows different m/n values in slope-area space and the main graph shows the same three ratios in elevation-distance space. (B) Two profiles with varying steepness indices. Note that, although stream B is twice as steep as stream A, they have the same concavity.

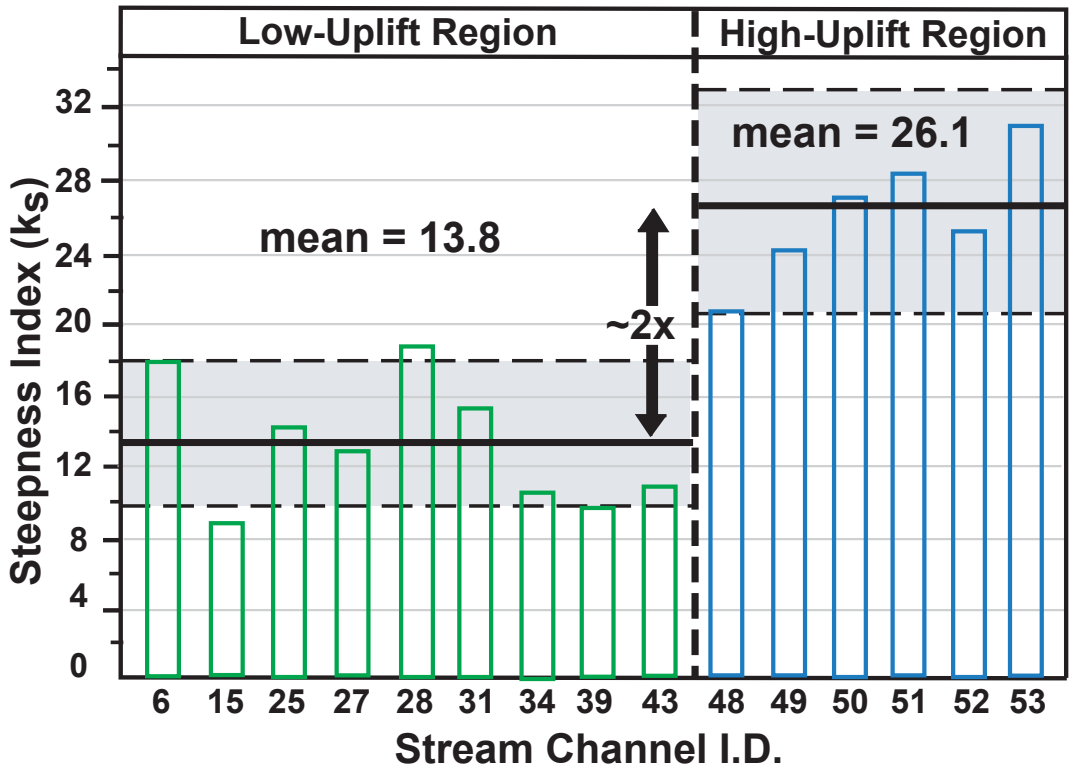


**Figure 4.** Steepness index ($k_s$) for all of the weak-rock only channels (identified by stream-channel I.D.#: Figure 2). Mean values and standard error of the mean for each regional dataset indicate an ~2 fold increase in $k_s$ in the high-uplift streams.

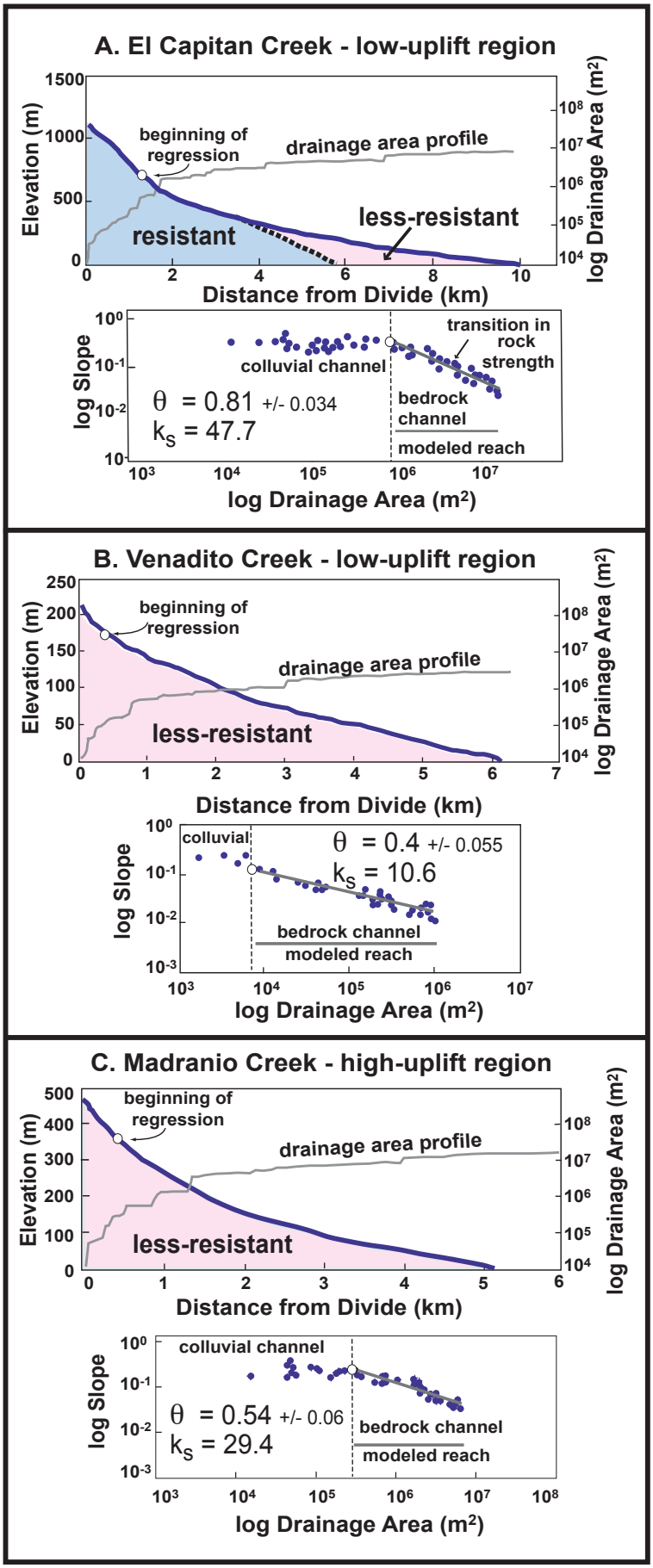


**Figure 5.** Examples of channel topographic data derived from a digital elevation model (A) El Capitan creek (#38), a low-uplift stream that crosses both resistant and less-resistant rocks, (B) Venadito creek (#34), a low-uplift stream draining only weak rocks, and (C) Madranio creek (#51), a high-uplift stream also eroding only weak rocks. For each stream, the top panel shows the channel profile (blue) and drainage area (gray) as a function of downstream distance. The white circle indicates the beginning of the fluvial part of the channel and the linear regression. The lower panel contains the slope and drainage area-data with regression lines. Slopes were calculated at 5-m vertical elevation intervals.

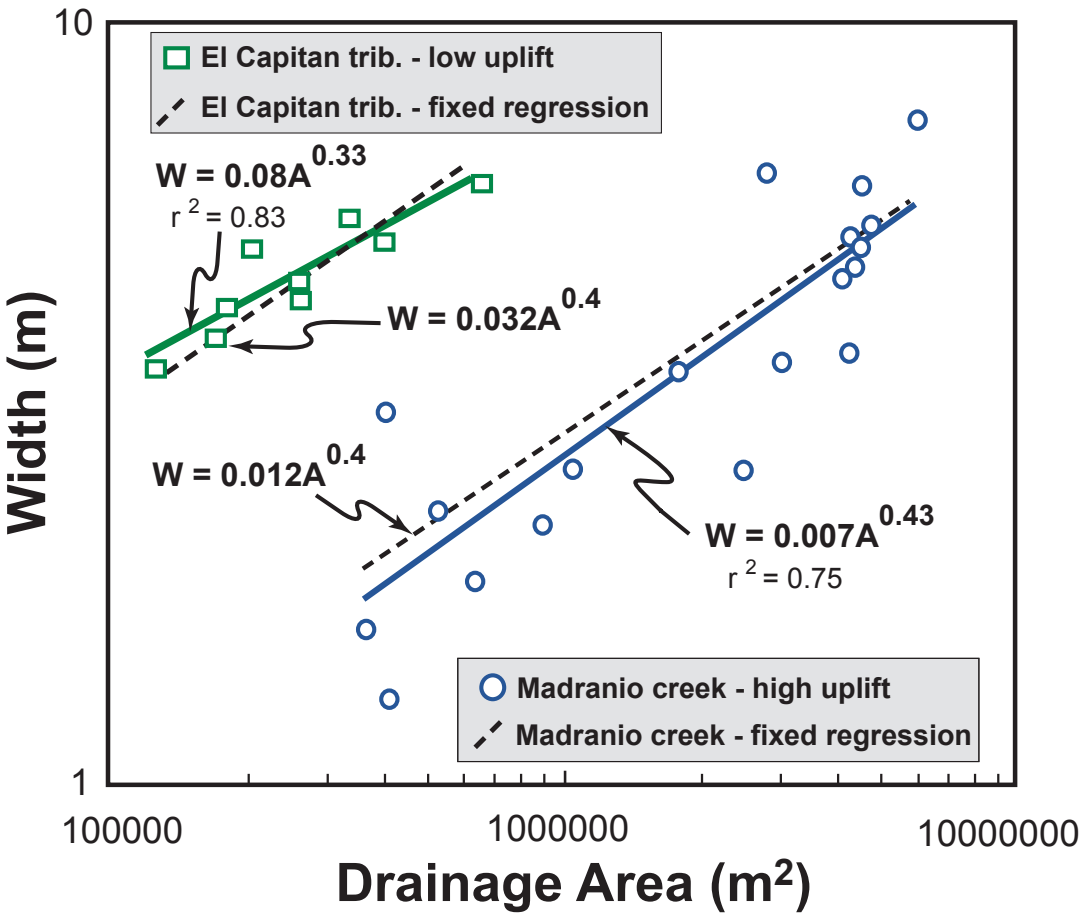


**Figure 6.** Channel width versus drainage area data for a tributary to El Capitan creek (open square) in the low-uplift region and Madranio creek (open circle) in the high-uplift region. Power-law regressions through each data set are shown. Channel data for each stream were fixed with an exponent of 0.4 to allow direct comparison of channel width between the two streams. Note that for similar drainage areas, the low-uplift stream is ~2.5 times narrower than the high-uplift stream.