Elucidating channel-hillslope coupling along a tectonic gradient: Co-variation in erosion rate and grain size sets channel form

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The topographic form of landscapes in tectonically active mountain range reflects the interplay among tectonics, climatically modulated surficial processes, and the erodibility of bedrock (e.g., Dietrich et al. 2003). Over the past two decades, a significant body of theoretical, experimental, and empirical work demonstrates that the adjustment of fluvial and hillslope erosion to differential rock uplift sets topographic relief in tectonically active landscapes (Whipple et al. 1999; Hilley et al. 2019). In regions where substrate erodibility and climate are relatively uniform, spatial and temporal patterns of differential rock uplift are encoded in the shape of Earth's surface topography (e.g., Kirby & Whipple 2012).

A primary challenge to the influence of rock uplift and/or erosion rates and patterns from topography emerges from the interplay among sediment caliber, precipitation/runoff distributions, and thresholds for channel incision (e.g., Lague et al. 2005; DiBiase & Whipple 2011). The evident dependence of grain size distributions on rock fracture density (Sklar et al. 2017) suggests the potential for incision thresholds that co-vary with rock uplift and/or erosion rate and may modulate the adjustment of river profiles (e.g., Shobe et al. 2018). Here, we evaluate relationships among channel steepness, landscape topography, grain size, and erosion rate along an apparent gradient in differential rock uplift in coastal California.

Bolinas Ridge is a 30-km-long NW-SE trending ridge parallel to the San Andreas Fault in Marin County, California. The elevation of the ridgecrest increases from <200 m at the northern end to >600 m near Mt. Tamalpais. Previous analysis of landscape topography along Bolinas Ridge suggests that both channels and hillslopes in low-order watersheds draining the flank of the ridge are adjusting to spatial gradients in rock uplift rate (Kirby et al. 2007; Hurst et al. 2019). However, the patterns of erosion rate are unknown along this transect, complicating a more mechanistic interpretation of the topographic adjustment to differential rock uplift. We exploited a recently available high-resolution topographic data set derived from lidar acquisitions to re-evaluate variations in channel profile steepness and interfluve curvature from >40 first-order watersheds draining the western flank of the ridge. Our results confirm that channel steepness increases by a factor of 5-6 along the ridge from north to south (Figure 1). Over the same distance, the convexity of interfluves increases by a factor of 2-3. As the curvature of soil-mantled interfluves is sensitive to the erosion rate (Roering 2008), regional estimates of landscape diffusivity (Heimsath et al. 1997, 2005) suggest that erosion rates of these interfluves vary from ~100 – 300 m/Myr along the transect (similar to findings of Hurst et al. 2019).

To evaluate the coupling between hillslope morphology, channel steepness and erosion rate, we conducted field surveys of channel bed morphology and hydraulic geometry. Our results reveal a systematic correlation among sediment caliber, interfluve curvature, and channel steepness. Channel widths appear to be invariant along the transect. We found that steeper watersheds transport sediment with coarser median grain sizes, implying that thresholds of sediment transport and incision in channels likely co-vary with topography and erosion rate. Analysis of hydroclimatic regimes from gauged watersheds throughout the region reveals stretched exponential discharge distributions (e.g., Rossi et al. 2016). These runoff characteristics are used in the application of a stochastic threshold channel incision model to derive scaling relationships for channel steepness, erosion rate, and transport threshold (e.g., Lague et al. 2005).

The results of this analysis provide an additional constraint on the rates of erosion along the transect. First, the variability and mean runoff implied by the discharge distributions predict a non-linear scaling between steady-state channel steepness and erosion rate (Figure 2). These relationships are represented by a family of non-linear curves that vary with magnitude of incision threshold (Figure 2). Second, assuming a Shield's criterion for grain motion, we relate the transport threshold to the median (D_{50}) grain size distributions in surveyed watersheds. Our results suggest that erosion rates along the transect from the stochastic threshold incision model compare favorably with those inferred from ridgecrest curvature and vary from <50 m/Myr to >400 m/Myr along the ridge (Figure 2).

Analysis of the ^{10}Be concentration of watershed sediment from these basins appears to confirm a north to south gradient in erosion rates, varying from ~60 m/Myr to ~160 m/Myr. The variation in erosion rates, however, appears to be subdued relative to rates inferred from both interfluve curvature and channel steepness. Whether these differences reflect incomplete mixing of sediment in low-order watersheds and underestimation of erosion rates (e.g., Yanites et al. 2009), inappropriate application of a simple landscape diffusivity to describe hillslope transport (e.g., Heimsath et al. 2005), or whether boulder transport by debris-flows becomes an important agent of erosion in the steepest channels (Penserini et al. 2017) remains uncertain.

Overall, our study highlights the intimate coupling of hillslopes and channels in landscape response to differential uplift of rock. Morphologic variations in both channel longitudinal profiles and hillslope ridgecrest can be an effective reconnaissance tool to interpret the spatial and temporal dynamics of active deformation, but variations in sediment grain size shed from hillslopes may drive the adjustment of topography to variable uplift. Thus, our results reinforce the need to understand the initial generation of grain sizes on rapidly eroding hillslopes.

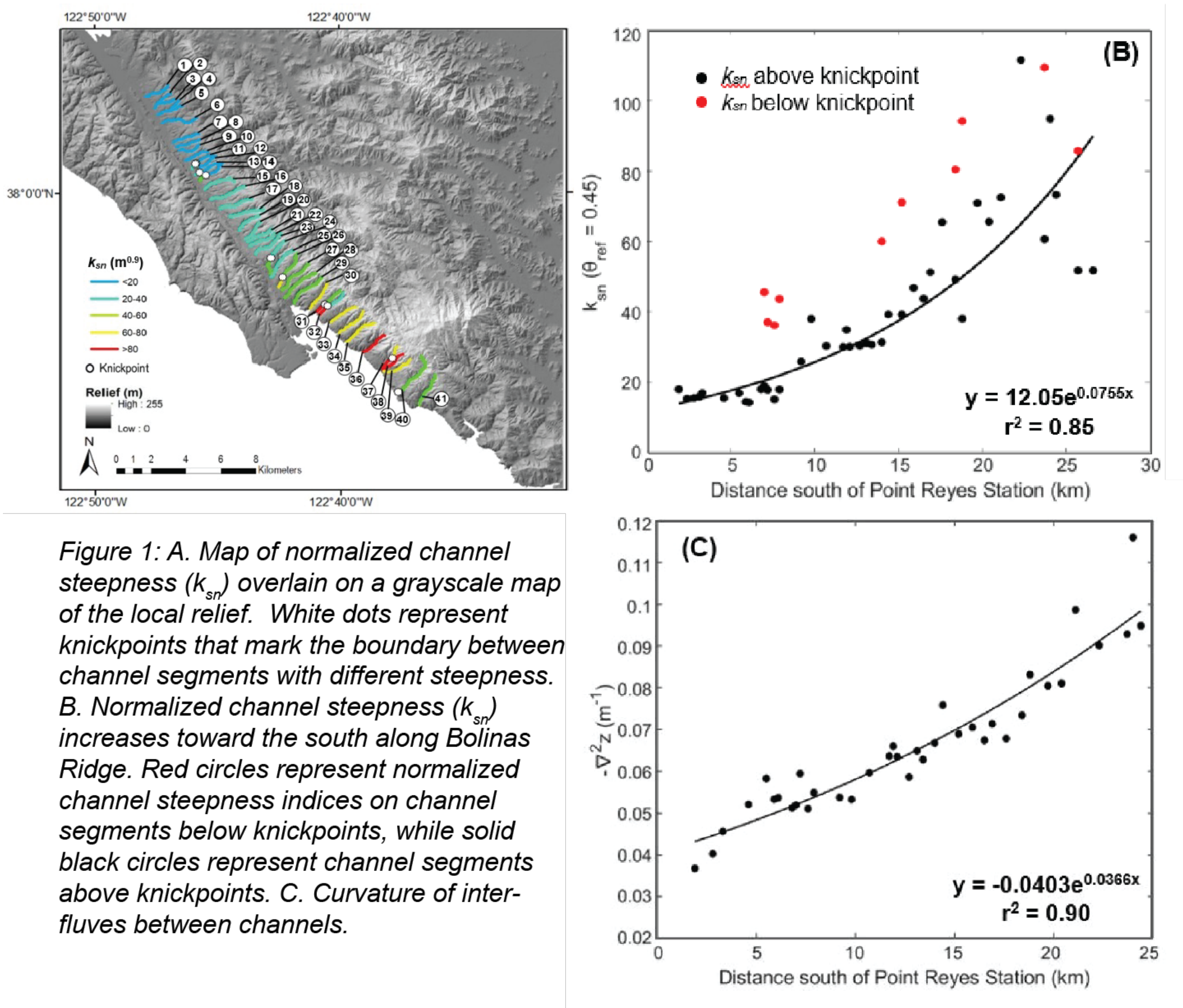

Figure 1: A. Map of normalized channel steepness (k_{sn}) overlain on a grayscale map of the local relief. White dots represent knickpoints that mark the boundary between channel segments with different steepness. B. Normalized channel steepness (k_{sn}) increases toward the south along Bolinas Ridge. Red circles represent normalized channel steepness indices on channel segments below knickpoints, while solid black circles represent channel segments above knickpoints. C. Curvature of interfluves between channels.

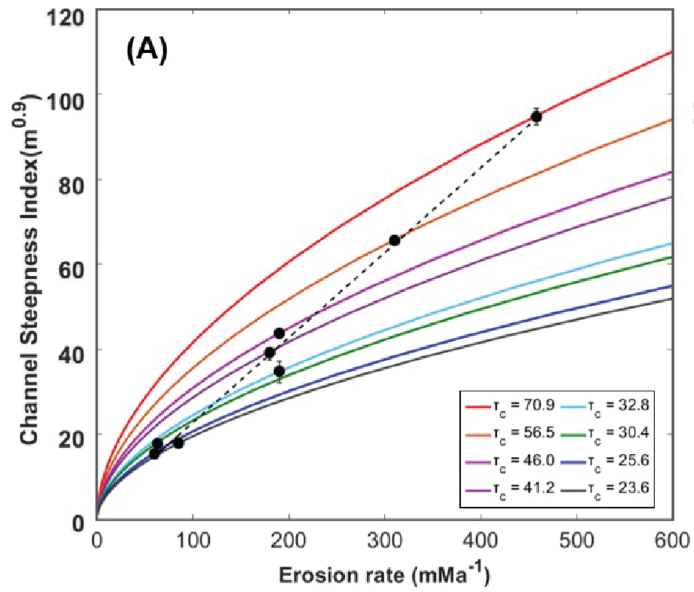

Figure 2: Plot of predicted scaling relationships between normalized channel steepness (k_{sn}) and erosion rate derived from the stochastic threshold incision model. Incision thresholds and runoff variability are calibrated to local discharge distributions using a stretched exponential distribution (Rossi et al., 2016). Black circles represent the observed channel steepness and incision thresholds inferred from grain size distributions for surveyed watersheds. Note that the increase in transport threshold with increasing channel steepness implies an apparent linear adjustment of channel steepness and erosion rate in this study area.

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