Geomorphology 282 (2017) 150–161

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

A morphologic proxy for debris flow erosion with application to the earthquake deformation cycle, Cascadia Subduction Zone, USA

Brian D. Penserini [a], Joshua J. Roering [a,*], Ashley Streig [b]

[a] Department of Earth Sciences, University of Oregon, Eugene, Oregon, 97403-1272, USA
[b] Department of Geology, Portland State University, Portland, Oregon, 97201, USA

ARTICLE INFO

Article history:
Received 1 August 2016
Received in revised form 11 January 2017
Accepted 12 January 2017
Available online 16 January 2017

Keywords:
debris flows
earthquakes
coseismic subsidence
LiDAR
valley networks
longitudinal profile
slope-area data

ABSTRACT

In unglaciated steeplands, valley reaches dominated by debris flow scour and incision set landscape form as they often account for >80% of valley network length and relief. While hillslope and fluvial process models have frequently been combined with digital topography to develop morphologic proxies for erosion rate and drainage divide migration, debris-flow-dominated networks, despite their ubiquity, have not been exploited for this purpose. Here, we applied an empirical function that describes how slope-area data systematically deviate from so-called fluvial power-law behavior at small drainage areas. Using airborne LiDAR data for 83 small (~1 km^2) catchments in the western Oregon Coast Range, we quantified variation in model parameters and observed that the curvature of the power-law scaling deviation varies with catchment-averaged erosion rate estimated from cosmogenic nuclides in stream sediments. Given consistent climate and lithology across our study area and assuming steady erosion, we used this calibrated denudation-morphology relationship to map spatial patterns of long-term uplift for our study catchments. By combining our predicted pattern of long-term uplift rate with paleoseismic and geodetic (tide gauge, GPS, and leveling) data, we estimated the spatial distribution of coseismic subsidence experienced during megathrust earthquakes along the Cascadia Subduction Zone. Our estimates of coseismic subsidence near the coast (0.4 to 0.7 m for earthquake recurrence intervals of 300 to 500 years) agree with field measurements from numerous stratigraphic studies. Our results also demonstrate that coseismic subsidence decreases inland to negligible values >25 km from the coast, reflecting the diminishing influence of the earthquake deformation cycle on vertical changes of the interior coastal ranges. More generally, our results demonstrate that debris flow valley networks serve as highly localized, yet broadly distributed indicators of erosion (and rock uplift), making them invaluable for mapping crustal deformation and landscape adjustment.

1. Introduction

In hilly and mountainous landscapes, changes in base level driven by rock uplift influence the shape of river longitudinal and hillslope profiles through process-form feedbacks. Given sufficient time, erosion tends to balance rock uplift such that steady state (or time invariant) conditions result (Mackin, 1948; Fernandes and Dietrich, 1997; Whipple and Tucker, 1999). Hillslope angles and the convexity of hilltops have been shown to provide quantitative constraints on the pace of base level lowering induced by uplift (Hurst et al., 2012; Sweeney et al., 2015; Mudd, 2016), and the characteristic concave form of fluvial longitudinal profiles has been frequently exploited to extract information on tectonic forcing in a vast array of geologic settings (Hack, 1973; Kirby and Whipple, 2001; Wobus et al., 2006; Perron and Royden, 2013; Cyr et al., 2010).

For stream networks in particular, the oft-observed inverse power-law dependence of drainage area on valley slope is consistent with stream power models of fluvial bedrock incision (Howard and Kerby, 1983; Whipple and Tucker, 1999; Lague, 2014). This functional relationship that relates longitudinal profiles to erosion (and uplift) allows spatial variations in tectonic forcing to be inferred from examination of readily available topographic information (Ahnert, 1970; Howard and Kerby, 1983; Milliman and Syvitski, 1992; Dietrich et al., 2003; Binnie et al., 2007). While the form of the stream power law states that incision rate is equivalent to the power law product of channel slope and drainage area (Whipple, 2004), alternative parameter-rich incision models demonstrate that concave power-law profiles also emerge from abrasion and plucking mechanisms that account for the opposing roles of fluvial sediments in providing tools for incision and coverage of stream beds (Sklar and Dietrich, 2004; Chatanantavet and Parker, 2009; Gasparini and Brandon, 2011; Shobe et al., 2016). While these sophisticated models are deemed physically relevant and have been supported by experiments (Sklar and Dietrich, 2001; Finnegan et al., 2007), their application for the interpretation of natural landscapes has yet to be

---

* Corresponding author.
E-mail address: jroering@uoregon.edu (J.J. Roering).

http://dx.doi.org/10.1016/j.geomorph.2017.01.018

realized, with a few exceptions (Attal et al., 2011; Gasparini and Brandon, 2011; Hobley et al., 2011; Sweeney and Roering, 2016). Rather, the stream power model has proven to be accessible and easily digestible for tasks such as mapping patterns of channel steepness and identifying the signature of transient adjustment (Crosby and Whipple, 2006; Whittaker et al., 2007; Mudd, 2016; Willett et al., 2014). The normalized slope of fluvial networks, termed the *steepness index*, can be extracted from slope-area data given constant concavity (i.e., constant power-law scaling) and has been shown to vary systematically with erosion rate (e.g., Lague et al., 2000; Snyder et al., 2000; Ouimet et al., 2009; DiBiase et al., 2010; Kirby and Whipple, 2012; Harel et al., 2016).

While these network analyses have proven to be astonishingly effective reconnaissance tools for detecting spatial and temporal variations in deformation and erosion, their scope may be limited to the fluvial-dominated portion of channel networks. Thus far, these analyses assume constant power-law scaling of slope-area data, and as a result their relevance for characterizing low-drainage area (or steep headwaters) portions of drainage basins is unclear. In these upper reaches of unglaciated mountainous catchments, the scaling often systematically deviates from constant concavity. Instead, valley slope angles tend to approach a threshold value set by the stability of colluvial hollows (Stock and Dietrich, 2003) and unconsolidated, in-channel sediment deposits (McCoy et al., 2012; Kean et al., 2013; Prancevic et al., 2014) that serve as the initiation zones for debris flows that transverse significant portions of the downstream network. Given the absence of significant fluvial transport (much less incision) in these areas (Fig. 1) that represent the transition between hillslopes and the channelized portions of networks (Montgomery and Buffington, 1997; Lague and Davy, 2003), debris flows typically are implicated as the primary incision process in so-called *colluvial valleys* (Dietrich and Dunne, 1978; Benda, 1990; Stock and Dietrich, 2003, 2006).

These steep, debris-flow-dominated reaches are typically found at relatively small drainage areas (<1 to 5 km^2) that often constitute $>80\%$ of the regional topographic relief (Stock and Dietrich, 2003). The transition between debris flow and fluvial-dominated portions of the drainage network is often debated as Stock and Dietrich (2006) reported that debris flow deposits overlap with the upstream extent of fluvial strath terraces in the Pacific Northwest. In the San Gabriel Mountains of southern California, debris flows frequently traverse the entire drainage network of many catchments before being arrested by engineered debris basins dotted along the range front to mitigate the hazard (Lavé and Burbank, 2004), although field observations reveal features characteristic of fluvial incision in some upstream reaches (DiBiase et al., 2012).

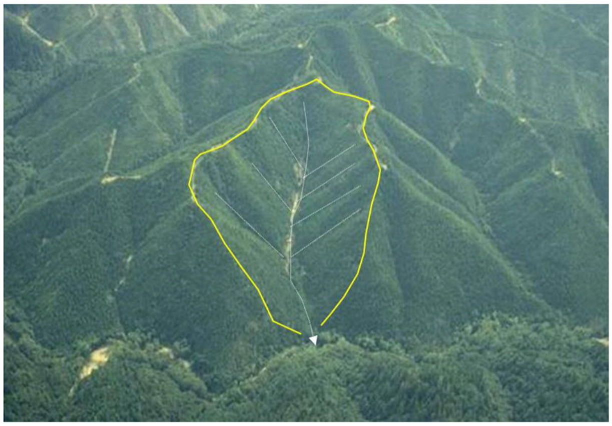

Fig. 1. Debris flow catchments. This oblique aerial photo (photo by J. Roering) shows characteristic debris-flow-dominated catchments in the Oregon Coast Range. Yellow outline delineates catchment boundaries while the dotted white lines illustrate the primary debris flow tracks that terminate in unchanneled valleys just below the ridgetops.

The morphology of debris-flow-dominated (or colluvial) profiles tends to be steeper and less concave than predicted by fluvial power-law scaling and instead approach a constant slope at very small drainage areas (~10^3 m^2), coincident with unchanneled valleys. It has been proposed that these colluvial reaches can be described by the concatenation of numerous power law relationships (Lague and Davy, 2003; Whipple and Tucker, 1999; DiBiase et al., 2012). In many settings, high-resolution laser altimetry reveals a smoothly varying (or curved) log-log slope-area topographic signature for debris flow valleys (Stock and Dietrich, 2003, 2006). Stock and Dietrich (2003) developed an empirical function for debris flow slope-area data, and their three-parameter function described the continuous transition from relatively constant slope angles (similar to threshold slopes) observed at small drainage areas to the inverse power law relationship of fluvial channels at larger drainage areas. Stock and Dietrich (2003) postulated that as erosion rates increase, the profile of steep, debris flow valleys lengthens, forcing the transition from debris flow to fluvial-dominated reaches to occur farther downstream in larger drainage areas. The mechanical model of Stock and Dietrich (2006) posited that valley slope (and the characteristic curved slope-area signature of steepland headwaters) results from the balance between processes that *increase* incision in the downvalley direction (such as increasing flow event frequency and sediment entrainment) and processes that *decrease* incision downstream (such as lower inertial stresses from lower slope angles and the prevalence of less weathered, more coherent bedrock). A recent theoretical contribution adopted a similar framework for general landscape and network evolution (Shelef and Hilley, 2016).

Given topographic data of sufficient resolution, small and ubiquitous debris flow catchments have the potential to serve as highly localized and broadly dispersed recorders of rock uplift that adjust rapidly to changes in tectonic forcing (Hurtrez et al., 1999). In this contribution, we explore whether the shape of debris flow valley profiles can be used to interpret patterns of erosion and rock uplift in active orogens. Specifically, we seek to reconcile long-term uplift patterns with the earthquake deformation cycle in the Pacific Northwest, where large megathrust events associated with the Cascadia Subduction Zone have occurred every 300-600 years during the Holocene (Goldfinger et al., 2012). These events result in substantial coseismic subsidence (>0.5 m) in coastal settings (Graehl et al., 2015), but the inland extent of this deformation that may reflect the geometry of plate locking and coseismic slip is unknown. By combining modern interseismic uplift data with estimates of earthquake recurrence intervals and our analysis of long-term uplift generated by debris flow network morphometry, we propose a means to predict the pattern of coseismic subsidence along the Pacific Northwest coastal ranges. This endeavor also begins to confront the role of earthquakes in the evolution of Cascadia landscapes, which has not been addressed despite abundant geomorphic research in the region.

2. Tectonic forcing and valley network morphology

2.1. Stream power and steepness index for fluvial networks

Fluvial channels typically exist at drainage areas >0.5 to 1 km^2 in steepland catchments, often associated with valley slopes <0.05 to 0.15 (Lague et al., 2000; Stock and Dietrich, 2003). In these reaches, the relationship between incision rate, channel slope, and drainage area is often expressed by the stream power law

$E = KA^mS^n$ (1)

where E is the rate of bedrock channel incision, K is the incision coefficient, A is drainage area, S is local channel slope, and m and n are empirically derived constants (Whipple, 2004). This form of the stream power law is practical as it is formulated in terms of local channel slope and upstream drainage area, two parameters that are easily estimated from digital elevation models (DEMs). Furthermore, given steady erosion (i.e., uplift = erosion), the stream power model can be recast