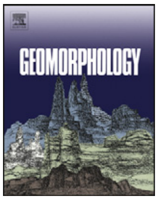
Geomorphology 236 (2015) 109–131

Contents lists available at ScienceDirect

Geomorphology

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



Review

Beyond the angle of repose: A review and synthesis of landslide processes in response to rapid uplift, Eel River, Northern California

Joshua J. Roering [a,*], Benjamin H. Mackey [b], Alexander L. Handwerger [a], Adam M. Booth [c], David A. Schmidt [d], Georgina L. Bennett [a], Corina Cerovski-Darriau [a]

[a] *Department of Geological Sciences, University of Oregon, Eugene, OR 97403-1272, USA*
[b] *Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand*
[c] *Department of Geology, Portland State University, PO Box 751, Portland, OR 97207-0751, USA*
[d] *Department of Earth and Space Sciences, University of Washington, 4000 15th Avenue NE, Seattle, WA 98195-1310, USA*

ARTICLE INFO

Article history:
Received 13 August 2013
Received in revised form 13 February 2015
Accepted 14 February 2015
Available online 23 February 2015

Keywords:
Landslide
Lidar
Landscape evolution
Insar
Erosion
Suspended sediment

ABSTRACT

In mountainous settings, increases in rock uplift are often followed by a commensurate uptick in denudation as rivers incise and steepen hillslopes, making them increasingly prone to landsliding as slope angles approach a limiting value. For decades, the threshold slope model has been invoked to account for landslide-driven increases in sediment flux that limit topographic relief, but the manner by which slope failures organize themselves spatially and temporally in order for erosion to keep pace with rock uplift has not been well documented. Here, we review past work and present new findings from remote sensing, cosmogenic radionuclides, suspended sediment records, and airborne lidar data, to decipher patterns of landslide activity and geomorphic processes related to rapid uplift along the northward-migrating Mendocino Triple Junction in Northern California. From historical air photos and airborne lidar, we estimated the velocity and sediment flux associated with active, slow-moving landslides (or earthflows) in the mélange- and argillite-dominated Eel River watershed using the downslope displacement of surface markers such as trees and shrubs. Although active landslides that directly convey sediment into the channel network account for only 7% of the landscape surface, their sediment flux amounts to more than 50% of the suspended load recorded at downstream sediment gaging stations. These active slides tend to exhibit seasonal variations in velocity as satellite-based interferometry has demonstrated that rapid acceleration commences within 1 to 2 months of the onset of autumn rainfall events before slower deceleration ensues in the spring and summer months. Curiously, this seasonal velocity pattern does not appear to vary with landslide size, suggesting that complex hydrologic–mechanical feedbacks (rather than 1-D pore pressure diffusion) may govern slide dynamics. A new analysis of 14 yrs of discharge and sediment concentration data for the Eel River indicates that the characteristic mid-winter timing of earthflow acceleration corresponds with increased suspended concentration values, suggesting that the seasonal onset of landslide motion each year may be reflected in the export of sediments to the continental margin. The vast majority of active slides exhibit gullied surfaces and the gully networks, which are also seasonally active, may facilitate sediment export although the proportion of material produced by this pathway is poorly known.

Along Kekawaka Creek, a prominent tributary to the Eel River, new analyses of catchment-averaged erosion rates derived from cosmogenic radionuclides reveal rapid erosion (0.76 mm/yr) below a prominent knickpoint and slower erosion (0.29 mm/yr) upstream. Such knickpoints are frequently observed in Eel tributaries and are usually comprised of massive (>10 m) interlocking resistant boulders that likely persist in the landscape for long periods of time (>10^5 yr). Upstream of these knickpoints, active landslides tend to be less frequent and average slope angles are slightly gentler than in downstream areas, which indicates that landslide density and average slope angle appear to increase with erosion rate. Lastly, we synthesize evidence for the role of large, catastrophic landslides in regulating sediment flux and landscape form. The emergence of resistant blocks within the mélange bedrock has promoted large catastrophic slides that have dammed the Eel River and perhaps generated outburst events in the past. The frequency and impact of these landslide dams likely depend on the spatial and size distributions of resistant blocks relative to the width and drainage area of adjacent valley networks. Overall, our findings demonstrate that landslides within the Eel River catchment do not occur randomly, but instead exhibit spatial and temporal patterns related to baselevel lowering, climate forcing, and lithologic variations. Combined with recent landscape evolution models that incorporate landslides, these results provide predictive capability for estimating erosion rates and managing hazards in mountainous regions.

---

* Corresponding author. Tel.: +1 541 346 5574.
E-mail address: jroering@uoregon.edu (J.J. Roering).

http://dx.doi.org/10.1016/j.geomorph.2015.02.013
0169-555X/

Contents

1. Introduction

In mountainous landscapes, landslides liberate soil and bedrock in response to tectonic uplift (e.g., Brunsden, 1999; Roering et al., 2005; Korup et al., 2007, 2010; Agliardi et al., 2013; Ekström and Stark, 2013). Characterizing how landslides contribute to landscape evolution in mountainous regions is challenging given that diverse geologic, climatic, and even biological factors influence slope stability. For example, relatively subtle variations in rock properties can dictate whether a mountain range will be subject to infrequent, deep-seated bedrock slumps or frequent rockfall and shallow landslides (e.g., Korup, 2008). Similarly, runout dynamics and material properties determine whether landslide materials deposited in valleys will tend to resist breaching and form lakes or become subject to downstream dispersal soon after failure occurs (e.g., Costa and Schuster, 1988; Iverson et al., 2000). These highly disparate responses highlight the challenge and importance of characterizing landslide processes in order to interpret and predict their role in shaping landscapes (Cendrero and Dramis, 1996). In this contribution, we review past work and highlight several new analyses that describe landslide dynamics and related geomorphic processes in response to rapid uplift in the Northern California Coastal Ranges. The approaches described here span a range of spatial and temporal scales, emphasizing the importance of integrating diverse tools for assessing how landslides shape mountainous terrain.

Early efforts to conceptualize landslide behavior over geologic timescales used the analogy of a dry sandpile to represent how landslides influence hillslope form and sediment fluxes (de la Noe and de Margerie, 1888; Strahler, 1950; Carson and Petley, 1970; Bak et al., 1987, 1988; Burbank et al., 1996; Densmore et al., 1997; Montgomery, 2001). In the sandpile analogy, when channels incise at a sufficient pace, hillslopes attain a threshold slope or 'angle of repose' as sand avalanches displace material downslope and generate erosion at a rate equal to that of river incision (Roering, 2012). Increasing the rate of incision has the effect of increasing the rate at which hillslopes deliver sand avalanches to channels but does not increase hillslope steepness because the maximum stable angle cannot be exceeded. This simple conceptual model implies that channel incision is immediately followed by uniform hillslope lowering of the same magnitude. In other words, the threshold slope model, strictly interpreted, suggests that hillslope erosion is directly and instantaneously coupled to vertical lowering of the valley network and occurs as uniform 'sheets' of erosion. While this framework is intuitively appealing, landslide erosion on natural hillslopes, and even laboratory sandpiles, does not manifest as contiguous sheets of cascading sediment or bedrock (Densmore et al., 1997; Roering et al., 2001; Malamud et al., 2004). Instead, both natural and experimental slopes exhibit discrete slope failures that are highly variable in both space and time. Many of the local factors that influence the propensity for landsliding are highly stochastic and difficult to characterize (e.g., rock mass strength, pore pressures, vegetation, rock fabric and slope orientation, the intensity and extent of storms, earthquake magnitude and recurrence, and channel–hillslope interactions) (Brunsden, 1993). As a result, it has proven challenging to test the central tenet of the threshold slope model: do natural hillslopes achieve a threshold state such that landslide erosion balances channel incision? Furthermore, assuming that slide-driven erosion can pace channel lowering, how do landslides organize themselves spatially and temporally in order to maintain this balance? Capturing and quantifying the relevant landslide patterns to tackle these queries proved beyond our reach until the accumulation of high-resolution remote sensing imagery in recent decades.

Landslide inventories are often produced by documenting failures over a given time interval or following major storms, earthquakes, or snowmelt events, and have become a favored tool for addressing how landslides influence landscape evolution (e.g., Hovius et al., 1997; Malamud et al., 2004; Schwab et al., 2008; Harp et al., 2011; Bennett et al., 2012; Larsen and Montgomery, 2012). These inventory studies are sometimes accomplished through field mapping but more typically via air photos, satellite imagery, or airborne lidar (Nichol and Wong, 2005; Guzzetti et al., 2012; Borgomeo et al., 2014; Tarolli, 2014). These studies often reveal that landslide density decreases nonlinearly with landslide area and in some cases the slope of this relationship implies that infrequent large landslides exhibit a disproportionate influence on denudation and valley dynamics (Stark and Hovius, 2001; Korup et al., 2007; Agliardi et al., 2013; Giordan et al., 2013). Numerous studies have proposed functional relationships to describe landslide area distributions, including commonly observed decreases (or rollovers) in frequency at small landslide areas that reflect changing landslide mechanics (Katz and Aharonov, 2006; Brunetti et al., 2009; Stark and Guzzetti, 2009), detection limitations due to data resolution (Simoni et al., 2013), or heterogeneity in boundary conditions (Pelletier et al., 1997; Roering et al., 2005).

When coupled with chronological constraints as well as depth–area scaling data, landslide density functions can be used to calculate denudation rates and determine the extent to which landslide erosion