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# Landslides, threshold slopes, and the survival of relict terrain in the wake of the Mendocino Triple Junction

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## ABSTRACT

Establishing landscape response to uplift is critical for interpreting sediment fluxes, hazard potential, and topographic evolution. We assess how landslides shape terrain in response to a wave of uplift traversing the northern California Coast Ranges (United States) in the wake of the Mendocino Triple Junction. We extracted knickpoints, landslide erosion rates, and topographic metrics across the region modified by Mendocino Triple Junction migration. Landslide erosion rates mapped from aerial imagery are consistent with modeled uplift and exhumation, while hillslope gradient is invariant across the region, suggesting that landslides accommodate uplift, as predicted by the threshold slope model. Landslides are concentrated along steepened channel reaches downstream of knickpoints generated by base-level fall at channel outlets, and

limit slope angles and relief. We find evidence that landslide-derived coarse sediment delivery may suppress catchment-wide channel incision and landscape denudation over the time required for the uplift wave to traverse the region. We conclude that a landslide cover effect may provide a mechanism for the survival of relict terrain in the northern Californian Coast Ranges and elsewhere over millennial time scales.

**INTRODUCTION**

While landsliding is commonly identified as the dominant erosional process in mountainous settings (Hovius et al., 1997; Bennett et al., 2012), we lack regional data sets of landslide erosion rates with which to constrain the response of landslides to tectonic uplift as well as their potential role in landscape evolution (Korup et al., 2010). Landslide deposits may dam rivers and even suppress upstream base-level transmission (Ouimet et al., 2007), but the long-term efficacy of hillslope-channel feedbacks and their influence on topographic response to uplift are poorly known (Egholm et al., 2013).

Transient landscapes in which the process rates and topography evolve across an uplift gradient are valuable for deciphering potential hillslope-channel feedbacks in landscape response to uplift (Miller et al., 2013). Commonly used channel incision models (e.g., Wobus et al., 2006) predict that channels respond to base-level fall via a wave of incision that sweeps upstream via knickpoint retreat. Knickpoints separate the actively adjusting channel commonly bounded by steep slopes and active landslides (e.g., Gallen et al., 2011) from gentler “relict” upstream terrain that has yet to experience base-level adjustment (Willenbring et al., 2013). In the simplest case, the stream power model, vertical and horizontal migration of knickpoints is predicted to be proportional to the rock uplift rate and the erodibility constant, K, respectively (Niemann et al., 2001). However, the model does not consider the role of sediment in modulating channel response (Sklar and Dietrich, 2001). Sediment cover may slow knickpoint retreat, delaying catchment denudation in response to base-level fall relative to the surrounding landscape (DiBiase et al., 2014). Alternatively, sediment may act as a tool, enhancing channel incision and landscape denudation (Sklar and Dietrich, 2001). The role of landslides in landscape response to uplift is important to elucidate, considering that landslides dominate sediment supply in mountainous settings and thus provide a potential feedback on landscape response rates (Egholm et al., 2013).

In this contribution, we investigate landscape response to a wave of transient uplift migrating northward through northern California (United States) in the wake of the Mendocino Triple Junction (MTJ) (Furlong and Govers, 1999). This tectonic setting enables us to observe the initiation of landsliding in response to fluvial incision on the leading edge of the uplift field, as well as landslide feedbacks on channel incision and denudation. In particular, we assess the role of landslides as either a tool enhancing denudation, or cover suppressing denudation in response to uplift.

## GEOLOGIC BACKGROUND

The northern Californian Coast Ranges are modified by geodynamic processes associated with the northward migration of the MTJ, which marks the transition from a subduction zone to a transform plate boundary along the western margin of North America (Fig. 1). MTJ migration is associated with regional changes in crustal thickness, heat flow, and volcanism associated with the formation of a slab window in the wake of the triple junction. A geodynamic model of this process, referred to as the Mendocino crustal conveyor (MCC), predicts a crustal thickening rate of ~8 mm $yr^{-1}$ just to the south

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of the MTJ and crustal thinning of up to ~6.5 mm $yr^{-1}$ farther south (Fig. 2A; Furlong and Govers, 1999, their figure. 3). Assuming local isostasy and density variations between mantle and crust (Lock et al., 2006), these rates translate into a rock uplift rate of ~1.2 mm $yr^{-1}$ and subsidence rate of ~1 mm $yr^{-1}$, respectively. Integrating rates of thickening and thinning through space and time produces a pattern of crustal thickness variation, which can be converted into a pattern of cumulative surface uplift over the past ~8 m.y. (Fig. 2B; Furlong and Govers, 1999, their figure. 3).

Past geomorphologic studies have found evidence for drainage capture and reorganization (Lock et al., 2006), knickpoint migration (Willenbring et al., 2013), and spatially variable erosion rates (Balco et al., 2013) attributed to MTJ migration. Studies of landsliding in the region have revealed pockets of pervasive earthflow erosion particularly within the mechanically weak Franciscan Mélange unit (KJf) making up the central belt of the Coast Ranges Franciscan Complex (Kelsey, 1978; Mackey and Roering, 2011). However, few have addressed hillslope-channel coupling (Roering et al., 2015), and more importantly, previous analysis has been spatially restricted, precluding a systematic comparison with the regional uplift pattern.

## METHODS

We measured landslide erosion rates through mapping of debris slides and earthflows from imagery in Google Earth™ spanning A.D. 1988–2014 (Table DR1 in the GSA Data Repository[1]). Debris slides are instantaneous failures that leave easily detectable scars in the landscape (Fig. DR2 in the Data Repository). Earthflows are slow-moving landslides that exhibit flow-like features (Fig. DR3).

Where present, we identified features on sequential images to measure earthflow velocity. We assigned the mean velocity (1.44 m $yr^{-1}$; Fig. DR4) to active earthflows with unconstrained velocities, as well as to dormant earthflows on the supposition that these features were active in the recent past based on their morphologic signature (Mackey and Roering, 2011). Earthflow width and depth were estimated from area using empirical scaling relationships (Handwerger et al., 2013; Fig. DR5). Finally, the earthflow sediment flux into the channel network was converted into a bedrock erosion rate following Mackey and Roering (2011).

We calculated debris-slide volume from mapped area using an empirical scaling relationship for landslides in northern California (Larsen et al., 2010). Volume was converted into annual flux to the channel network using the estimated age of debris-slide scars. We determined that 10–30 yr is required to revegetate debris scars, enabling us to estimate a range of debris-slide erosion rates (Fig. DR2).

We calculated topographic slope and local relief with a 10 m U.S. Geological Survey (USGS) National Elevation Dataset (NED) digital elevation model, and extracted normalized channel steepness index ($k_{sn}$) (e.g., Kirby and Whipple, 2012) using a reference concavity index of 0.55 (Shi, 2011). We developed an automated technique to map migratory knickpoints, calibrated on knickpoints in the southern part of the study area (Shi, 2011). To avoid anchored knickpoints, we omitted knickpoints within 1 km of a geological contact (Fig. DR1) and those associated with reservoirs.

We analyzed our data by swath along the MCC model transect (Fig. 1) and by subcatchment (Fig. DR8) for comparison with published cosmogenic nuclide (CN) and suspended sediment erosion rates and modeled uplift. In order to detect any lithological control on landscape response to uplift, we also separated data by geology, differentiating between the KJf unit prone to earthflows (Fig. 1A) and other predominantly sandstone units making up the coastal belt of the Coast Ranges that we collectively refer to as non-KJf (Fig. DR1).

**RESULTS**

We mapped 122 knickpoints (Fig. 1B), 1600 debris slides, 246 active earthflows (174 with measured velocities), and 324 dormant earthflows across the study area (Fig. 1A). Taken together, these two styles of landsliding denude the study area at an average rate of 0.18 ± 0.04 mm $yr^{-1}$ (Table DR2).

Mean hillslope gradient (~20°) is relatively invariant across the zone of uplift, while landslide erosion rates are highly variable and broadly reflect modeled uplift and exhumation (Fig. 2).

Our landslide erosion rates broadly correspond with published CN erosion rates (Balco et al., 2013; Willenbring et al., 2013; Roering et al., 2015) and suspended sediment erosion rates (Wheatcroft and Sommerfield, 2005) (Fig. 2E; Fig. DR9), suggesting persistence of the present-day spatial pattern of landsliding over cosmogenic (100–1000 yr) time scales.

Comparison of subcatchment-averaged hillslope gradient and $k_{sn}$ (Fig. 3A; Fig. DR8) reveals that hillslope gradient becomes insensitive to further increases in $k_{sn}$ (and by inference, uplift) (Ouimet et al., 2009) at 15–20°. The coincidence of threshold hillslopes with the highest density of active earthflows suggests that earthflows are responsible for maintaining this gradient.

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Faster landslide erosion rates coincide with higher $k_{sn}$ (Fig. 3B), particularly below knickpoints (e.g., Fig. 3C; Roering et al., 2015). Analysis of the Mad River on the leading edge of the uplift wave reveals a concentration of landslides along a steep knickzone with high $k_{sn}$ and hillslope relief containing several knickpoints (Figs. 4A–4E). Similar patterns are found along other channels within unit KJf lithology (Figs. DR10 and DR11). We consider lower-relief terrain above these knickzones to be “relict” topography yet to experience the observed pulse of erosion (Figs. 1B and 4).

We observe that subcatchment-averaged landslide erosion rates correlate with $k_{sn}$ < 400 $m^{1.1}$ (Fig. 3B); this correlation may disappear for steeper channels. We observe a similar relationship of CN erosion rates with $k_{sn}$ (Fig. 3C) and note that streams in unit KJf are steeper for a given erosion rate than streams in non-KJf units, suggesting that the former have a lower erosional efficiency. We also observe that landslide erosion rate peaks in non-KJf units ~0.5° in latitude to the south (Fig. 2E), i.e., farther upstream, compared to the parallel KJf domain, suggesting a shorter erosional response time in non-KJF watersheds.

**DISCUSSION**

Our results suggest that the northward-migrating increase in crustal thickness predicted by the MCC model is accommodated by increased landslide erosion rather than hillslope steepening, lending support to the threshold slope model (Burbank et al., 1996; Larsen and Montgomery, 2012). We find that landsliding is driven by focused channel incision downstream of knickpoints that were initiated by uplift and relative base-level fall at channel outlets. The prevalence of threshold hillslopes and existence of scattered knickpoints and landslides above the zone of rapid erosion (e.g., Fig. 4) may result from either previous waves of erosion (e.g., Grimaud et al., 2015) or background erosion processes. We may also be observing remnants of past divide migration and internal drainage reorganization (Lock et al., 2006). We thus use the term “relict” topography to describe relatively low-relief topography at the heads of our catchments yet to experience the current pulse of erosion.

We find evidence for a profound lithological control on landscape response to uplift, though one that counters expectations. If we consider that the relationship between erosion rate and $k_{sn}$ (Fig. 3C) is a function of K (erodibility) and $Q_s$ (sediment supply) (Gasparini et al., 2006), this implies either a difference in lithology or the role of sediment (i.e., tools/cover effect) between KJf and non-KJf units, given a constant climate. Catchments within unit KJf, dominated by highly sheared mudstones, might be expected to have a greater erosional efficiency than those in non-KJf units of predominantly sandstone, given the higher relative erodibility of mudstone (Sklar and Dietrich, 2001). However, KJf catchments exhibit lower erosional efficiency and a longer response time. We observe prevalent channel reaches mantled by boulders (commonly >10 m) within unit KJf, particularly at earthflow toes (Figs. DR2A and DR12), that are not apparent in channels within non-KJf units. We suggest that resistant blocks eroded from the mélange by earthflows armor the channel bed and have a negative feedback on ongoing landscape response to uplift, i.e., slowing channel incision and knickpoint propagation and ultimately retarding landscape denudation (DiBiase et al., 2014). This would imply that the current pulse of erosion may be stalled on the frontal edge of the uplift wave in unit KJf, providing an appealing explanation for the long-lived nature of the landslide erosion pattern we infer from the close correspondence of landslide and cosmogenic erosion rates.

It remains to be seen whether the observed pulse of erosion will continue to migrate up the channel network in the time it takes for the uplift wave to pass through the region in the wake of the MTJ at 50 km m.y.$^{-1}$ (Furlong and Govers, 1999), i.e., ~2 m.y. If not, the landslide cover effect described here may provide a mechanism for the survival of relict terrain at the head of unit KJf–dominated catchments in this landscape and more broadly in active tectonic landscapes over million-year time scales (e.g., Egholm et al., 2013; Yang et al., 2015).

## SUMMARY

We observe a complex landscape response to uplift associated with the passage of the MTJ. Landslide erosion rates estimated from aerial imagery are consistent with the modeled uplift field, while hillslope gradient is invariant across the region of uplift, providing strong support for the threshold slope model. We observe the initiation of landslide erosion and concomitant attainment of threshold slopes downstream of migratory knickpoints on the leading edge of the uplift wave. However, our data further suggest that through the delivery of megaclasts to channel beds, landslides may have a negative feedback on ongoing channel incision, landslide erosion, and landscape denudation in the wake of knickpoints. Thus we suggest that some parts of the landscape may temporarily escape adjustment to increased uplift, providing a mechanism for the preservation of relict terrain in the landscape.

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**FIGURE CAPTIONS**

Figure 1. A: Regional and geological setting and landslides mapped within four study catchments spanning Mendocino crustal conveyer (MCC) transect in B (northern California, USA). B: Normalized channel steepness index, $k_{sn}$, and knickpoints mapped across study catchments. MTJ—Mendocino Triple Junction; CA—California.

Figure 2. A: Predicted uplift rate calculated from crustal thickening rate as modeled along Mendocino crustal conveyer (MCC) transect in Figure 1B. B: Observed elevation (*z*) and modeled cumulative uplift as calculated from MCC-modeled crustal thickness variation.

C: Franciscan Mélange unit (KJf) swath-averaged hillslope gradient. D: Unit KJf normalized channel steepness index, $k_{sn}$, averaged by swath and downstream of knickpoints. E: Swath-averaged landslide erosion rates in KJf and non-KJf lithologies compared to cosmogenic nuclide and suspended sediment erosion rates (latter converted from catchment yields based on bedrock density of 2.5 g $cm^{-3}$) and predicted exhumation as depicted in A. Tails on cosmogenic nuclide and suspended sediment erosion rates depict upstream area over which these rates integrate.

Figure 3. A: Relationship between mean hillslope gradient and mean normalized channel steepness index, $k_{sn}$, calculated for catchments with >50% Franciscan Mélange unit (KJf), overlaid by kernel density of mean slope gradient and $k_{sn}$ of active earthflows. The $k_{sn}$ of an earthflow is that of the closest 10 m channel node. Points are colored by subcatchment average landslide erosion rate. B: Relationship of landslide erosion rate with $k_{sn}$. Gray shading denotes potential cover effect at high $k_{sn}$ by which landslide deposits limit further channel incision and landslide erosion. C: Relationship of cosmogenic nuclide erosion rate with $k_{sn}$ showing decreased landslide erosion at high $k_{sn}$ and also showing higher erosional efficiency, K, in non-KJf compared to KJf catchments. Points 1 and 2 refer to above and below the Kekawaka knickzone, respectively (Fig. DR11 in the Data Repository [see footnote 1]).

Figure 4. A: Landslides and knickpoints along Mad River, California (USA)**a**. Only streams of order >2 are shown. Vertical lines depict landslide elevation range, with dots denoting their median elevations. B: Mean normalized channel steepness index, $k_{sn}$,

calculated in 100 swaths (~160 m) along channel. C: Mean relief calculated as difference between ridgeline and channel elevation. D: Mean hillslope gradient. E: Mean landslide erosion rates. Gray shading denotes main knickzone.

[1]GSA Data Repository item 2016xxx, Figures DR1–DR12 and Tables DR1 and DR2, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.