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

Georgina L. Bennett[1][*], Scott R. Miller[2], Joshua J. Roering[1], and David A. Schmidt[3]

[1]*Department of Geological Sciences, University of Oregon, 1275 E 13th Ave, Eugene,*

Oregon 97403-1272, USA

[2]*Department of Geology and Geophysics, University of Utah, 115 S 1460 E, Salt Lake*

City, Utah 84112-0102, USA

[3]*Department of Earth and Space Sciences, University of Washington, 4000 15th Avenue,*

Seattle, Washington 98195-1310, USA

*Current address: Department of Geosciences, Colorado State University, 1482 Campus

Delivery, Fort Collins, Colorado 80523-1482, USA

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

23   limit slope angles and relief. We find evidence that landslide-derived coarse sediment

24   delivery may suppress catchment-wide channel incision and landscape denudation over

25   the time required for the uplift wave to traverse the region. We conclude that a landslide

26   cover effect may provide a mechanism for the survival of relict terrain in the northern

27   Californian Coast Ranges and elsewhere over millennial time scales.

28   **INTRODUCTION**

29   While landsliding is commonly identified as the dominant erosional process in

30   mountainous settings (Hovius et al., 1997; Bennett et al., 2012), we lack regional data

31   sets of landslide erosion rates with which to constrain the response of landslides to

32   tectonic uplift as well as their potential role in landscape evolution (Korup et al., 2010).

33   Landslide deposits may dam rivers and even suppress upstream base-level transmission

34   (Ouimet et al., 2007), but the long-term efficacy of hillslope-channel feedbacks and their

35   influence on topographic response to uplift are poorly known (Egholm et al., 2013).

36   Transient landscapes in which the process rates and topography evolve across an

37   uplift gradient are valuable for deciphering potential hillslope-channel feedbacks in

38   landscape response to uplift (Miller et al., 2013). Commonly used channel incision

39   models (e.g., Wobus et al., 2006) predict that channels respond to base-level fall via a

40   wave of incision that sweeps upstream via knickpoint retreat. Knickpoints separate the

41   actively adjusting channel commonly bounded by steep slopes and active landslides (e.g.,

42   Gallen et al., 2011) from gentler "relict" upstream terrain that has yet to experience base-

43   level adjustment (Willenbring et al., 2013). In the simplest case, the stream power model,

44   vertical and horizontal migration of knickpoints is predicted to be proportional to the rock

45   uplift rate and the erodibility constant, K, respectively (Niemann et al., 2001). However,

46 the model does not consider the role of sediment in modulating channel response (Sklar

47 and Dietrich, 2001). Sediment cover may slow knickpoint retreat, delaying catchment

48 denudation in response to base-level fall relative to the surrounding landscape (DiBiase et

49 al., 2014). Alternatively, sediment may act as a tool, enhancing channel incision and

50 landscape denudation (Sklar and Dietrich, 2001). The role of landslides in landscape

51 response to uplift is important to elucidate, considering that landslides dominate sediment

52 supply in mountainous settings and thus provide a potential feedback on landscape

53 response rates (Egholm et al., 2013).

54   In this contribution, we investigate landscape response to a wave of transient

55 uplift migrating northward through northern California (United States) in the wake of the

56 Mendocino Triple Junction (MTJ) (Furlong and Govers, 1999). This tectonic setting

57 enables us to observe the initiation of landsliding in response to fluvial incision on the

58 leading edge of the uplift field, as well as landslide feedbacks on channel incision and

59 denudation. In particular, we assess the role of landslides as either a tool enhancing

60 denudation, or cover suppressing denudation in response to uplift.

61 **GEOLOGIC BACKGROUND**

62   The northern Californian Coast Ranges are modified by geodynamic processes

63 associated with the northward migration of the MTJ, which marks the transition from a

64 subduction zone to a transform plate boundary along the western margin of North

65 America (Fig. 1). MTJ migration is associated with regional changes in crustal thickness,

66 heat flow, and volcanism associated with the formation of a slab window in the wake of

67 the triple junction. A geodynamic model of this process, referred to as the Mendocino

68 crustal conveyor (MCC), predicts a crustal thickening rate of ~8 mm yr^{-1} just to the south

69   of the MTJ and crustal thinning of up to ~6.5 mm yr^{-1} farther south (Fig. 2A; Furlong and

70   Govers, 1999, their figure. 3). Assuming local isostasy and density variations between

71   mantle and crust (Lock et al., 2006), these rates translate into a rock uplift rate of ~1.2

72   mm yr^{-1} and subsidence rate of ~1 mm yr^{-1}, respectively. Integrating rates of thickening

73   and thinning through space and time produces a pattern of crustal thickness variation,

74   which can be converted into a pattern of cumulative surface uplift over the past ~8 m.y.

75   (Fig. 2B; Furlong and Govers, 1999, their figure. 3).

76   Past geomorphologic studies have found evidence for drainage capture and

77   reorganization (Lock et al., 2006), knickpoint migration (Willenbring et al., 2013), and

78   spatially variable erosion rates (Balco et al., 2013) attributed to MTJ migration. Studies

79   of landsliding in the region have revealed pockets of pervasive earthflow erosion

80   particularly within the mechanically weak Franciscan Mélange unit (KJf) making up the

81   central belt of the Coast Ranges Franciscan Complex (Kelsey, 1978; Mackey and

82   Roering, 2011). However, few have addressed hillslope-channel coupling (Roering et al.,

83   2015), and more importantly, previous analysis has been spatially restricted, precluding a

84   systematic comparison with the regional uplift pattern.

85   **METHODS**

86   We measured landslide erosion rates through mapping of debris slides and

87   earthflows from imagery in Google Earth™ spanning A.D. 1988–2014 (Table DR1 in the

88   GSA Data Repository[1]). Debris slides are instantaneous failures that leave easily

89   detectable scars in the landscape (Fig. DR2 in the Data Repository). Earthflows are slow-

90   moving landslides that exhibit flow-like features (Fig. DR3).

91   Where present, we identified features on sequential images to measure earthflow

92   velocity. We assigned the mean velocity (1.44 m yr^{-1}; Fig. DR4) to active earthflows

93   with unconstrained velocities, as well as to dormant earthflows on the supposition that

94   these features were active in the recent past based on their morphologic signature

95   (Mackey and Roering, 2011). Earthflow width and depth were estimated from area using

96   empirical scaling relationships (Handwerger et al., 2013; Fig. DR5). Finally, the

97   earthflow sediment flux into the channel network was converted into a bedrock erosion

98   rate following Mackey and Roering (2011).

99   We calculated debris-slide volume from mapped area using an empirical scaling

100   relationship for landslides in northern California (Larsen et al., 2010). Volume was

101   converted into annual flux to the channel network using the estimated age of debris-slide

102   scars. We determined that 10–30 yr is required to revegetate debris scars, enabling us to

103   estimate a range of debris-slide erosion rates (Fig. DR2).

104   We calculated topographic slope and local relief with a 10 m U.S. Geological

105   Survey (USGS) National Elevation Dataset (NED) digital elevation model, and extracted

106   normalized channel steepness index (k_{sn}) (e.g., Kirby and Whipple, 2012) using a

107   reference concavity index of 0.55 (Shi, 2011). We developed an automated technique to

108   map migratory knickpoints, calibrated on knickpoints in the southern part of the study

109   area (Shi, 2011). To avoid anchored knickpoints, we omitted knickpoints within 1 km of

110   a geological contact (Fig. DR1) and those associated with reservoirs.

111   We analyzed our data by swath along the MCC model transect (Fig. 1) and by

112   subcatchment (Fig. DR8) for comparison with published cosmogenic nuclide (CN) and

113   suspended sediment erosion rates and modeled uplift. In order to detect any lithological

114 control on landscape response to uplift, we also separated data by geology, differentiating

115 between the KJf unit prone to earthflows (Fig. 1A) and other predominantly sandstone

116 units making up the coastal belt of the Coast Ranges that we collectively refer to as non-

117 KJf (Fig. DR1).

118 **RESULTS**

119   We mapped 122 knickpoints (Fig. 1B), 1600 debris slides, 246 active earthflows

120 (174 with measured velocities), and 324 dormant earthflows across the study area (Fig.

121 1A). Taken together, these two styles of landsliding denude the study area at an average

122 rate of 0.18 ± 0.04 mm yr^{-1} (Table DR2).

123   Mean hillslope gradient (~20°) is relatively invariant across the zone of uplift,

124 while landslide erosion rates are highly variable and broadly reflect modeled uplift and

125 exhumation (Fig. 2).

126   Our landslide erosion rates broadly correspond with published CN erosion rates

127 (Balco et al., 2013; Willenbring et al., 2013; Roering et al., 2015) and suspended

128 sediment erosion rates (Wheatcroft and Sommerfield, 2005) (Fig. 2E; Fig. DR9),

129 suggesting persistence of the present-day spatial pattern of landsliding over cosmogenic

130 (100–1000 yr) time scales.

131   Comparison of subcatchment-averaged hillslope gradient and k_{sn} (Fig. 3A; Fig.

132 DR8) reveals that hillslope gradient becomes insensitive to further increases in k_{sn} (and

133 by inference, uplift) (Ouimet et al., 2009) at 15–20°. The coincidence of threshold

134 hillslopes with the highest density of active earthflows suggests that earthflows are

135 responsible for maintaining this gradient.

136   Faster landslide erosion rates coincide with higher k_{sn} (Fig. 3B), particularly

137   below knickpoints (e.g., Fig. 3C; Roering et al., 2015). Analysis of the Mad River on the

138   leading edge of the uplift wave reveals a concentration of landslides along a steep

139   knickzone with high k_{sn} and hillslope relief containing several knickpoints (Figs. 4A–4E).

140   Similar patterns are found along other channels within unit KJf lithology (Figs. DR10 and

141   DR11). We consider lower-relief terrain above these knickzones to be "relict" topography

142   yet to experience the observed pulse of erosion (Figs. 1B and 4).

143   We observe that subcatchment-averaged landslide erosion rates correlate with k_{sn}

144   < 400 m$^{1.1}$ (Fig. 3B); this correlation may disappear for steeper channels. We observe a

145   similar relationship of CN erosion rates with k_{sn} (Fig. 3C) and note that streams in unit

146   KJf are steeper for a given erosion rate than streams in non-KJf units, suggesting that the

147   former have a lower erosional efficiency. We also observe that landslide erosion rate

148   peaks in non-KJf units ~0.5° in latitude to the south (Fig. 2E), i.e., farther upstream,

149   compared to the parallel KJf domain, suggesting a shorter erosional response time in non-

150   KJF watersheds.

151   **DISCUSSION**

152   Our results suggest that the northward-migrating increase in crustal thickness

153   predicted by the MCC model is accommodated by increased landslide erosion rather than

154   hillslope steepening, lending support to the threshold slope model (Burbank et al., 1996;

155   Larsen and Montgomery, 2012). We find that landsliding is driven by focused channel

156   incision downstream of knickpoints that were initiated by uplift and relative base-level

157   fall at channel outlets. The prevalence of threshold hillslopes and existence of scattered

158   knickpoints and landslides above the zone of rapid erosion (e.g., Fig. 4) may result from

159   either previous waves of erosion (e.g., Grimaud et al., 2015) or background erosion

160   processes. We may also be observing remnants of past divide migration and internal

161   drainage reorganization (Lock et al., 2006). We thus use the term "relict" topography to

162   describe relatively low-relief topography at the heads of our catchments yet to experience

163   the current pulse of erosion.

164   We find evidence for a profound lithological control on landscape response to

165   uplift, though one that counters expectations. If we consider that the relationship between

166   erosion rate and k_{sn} (Fig. 3C) is a function of K (erodibility) and Q_s (sediment supply)

167   (Gasparini et al., 2006), this implies either a difference in lithology or the role of

168   sediment (i.e., tools/cover effect) between KJf and non-KJf units, given a constant

169   climate. Catchments within unit KJf, dominated by highly sheared mudstones, might be

170   expected to have a greater erosional efficiency than those in non-KJf units of

171   predominantly sandstone, given the higher relative erodibility of mudstone (Sklar and

172   Dietrich, 2001). However, KJf catchments exhibit lower erosional efficiency and a longer

173   response time. We observe prevalent channel reaches mantled by boulders (commonly

174   >10 m) within unit KJf, particularly at earthflow toes (Figs. DR2A and DR12), that are

175   not apparent in channels within non-KJf units. We suggest that resistant blocks eroded

176   from the mélange by earthflows armor the channel bed and have a negative feedback on

177   ongoing landscape response to uplift, i.e., slowing channel incision and knickpoint

178   propagation and ultimately retarding landscape denudation (DiBiase et al., 2014). This

179   would imply that the current pulse of erosion may be stalled on the frontal edge of the

180   uplift wave in unit KJf, providing an appealing explanation for the long-lived nature of

181   the landslide erosion pattern we infer from the close correspondence of landslide and

182   cosmogenic erosion rates.

183   It remains to be seen whether the observed pulse of erosion will continue to

184   migrate up the channel network in the time it takes for the uplift wave to pass through the

185   region in the wake of the MTJ at 50 km m.y.$^{-1}$ (Furlong and Govers, 1999), i.e., ~2 m.y.

186   If not, the landslide cover effect described here may provide a mechanism for the survival

187   of relict terrain at the head of unit KJf–dominated catchments in this landscape and more

188   broadly in active tectonic landscapes over million-year time scales (e.g., Egholm et al.,

189   2013; Yang et al., 2015).

190   **SUMMARY**

191   We observe a complex landscape response to uplift associated with the passage of

192   the MTJ. Landslide erosion rates estimated from aerial imagery are consistent with the

193   modeled uplift field, while hillslope gradient is invariant across the region of uplift,

194   providing strong support for the threshold slope model. We observe the initiation of

195   landslide erosion and concomitant attainment of threshold slopes downstream of

196   migratory knickpoints on the leading edge of the uplift wave. However, our data further

197   suggest that through the delivery of megaclasts to channel beds, landslides may have a

198   negative feedback on ongoing channel incision, landslide erosion, and landscape

199   denudation in the wake of knickpoints. Thus we suggest that some parts of the landscape

200   may temporarily escape adjustment to increased uplift, providing a mechanism for the

201   preservation of relict terrain in the landscape.

202   **ACKNOWLEDGMENTS**

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306   **FIGURE CAPTIONS**

307   Figure 1. A: Regional and geological setting and landslides mapped within four study

308   catchments spanning Mendocino crustal conveyer (MCC) transect in B (northern

309   California, USA). B: Normalized channel steepness index, k_{sn}, and knickpoints mapped

310   across study catchments. MTJ—Mendocino Triple Junction; CA—California.

311

312   Figure 2. A: Predicted uplift rate calculated from crustal thickening rate as modeled along

313   Mendocino crustal conveyer (MCC) transect in Figure 1B. B: Observed elevation (z) and

314   modeled cumulative uplift as calculated from MCC-modeled crustal thickness variation.

315   C: Franciscan Mélange unit (KJf) swath-averaged hillslope gradient. D: Unit KJf

316   normalized channel steepness index, k_{sn}, averaged by swath and downstream of

317   knickpoints. E: Swath-averaged landslide erosion rates in KJf and non-KJf lithologies

318   compared to cosmogenic nuclide and suspended sediment erosion rates (latter converted

319   from catchment yields based on bedrock density of 2.5 g cm^{-3}) and predicted exhumation

320   as depicted in A. Tails on cosmogenic nuclide and suspended sediment erosion rates

321   depict upstream area over which these rates integrate.

322

323   Figure 3. A: Relationship between mean hillslope gradient and mean normalized channel

324   steepness index, k_{sn}, calculated for catchments with >50% Franciscan Mélange unit (KJf),

325   overlaid by kernel density of mean slope gradient and k_{sn} of active earthflows. The k_{sn} of

326   an earthflow is that of the closest 10 m channel node. Points are colored by subcatchment

327   average landslide erosion rate. B: Relationship of landslide erosion rate with k_{sn}. Gray

328   shading denotes potential cover effect at high k_{sn} by which landslide deposits limit further

329   channel incision and landslide erosion. C: Relationship of cosmogenic nuclide erosion

330   rate with k_{sn} showing decreased landslide erosion at high k_{sn} and also showing higher

331   erosional efficiency, K, in non-KJf compared to KJf catchments. Points 1 and 2 refer to

332   above and below the Kekawaka knickzone, respectively (Fig. DR11 in the Data

333   Repository [see footnote 1]).

334

335   Figure 4. A: Landslides and knickpoints along Mad River, California (USA)**a**. Only

336   streams of order >2 are shown. Vertical lines depict landslide elevation range, with dots

337   denoting their median elevations. B: Mean normalized channel steepness index, k_{sn},

338   calculated in 100 swaths (~160 m) along channel. C: Mean relief calculated as difference

339   between ridgeline and channel elevation. D: Mean hillslope gradient. E: Mean landslide

340   erosion rates. Gray shading denotes main knickzone.

341

342   [1]GSA Data Repository item 2016xxx, Figures DR1–DR12 and Tables DR1 and DR2, is

343   available online at www.geosociety.org/pubs/ft2016.htm, or on request from

344   editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO

345   80301, USA.