What does a mean mean? The temporal evolution of detrital cosmogenic denudation rates in a transient landscape

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ABSTRACT
In equilibrium landscapes, 10Be concentrations within detrital quartz grains are expected to quantitatively reflect basin-wide denudation rates. In transient landscapes, though detrital quartz is derived from both the incising, adjusting lowland and the unadjusted, relic upland, the integrated 10Be concentrations still provide a denudation rate averaged across the two domains. Because field samples can provide only a snapshot of the current upstream-averaged erosion rate, we employ a numerical landscape evolution model to explore how 10Be-derived denudation rates vary over time and space during transient adjustment. Model results suggest that the longitudinal pattern of mean denudation rates is generated by the river’s progressive dilution of low-volume, high-concentration detritus from relic uplands by the integration of high-volume, low-concentration detritus from adjusting lowlands. The proportion of these materials in any detrital sample depends on what fraction of the upstream area remains unadjusted. Because the boundary of the adjusting part of the landscape changes over time, the longitudinal trend in cosmogenic nuclide-derived erosion rates changes over time. These insights are then used to guide our interpretation of geomorphic and longitudinal cosmogenic nuclide data from the South Fork Eel River (SFER) in the California Coast Range (United States). The northward-propagating crustal thickening and rock uplift associated with the passage of the Mendocino triple junction generates a mobile wave of uplift that progressively sweeps longitudinally down the SFER. The consequences of this forcing can be both replicated in the model environment and observed in the field. The SFER contains transient landforms including knickpoints and river terraces along mainstem and tributary channels that define a clear boundary between an incised, adjusting lowland and an unadjusted, relic upland. We report nine nested, basin-wide denudation rates in the mainstem of the SFER using terrestrial cosmogenic 10Be in river-borne sediment. We find that denudation rates increase in the downstream direction from ~0.2 mm/yr in the upper catchment to ~0.5 mm/yr at the outlet. Using comparisons to the modeled landscape, we show that this pattern of denudation rates, paired with the distribution of relic topography throughout the watershed, reflect the immaturity of the landscape’s transient adjustment. Later in this modeled transient, the predicted erosion rates decrease downstream before they become uniform. This interpretation of our data has potentially far-reaching implications for quantifying the uplift history and response time of transient landscapes using cosmogenic nuclides.

INTRODUCTION
In an equilibrium landscape, detrital cosmogenic 10Be concentrations in quartz provide the mean denudation rate upstream of a sample point, averaged over 103–106 yr (Lal, 1991). Therefore, the 10Be concentration in river sediment is inversely related to the mean erosion rate in the upstream drainage basin (Lal, 1991). Over time, a steady state may exist where the 10Be produced equals the export of 10Be in sediment leaving the catchment (Grainger et al., 1996). Basin-wide erosion rates have been used mainly to study steady-state topography (e.g., von Blanckenburg, 2005). Following a tectonic or base-level disturbance, a signal of transient denudation propagates upstream through a channel network in an organized, predictable fashion with knickpoints defining the fluvial boundary between the relic upstream topography and the actively adjusting downstream topography (Rosenbloom and Anderson, 1994; Crosby and Whipple, 2006). Quaternary changes in climate and fluctuations in tectonic activity assure that many landscapes and watersheds are out of equilibrium with respect to cosmogenic nuclide concentrations (Reinhardt et al., 2007). Schaller and Ehlers (2006) explored the framework for the response time of a basin to such changes in denudation rate due to climatic or base-level perturbations using cosmogenic nuclides, but assumed that denudation rates changed uniformly throughout the basin. In this study, we explore how the progressive adjustment of a basin during transience affects detrital upstream average erosion rates. As many landscapes have a transient component, the mean observed denudation rate could reflect a mixture of two landscapes.

Here, we show that the observed 10Be concentration at a given point in the network is a result of the transient response of incision rates throughout a fluvial network that creates significant spatial differences in observed cosmogenic nuclide concentrations. The concentration is a function of (1) the proportion of the upstream area that lies in each domain and (2) the particular erosion rate in each of the two domains. We hypothesize that the downstream trends in cosmogenic 10Be concentrations along the main river channel allow the erosion response time and magnitude to be reconstructed from a spatial analysis.

We test this hypothesis with a numerical model and with data from the South Fork Eel River (SFER) watershed, northern California (United States; Fig. 1A). The SFER was subject to a mobile wave of increased uplift (Furlong and Govers, 1999) that occurred in the uppermost reaches of the landscape ~3 m.y. ago and in the lowermost reaches ~1 m.y. ago (Atwater and Stock, 1998), but the resulting incision has not yet propagated through the entire river system (Foster and Kelsey, 2012). We numerically simulate the evolution of a landscape with a similar geometry and uplift history as the SFER and assess the temporal evolution of detrital erosion rates and relic landscape areas during a transient.

SETTING
The SFER drains northward, parallel to the California Coast Ranges, which were uplifted during the migration of the Mendocino triple junction (MTJ) (Zandt and Furlong, 1982). A geodynamic model of lithospheric deformation (the Mendocino crustal conveyor, or MCC, model) (Furlong and Govers, 1999) predicts that a transient wave of rock uplift due to crustal thickening and thinning propagates northward with the migration of the MTJ. This prediction is supported by sequential northward deposition of sediment eroded from emerging coastal mountains (Lock et al., 2006). On the basis of the movement of the MTJ (Atwater and Stock, 1998), a transient wave of rock uplift has passed from the headwaters to the outlet of the SFER drainage during the last ~3 m.y., which translates...
to an uplift wave migrating through the landscape with rates that range from ~25 mm/yr (Atwater and Stock, 1998) to 56 mm/yr (Engebretson et al., 1985). These estimates constrain the form and magnitude of the transient disturbance we use in our landscape evolution simulations.

As a result of this tectonic disturbance, the present-day topography and denudation rates reflect transient, post–MTJ uplift adjustment. River incision rates inferred from strath terraces (0.39–0.55 mm/yr) in the southern end of the catchment outpace denudation rates approximately by a factor of 2, which yields an increase in local relief of 0.17–0.37 mm/yr since the Pleistocene-Holocene transition (Fuller et al., 2009). Uplift rates, inferred from marine-terrace elevations mapped along the northwest Coastal Ranges south of Cape Mendocino (CM in Fig. 1A), are 0.3–1.2 mm/yr with the topography at the northern outlet uplifting faster than the upstream portions (Merritts and Bull, 1989; McLaughlin et al., 1983).

The northern California Coast Ranges are underlain by the diverse Franciscan Complex, composed of poorly consolidated mélangé as well as more competent sandstone units (Blake et al., 1985; see Fig. DR1 in the GSA Data Repository1 for lithologic and structural unit delineation). As a consequence of the fluvial incision associated with the passage of the uplift wave, hillslopes are steep and unstable, scarred by both shallow and deep-seated landslides. Though the steep slopes, mechanically weak lithologies, and infrequent, high-intensity storms (Herring, 1997) in this region result in some of the highest sediment yields observed in the contiguous United States (Brown and Ritter, 1971), the narrow, incised channel corridors inhibit long-term sediment storage.

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Footnotes:
1GSA Data Repository item 2013342, Table DR1 (10Be data, sample positions and catchment data), Figures DR1 and DR2 (maps of South Fork Eel River catchment), and Video DR1 (animation of CHILD landscape response to a wave of rock uplift), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
NUMERICAL MODELING OF DETRITAL EROSION RATES

We use the CHILD (channel-hillslope integrated landscape evolution model (Tucker et al., 2001) to track the evolving topography and denudation patterns produced by an uplift scenario similar to the predicted MCC model (cf. Furlong and Govers, 1999). Our intention is not to replicate all of the active processes or calibrate the model to the SFER system, but rather to test how basin-wide detrital erosion rates evolve during the transient response to an uplift wave. The model domain roughly mimics the SFER system. The initial condition is an elongated, steady-state watershed with uniform uplift and denudation rates of 0.1 mm/yr and a resolution of ~500 m (Fig. 1C). This initial landscape then experiences a Gaussian wave of uplift that moves from the headwaters toward the mouth at a rate of 56 mm/yr (cf. Engelbreton et al., 1985) with a wavelength of 30 km and minimum and maximum uplift rates of 0.1 and 2.1 mm/yr, respectively (see Video DR1 in the Data Repository). We illustrate results from experiments that model only fluvial denudation using the stream-power equation, \( I = K\alpha S^n \) (where \( I \) is incision rate in m/yr, \( \alpha \) is drainage area in m\(^2\), \( S \) is channel slope, and \( K, \alpha, \) and \( n \) are parameters set to 8 \( \times 10^{-7} \) m\(^3\)/yr, 0.5, and 1, respectively) (e.g., Rosenbloom and Anderson, 1994).

Basin-wide erosion rates are estimated from incision rates (averaged over 100 yr) that are output every 10 k.y. for each point on the landscape (Video DR1). Nine unique upstream catchments are delineated above nine points distributed along the modeled mainstem. The spatially averaged incision rate is calculated for each of the nine nested watersheds and averaged over two time-outputs to approximate the time scale of \( ^{10} \)Be-derived denudation rates. In the numerical experiment, the period over which erosion rates are averaged (10 k.y.) is in the range of the period over which the detrital cosmogenic data are averaged (see below).

We calculate the normalized channel steepness index, \( k_n = S/\alpha \) (e.g., Wobus et al., 2006), at every cell in the model to determine the locations of the boundary between the adjusting and relict domains in the watershed (Fig. 1D). Adjusting cells are defined by a \( k_n \) value above 1000 m. Using this boundary, we calculate the temporal evolution of the proportion of relict area in each of the nine nested watersheds.

Model Results

Each “sampling point” along the modeled mainstem exhibits a unique time series of basin-wide erosion rates in response to the uplift wave (Fig. 1F). The basin-wide erosion rate at each of the nine sampling points rises and falls over time with elevated rates persisting longer than it took the uplift wave to traverse the basin. Though the peak uplift rate was 2.1 mm/yr, the modeled basin-wide erosion rates reached maxima near 0.5 mm/yr. The downstream trend in basin-wide erosion rates depends on the maturity of the transient. Early in the transient, basin-wide erosion rates increase downstream whereas in the latter period, these rates decrease in the downstream direction (Fig. 1G; Video DR1). We find that the general temporal pattern in erosion rates at a given location is not dependent on the \( K \) value in the incision equation, but the response time varies inversely with \( K \) and the maximum erosion varies directly with \( K \).

At each of the nine sample points we also recognize a distinct pattern of how basin-wide erosion rate varies with respect to the proportion of relict landscape above that point (Fig. 1F; Video DR1). All points start as fully relict, and the downstream points are the first to start adjusting. As the erosion signal propagates through the basin, mainstem points have less and less relict area upstream. Independent of drainage area, all mainstem points follow a similar erosion trajectory as the proportion of relict area decreases. We note that the shape of the erosion trajectory with proportion of relict area is not dependent on the \( K \) value used in the incision equation.

TOPOGRAPHIC SIGNATURE OF TRANSIENCE

The extent and form of transient adjustment in the SFER was evaluated using 10 m U.S. Geological Survey and 1 m NCALM (National Center for Airborne Laser Mapping) Lidar digital elevation models, stereo aerial photos from 1976 and 1984, and field visits. These data sets enabled the delineation of a mapped boundary between adjusting and relict topography based on the location of knickpoints, fluvial terraces, contrasts in channel steepness, hillslope curvature, and surface roughness (Figs. 1A and 1B; Fig. DR2). A large, diffuse knickpoint separates the upper quarter of the SFER watershed from the incising region downstream (Fig. 1B). An extensive terrace surface is observed ~100 m above the SFER trunk channel in the middle of the basin. Its relief above the channel decreases toward the outlet and only a small fraction of the incision signal extends upstream of the mainstem knickpoint (cf. Berlin and Anderson, 2009). Most tributaries contain knickpoints, and in smaller tributaries the elevation of the most prominent knickpoint is close to that of the mainstem terrace. In larger tributaries, knickpoints have retreated further upstream and are at elevations significantly higher than the mainstem terrace. Tributaries’ relict channel profiles can be projected downstream and are found to intersect the mainstem close to the elevation of the extensive terrace.

COSMOGENIC NUCLIDE SIGNATURE OF TRANSIENCE

In the SFER, the 0.25–0.85 mm grain size fraction of river bedload was collected from active ripples every ~10 km down the mainstem. Each sample was sieved, boiled in phosphoric acid, and then treated using a procedure similar to that described in Fuller et al. (2009) with added \(^{10}\)Be carrier with a measured ratio of \(^{10}\)Be/Be = 5 \( \times 10^{-5} \). The \(^{10}\)Be/Be ratio was measured at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab, Indiana, USA) using the Nishizumi standard (Nishizumi et al., 2007). To calculate denudation rates from the concentrations, we accounted for \(^{10}\)Be production in the watershed, and the denudation rate was calculated using the online CRONUS calculator (http://crONUS.ess.washington.edu/) and the methods outlined by Balco et al. (2008) and Fuller et al. (2009).

Denudation rates increase downstream, from 0.17 mm/yr in the upper basin to 0.52 mm/yr in the lower portion of the landscape (Fig. 1B; Table DR1). Although our results agree in magnitude with several previously published cosmogenic \(^{10}\)Be denudation rate measurements bracketing our study area (Fuller et al., 2009; Ferrier et al., 2005), the downstream increase in rates we observe has not been previously reported for nested \(^{10}\)Be-derived denudation rates. Given this distribution of observed denudation rates along the mainstem (Fig. 1B), we suggest that the \(^{10}\)Be concentrations reflect the progressive rejuvenation of denudation as knickpoints migrate up the watershed and slowly encompass a greater proportion of the landscape. This adjustment provides high volumes of low-concentration sediment to the stream, diluting the low-volume, high-concentration sediment delivered from the slowly eroding relict landscape.

Modeled patterns in basin-wide erosion rates compare well with the results derived from our \(^{10}\)Be concentrations. The measured percentage of relict topography in the SFER is between 75% and 98%, confirming that the transient adjustment is in the early phase following passage of the MTJ. In addition, downstream-increasing erosion rates are only observed during the early phase of the modeled transient adjustment (Fig. 1E).

CONCLUSIONS AND IMPLICATIONS FOR \(^{10}\)Be-DERIVED DETRITAL DENUDATION RATES IN TRANSIENT LANDSCAPES

We use topographic analysis and a landscape evolution model to identify how spatially varying denudation rates across a transient landscape might be represented in \(^{10}\)Be-derived detrital denudation rates. We then test these model predictions against analytical \(^{10}\)Be-derived detrital denudation rates and find numerous similarities. We find that the time scale for landscape adjustment to a new steady state can persist much longer than the time scale of the tectonic perturbation and certainly longer than the averaging time of cosmogenic nuclide measurements. This results in a prolonged, complex pattern of erosion.
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