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Evaluating hillslope diffusion and terrace riser degradation in New Zealand and Idaho

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The relationship of sediment flux to surface slope is a predominant control on the evolution of transport-limited hillslopes. Although both linear and nonlinear sediment flux models have been proposed and widely debated, this functional relationship remains one of the outstanding questions in geomorphology. We examine degradation of fluvial terrace risers in New Zealand and Idaho in order to test the linear diffusion model and to better understand the relationship between sediment flux and slope. We implement three techniques based on the linear diffusion model, as well as a geometric scaling method that uses proportional relationships in riser geometry rather than a specific transport equation model, to assess rates of degradation. We show that techniques that utilize the riser midpoint slope as the primary metric of degradation, as opposed to the full scarp profile, offer the simplest and most reliable assessment of riser degradation. Our findings suggest that the linear diffusion model does not accurately describe terrace riser degradation, except for low-angle risers for which linear and nonlinear forms are indistinguishable. Results from the geometric scaling method show that degradation rates in both regions differ by a factor of two between equator- and pole-facing risers and that diffusion ages of Idaho risers are approximately 2 times those of New Zealand risers. Similar geometric trends in riser evolution from both regions reveal that terrace riser degradation is governed by a widely applicable relationship between sediment flux and slope.


1. Introduction

[2] Hillslope processes are fundamental to shaping the surface of the earth. In regions where erosion rates do not exceed soil production rates, soil mantled hillslopes dominate the landscape, and downslope sediment transport is governed by gravitationally driven diffusive processes.

[3] Davis [1892] and Gilbert [1877] proposed that downslope sediment transport, in transport-limited landscapes, is not controlled by slope wash or overland flow, but rather by disturbance-driven processes, such as creep or dry ravel. In such cases, downslope sediment transport is fundamentally driven by gravity and resisted by friction, such that transport rates are argued to be linearly proportional to slope (Figure 1). This linear relationship predicts that hillslopes will develop curved profile forms, with negative curvatures or convex slopes from the hillcrest to a midslope inflection point, below which erosive processes give way to deposition and positive curvatures or concave slopes.

[4] Recent studies, however, have challenged the linear flux model arguing that hillslopes do not evolve toward a curved profile form, but rather only the hillcrest or divide has a significant degree of curvature and that, with sufficient relief, hillslopes become increasingly planar with distance from the divide [Andrews and Bucknam, 1987; Anderson, 1994; Howard and Selby, 1994]. These observations have prompted development of nonlinear sediment flux models that predict sediment flux increases more rapidly for steeper slopes (Figure 1), thus producing long planar hillslopes at or near threshold angles [Andrews and Bucknam, 1987; Hanks and Andrews, 1989; Howard and Selby, 1994; Roering et al., 1999]. Such nonlinear models are argued to provide a better approximation of downslope sediment transport for hillslopes at all scales and gradients [Anderson, 1994; Fernandes and Dietrich, 1997; Roering et al., 1999, 2001a, 2001b; Jimenez-Hornero et al., 2005], whereas the linear transport function is argued to only accurately describe observed hillslope processes at low slopes (<20°) and small scales [Hanks, 2000, and references therein]. Field and theoretical evidence of the physical mechanisms that are defined by a nonlinear functional form is still limited. Consequently, the nature and analytical form of a nonlinear model is still debated.

[5] Assessment of the suitability of linear or nonlinear sediment flux models for actual landscapes has proven to be complex, in part due to the difficulty of comparing idealized numerical models to far coarser resolution measurements taken in the field. For most hillslopes in the natural world, the exact age of formation and initial geometry are unknown.
variables, so that measurements of change are typically difficult to make or speculative. Consequently, many studies have focused on small-scale hillslopes with known initial conditions, such as terrace risers (fluvial or pluvial lake) or fault scarps [Bucknam and Anderson, 1979; Nash, 1980, 1984; Hanks et al., 1984; Andrews and Hanks, 1985; Pierce and Colman, 1986; Avouac, 1993; Hanks, 2000]. These landforms provide a small-scale analog to larger hillslopes, but with more well constrained initial conditions and formation ages.

[6] Even with over a century of work examining hillslope processes and how they shape the landscape, our understanding about how these processes operate has changed modestly since the observations of Davis [1892] and Gilbert [1877]. Here we test the predictions of the linear diffusion model against an extensive, high-resolution topographic data set. Utilizing surveys of over 320 fluvial terrace riser profiles, we examine how diffusive processes degrade hillslopes and assess influences on degradation rates. We examine terrace risers incised into aggradational fill from two distinct regions: the South Island of New Zealand and Idaho, North America. Through this comparison, we examine the ability of the linear diffusion equation to accurately describe the degradation of terrace risers in both regions. We implement four different techniques to assess the relationship between sediment flux and riser slope; three methods based on the linear diffusion model and a fourth method that utilizes geometric relationships as opposed to a particular diffusive model. We compare north and south facing terrace risers over a wide range of riser heights to evaluate the influence of riser orientation and scale on rates of degradation. Through this comparative analysis, we are able to identify fundamental relationships between sediment flux and surface slopes and provide a rigorous assessment of the methods used to analyze hillslope processes.

2. Background and Study Area

2.1. Fluvial Terrace Formation

[7] We focus on suites of fluvial terraces that were incised into aggradational fill in New Zealand and Idaho. Fluvial terrace risers provide a small-scale analog to larger hillslopes, but have the advantage of being formed at a known initial geometry in which the riser lies at the angle of repose. In addition, because these terraces are cut into unconsolidated material, they are usually transport limited, thereby eliminating most constraints attributable to “weathering out” or “loosening” of material [Gilbert, 1877; Culling, 1960; Carson and Kirkby, 1972]. The modern-day geometry of terrace risers can be accurately measured at high resolution, and the initial geometry can often be closely estimated from empirical data or from field measurements of recently formed risers from the same region. In some cases, an estimate for the age of formation can be determined from absolute dating methods or through relative dating and correlation with climatic events. Additionally, terrace riser degradation occurs in a nearly closed system with little addition or removal of material as it is transported from the upper tread, down the riser, and deposited on the lower tread. Because fluvial terraces occur in high densities in many areas around the world, numerous individual riser profiles can commonly be measured over a wide range of scales and orientations within a compact area. Suites of fluvial terraces, cut into an aggradational fill, often have the advantage of all being composed of similar material. Such homogeneity removes a key and typically poorly constrained source of variability. If two risers were composed of different unconsolidated material (grain size, shape, or texture), then there is little reason to expect them to have the same initial geometry or to degrade at the same rate. For example, both linear and nonlinear models have been advanced to describe the same pluvial terraces that were cut by Lake Bonneville in Utah [Bucknam and Anderson, 1979; Hanks and Andrews, 1989; Mattson and Bruhn, 2001]. Pelletier et al. [2006], however, pointed out that differences in slopes and heights for these terraces are largely a function of textural variations. Fluvial terraces cut into spatially similar aggradational fill, on the other hand, avoid the uncertainty imposed by varying compositional textures and thus allow for more constrained comparisons and more reliable assessment of the influence of other parameters, such as height, slope, and orientation.

[8] Fluvial terrace risers, such as those in this study, are commonly formed by a three-step process. Initially, a river bevels laterally into older aggradational fill. Because such fill is typically weakly consolidated, lateral planation can occur over short time intervals during a period of relatively stable base level. Subsequently, incision by the formative river occurs due to some external control, such as a lowering of base level or changes in discharge or sediment fluxes. This incision isolates the previously beveled surface, which now forms a terrace tread above the newly incised river plane. The proximal and distal margins of this newly abandoned surface are defined by risers that connect it to the next lowest and highest surfaces, respectively [Bull and Knuepfer, 1987] (Figure 2). Following this abandonment, oversteepened terrace risers ravel to a stable angle of repose, generally 28°–37° depending on the characteristics of the aggradational fill. Although poorly constrained, attainment of the angle of repose in unconsolidated gravels is assumed to occur within 10–100 years [Wallace, 1977; Avouac, 1993], and subsequently diffusive slope processes are assumed to dominate slope degradation. The morphologic age of a fluvial terrace riser is the time since diffusive processes have become the active mechanism for morphologic change. This time is commonly
assumed to closely correspond to the time of river abandonment of the lower tread surface.

2.2. Diffusive Hillslope Degradation

The downslope diffusion of material, which degrades the initial terrace form, has most commonly been modeled as a linear relation between sediment flux and surface gradient (Figure 1). Culling [1960] and Kirkby [1971] quantified the ideas of Davis [1892] and Gilbert [1877] by implementing the linear, slope-dependent sediment flux equation

$$q_s = \kappa \frac{\partial h}{\partial x}. \quad (1)$$

where $q_s$ is downslope sediment flux in units of volume (m$^3$/m) per contour length (m) per time (t), $\kappa$ is the diffusivity constant (m$^2$/t), which determines the base rate of sediment flux, $x$ is the horizontal distance along the slope profile, $h$ is the vertical height of a given point along the profile, and $\partial h/\partial x$ is the surface gradient.

Nonlinear sediment flux equations range from simply power function of slope [Andrews and Bucknam, 1987; Nash and Beaufion, 2006] to more complex nonlinear functions that approximate the linear sediment flux function at low angles, but rapidly approach infinite flux as slope increase to a threshold slope (Figure 1) [Hanks and Andrews, 1989; Roering et al., 1999; Matson and Bruhn, 2001]. Nonlinear threshold functions such as

$$q_s = \kappa \left( \frac{\partial h}{\partial x} \right)^2, \quad (2)$$

where $S_c$ is the critical or threshold gradient, closely approximate the linear flux function for low gradients but increase rapidly as gradient approaches the threshold, $S_c$ (Figure 1).

Due to the wide debate over whether sediment flux is linearly or nonlinearly proportional to surface gradients, we focus on testing the linear diffusion equation to determine under what conditions it accurately models terrace riser degradation or if a more complicated sediment flux equation is necessary.

[12] The continuity equation

$$\frac{\partial h}{\partial t} = \frac{\partial q_s}{\partial x}, \quad (3)$$

relates the change in surface elevation through time, $\partial h/\partial t$, at a given point to the difference between the flux of sediment into and out of that point. Combining the continuity equation and the linear sediment flux equation yields the linear diffusion equation

$$\frac{\partial h}{\partial t} = \kappa \left( \frac{\partial^2 h}{\partial x^2} \right), \quad (4)$$

which relates the rate of change in surface elevation to hillslope curvature. This linear diffusion equation has been used in many cases to model hillslope diffusion and scarp degradation [Colman and Watson, 1983; Hanks et al., 1984; Ahnert, 1987; Fernandes and Dietrich, 1997].

Hanks and Andrews [1989] provided a solution to the linear diffusion equation based on the initial geometry of terrace risers. Their solution describes the surface height of a terrace riser along a profile perpendicular to its strike, such that

$$h(x, t) = (\alpha - b) \left( \frac{x + a}{(\alpha - b)^2} \right) \exp \left( -\frac{(x + a)^2}{4\kappa t} \right) - \exp \left( -\frac{(x - a)^2}{4\kappa t} \right) + \frac{(\alpha - b)}{2} \left\{ \left( x + \frac{a}{(\alpha - b)} \right) \text{erf} \left( \frac{x + a}{(\alpha - b)} \sqrt{4\kappa t} \right) - \left( x - \frac{a}{(\alpha - b)} \right) \text{erf} \left( \frac{x - a}{(\alpha - b)} \sqrt{4\kappa t} \right) \right\} + bx,$$

where $\alpha$ is the initial riser gradient, $b$ is the far-field gradient of the terrace tread, and $2a$ is the height of the riser (Figure 2). The reduced initial gradient, $\alpha - b$, is used to mathematically account for the influence of the far-field slope on terrace degradation [Hanks and Andrews, 1989]. The derivative of equation (5) with respect to distance along the profile, $x$, describes the gradient profile. Again, to accurately account for the influence of the far-field slope, the function is modified to produce a profile of the reduced gradient, $\partial h/\partial x - b$ [Hanks and Andrews, 1989; Pelletier et al., 2006]

$$\frac{\partial h(x, t)}{\partial x} - b = \frac{(\alpha - b)}{2} \left( \text{erf} \left( \frac{x + a}{(\alpha - b)} \sqrt{4\kappa t} \right) - \text{erf} \left( \frac{x - a}{(\alpha - b)} \sqrt{4\kappa t} \right) \right). \quad (6)$$

When the riser height ($2a$) and far-field gradient of the treads ($b$) are measured in the field, equations (5) and (6) can be used to produce synthetic elevation and gradient profiles or can be inverted and solved directly to match observed data by changing the values of $\alpha$, $\kappa$, and $t$. In many cases neither the age nor diffusivity is known. In such cases, the unknown variables are combined into a single variable $\kappa t$, diffusion age, with units of m$^2$, which can be solved for by inverting...
2.3. Study Sites

Terrace riser profiles were surveyed along the Ohau River on the South Island of New Zealand (Figure 4) and along the Big and Little Lost Rivers, Idaho, USA (Figure 5). Following geomorphic mapping (see auxiliary material), relative age relationships were determined based on correlating surfaces from aerial photographs (USGS 1:24000 7.5 min DOQ), DEM-derived elevation profiles, field observations, and crosscutting relationships. Because terrace risers are assumed to have formation ages similar to the time of abandonment of their lower tread, risers in this study are named by the relative age of their lower tread surface in chronological order of formation. For instance, a riser that connects a T4 lower tread to a T3 upper tread would be classified as a T4 riser. In New Zealand, the Ohau River has incised into unconsolidated glacial outwash forming a series of north and south facing inset terraces. The outwash was deposited ~19–22 ka, during the Mt. John glacial advance, the largest advance of the last glacial period [Schaefer et al., 2001, 2006; Amos et al., 2007; Doughty et al., 2009; Putnam et al., 2009]. Prior to ~18 ka, nearby glacier termini retreated 1–5 km and ~25 m of incision occurred down to the T2 (Tekapo advance) terrace at our study site (see auxiliary material). Incision was, therefore, rapid: ~10 m/ky. In the next ~4–5 ka [Doughty et al., 2009], glacier termini retreated another 15–35 km [Porter, 1975]. We argue that, during this interval, an additional 30–35 m of incision (at 6–9 m/ka) likely occurred down to ~10 m above the modern river, which is equivalent to our lowest surveyed terraces. Hence, we interpret all these terrace risers to have formed between 18 and 13 ka. Geomorphic mapping of the study site reveals eleven different terrace levels (Figure 4). In total 140 terrace profiles were collected from north and south facing terrace risers, ranging in height from ~1 to 60 m at an elevation of ~500 masl and situated at least 10 m above the modern river.

In Idaho, terrace data were collected from the Ramshorn and Mormon glacial outwash fans on the east side of the Big and Little Lost Rivers, respectively (Figure 5). On both fans, westward flowing fluvial channels have incised into the outwash material, thereby forming an inset series of north and south facing terraces. The Ramshorn fan is the site of the widely cited Pierce and Colman [1986] study that was one of the first to recognize the influence of slope orientation and microclimate on rates of degradation. Both the Ramshorn and Mormon fans are composed of outwash deposited during the Last Glacial period. The terraces at this site are interpreted to have formed by lateral planation and climate-induced incision over a short period of time around 15 ± 4 ka [Pierce and Scott, 1982; Pierce and Colman, 1986]. Geomorphic mapping in this region revealed four terrace levels on the Ramshorn Fan and three levels on the Mormon Fan (Figure 5). In total, 180 terrace profiles were surveyed on the Ramshorn and Mormon Fans, where north and south facing terrace risers with a range of heights from ~1–13 m were measured at an elevation of ~1800 masl.

The texture and composition of unconsolidated fills in which terraces are formed influences the initial riser geometry and rates of diffusion. Terraces in this study comprise fluvial...
Figure 4. Location map of New Zealand study site. The yellow lines show the locations of terrace riser profile surveys. Each riser is assigned the age of the lower tread surface. Inset map shows South Island of New Zealand with the study site (red star).

ally deposited, poorly sorted, clast–supported glacial outwash. We found no evidence of more than one aggradation and incision cycle in any suite of risers. In New Zealand, the terrace clasts are composed of greywacke and low-grade metamorphic rocks from the Southern Alps. The Idaho terraces comprise predominantly Paleozoic carbonate rock from nearby ranges. In both regions, clasts are subangular to sub-rounded, but clast shape in Idaho is more elliptical to blocky with little or no platy material. At two sites in New Zealand and one in Idaho, 100 measurements of clast long-axis length reveal strikingly similar mean clast size and standard deviation of $\pm 1.2\varphi$ and $\pm 1.1\varphi$, respectively (see auxiliary material). Because only thin, variable soils and loess exist in both regions, terraces were correlated primarily based on height, position, and continuity.

In addition to compositional contrasts, differences in climate, biota, and the dominant diffusive processes (e.g., creep, dry ravel) can affect diffusivity. Climatic effects on the diffusion processes are influenced by regional temperature and precipitation patterns and are modulated by localized riser slope and orientation which, in turn, affect the amount of incident solar radiation, vegetation, and water content. Past studies, for example, suggest that greater amounts of radiation increase diffusion rates due to the drying of material and reduced cohesion [Pierce and Colman, 1986]. Both of our sites are located in temperate to semiarid grasslands, $\sim 43^\circ$ from the equator. At present, both sites receive precipitation that is evenly distributed throughout the year, but the New Zealand site receives about 2.5 times more precipitation than the Idaho site (see auxiliary material). In contrast, Idaho experiences both hotter summers and colder winters. We estimate that freeze–thaw cycles occur during $\sim 6$ months/year in Idaho, but only $\sim 3$ months/year at our New Zealand site. Despite these known climatic contrasts, we have no direct way to calibrate the relative effects of precipitation or freeze–thaw cycles on diffusivity, nor how they might have changed in the past.

Likewise, both study sites are dominated by grasslands and appear similar today, but their floral history is not well known. Even over the past few decades, the patterns of vegetation appear to have changed on the Idaho terrace risers (see auxiliary material). Hence, long-term similarities or contrasts between the sites are difficult to evaluate. One clear biotic difference between the sites is the absence in New Zealand of burrowing mammals (except two species of bat) until the past millennium. To the extent that burrowing promotes downslope sediment transport rates [Black and Montgomery, 1991; Gabet, 2000], we expect a far greater effect in Idaho.

Despite the specific differences among the study sites, they are quite similar in a more global context. They both represent semiarid, midlatitude, temperate sites. Both regions have late glacial north and south facing terrace risers that are composed of near equivalent glacial outwash material and encompass a wide range of riser heights. Comparisons of terrace riser degradation from these latitudinally antipodal sites yield insights on intrinsic factors that may influence hillslope processes globally, as well as on local factors that drive differential degradation at each site.

2.4. Survey Site Selection

In both study regions, survey sites were chosen that appeared to represent characteristic riser slopes. All surveyed risers have elevation profiles with no inconsistent or unusual changes in slope. In New Zealand, fluvial modification, identifiable in the aerial photographs by the irregular upper tread edge (Figure 4), appears to be related to the remnant microtopography from the paleochannel network developed during deposition of the outwash material. Such irregularities appear more pronounced on older terrace risers that are connected to more expansive upper treads. We interpret this riser modification to result from localized channeling of surface flow that is restricted to riser sections that happen to intersect paleochannel topography. Such regions were avoided as survey sites. No evidence of mass movement processes, such as slumps or shallow landslides, were observed on the New Zealand risers. Similarly, in Idaho, mass movements appear very limited. The only slump that we found occurred directly downslope from a small channel debouching onto the fan surface. We observed no fluvial modification of the terrace risers on the Idaho fans.

2.5. Terrace Surveys and Data Collection

High-resolution surveys of terrace profiles were measured using a Trimble 4700 differential global positioning system (dGPS). Elevation measurements were collected every $\sim 0.5 – 1$ m along the riser profile, yielding $\sim 50–
100 dGPS measurements on a typical profile. All terraces were surveyed perpendicular to the strike of the riser plane. Additionally, survey measurements were continued well beyond the terrace riser along the same bearing as the riser profile in order to measure the far-field gradient to the terrace tread. These far-field gradient values ranged from $-0.05$ to $0.09$. To permit side-by-side numerical comparison and scaling, all surveyed terrace risers were aligned such that the riser midpoint was located at distance $x = 0$ (Figures 2 and 6). Based on the elevation profiles (Figure 6), slope and curvature profiles were calculated with a best fit linear regression to a nine-point moving window (Figure 7). The nine-point window provides an optimum analysis range that reduces noise in the data that causes anomalous spikes, while still avoiding overdamping the slope and curvature values (Figure 7). From these profiles, metrics of midpoint gradient, terrace riser height, far-field gradient, and maximum and minimum curvature can be measured (Figures 2 and 7).

3. Results

This study has two foci. First, we test the ability of the linear diffusion model to accurately describe terrace riser degradation by comparing predicted results from the linear diffusion model to patterns observed in the actual data. We use results from three linear diffusion based methods to test the applicability of the model and to assess variations in degradation patterns within and between the two regions. Second, we implement a geometric scaling method that uses proportional relationships in terrace geometry, rather than a specific sediment flux equation, to derive relative differences in formation age or diffusion rate. Based on these proportional differences, and assumptions about terrace riser formation ages, we assess relative differences in degradation rates between north and south facing risers within each region and make interhemispheric comparisons.

A comparison of the maximum (largest positive) and minimum (largest negative) curvature values for each of the terrace profiles reveal a near equivalence (Figure 8) that is indicative of diffusive processes, as opposed to modification by overland flow or slope wash [Kirkby, 1971; Carson and Kirkby, 1972; Pierce and Colman, 1986]. It must be noted that this is only a first-order comparison. Although the
numerical models would predict an exact 1:1 curvature relationship for diffusive processes, actual field measurements contain significant noise due to microsurface topography, which could easily cause local deviations of ±5–10 cm [Mattson and Bruhn, 2001; Pelletier et al., 2006]. Furthermore, the smoothing window has a known damping effect on regions with the greatest absolute curvature. Given the expected noise and damping, this approximate equivalence is, therefore, impressive and suggests that diffusive processes dominate geomorphic modification of risers in both regions.

Terrace geometry, in all applied methods, is defined by riser height and the maximum gradient located at the riser midpoint. One benefit of using these metrics is that they are reliably and easily measured on all terrace risers. Although riser height does not change at any stage in terrace evolution, riser gradient decreases through time (Figures 2 and 3). A lag time exists, however, between when a riser starts to degrade through diffusive processes and when the midpoint gradient will decreases by a measurable amount (Figure 3). This lag is most pronounced for tall scarps and can lead to anomalously low calculated diffusion ages [Pelletier et al., 2006]. In all of the applied methods, we try to assess when each method is most applicable for use and when methodological limitations require extra precautions. Pelletier et al. [2006] provided an excellent analysis of both the uncertainties in many of these techniques as well as the influence of noise in the observed data and uncertainty in the initial conditions. Here, we focus on applying these methods to actual data. By using these methods in concert with each other, we are able to constrain

Figure 7. Elevation, gradient, and curvature profiles. Thin line with black dots shows the measured elevation data and the optimum calculated gradient and curvature profiles using a nine-point smoothing window. Results of other smoothing window sizes are shown for the gradient and curvature profiles (only regions with continuously positive slope data are displayed). A nine-point window was assessed as optimal to reduce the signal-to-noise ratio without overdamping the gradient and curvature values.

Figure 8. Maximum and minimum curvature. Plots of maximum versus minimum curvature for each riser profile reveal a close correspondence in the degree of curvature between the upper and lower portions of the riser, indicative of diffusive processes. Outliers from the general 1:1 relationship in both regions are mostly from small risers (<2 m high) where noise-to-signal ratios are highest.
variables which otherwise may need to be estimated or simply assumed.

3.1 Linear Diffusion Modeling Methods

3.1.1 Slope Offset Method

Early studies of fault and terrace scarp degradation identified a correlation between the height, or offset, of the scarp and the maximum gradient located at the midpoint of the scarp riser [Bucknam and Anderson, 1979; Hanks et al., 1984; Hanks and Andrews, 1989]. The slope offset method analyzes the relationship between the reduced maximum gradient (riser slope minus the far-field tread slope; Figure 2) and riser height for an entire collection of terraces from the same region [Hanks and Andrews, 1989]. Due to the increases in volume with increased riser height, higher risers take longer to degrade and, therefore, maintain steeper slopes longer than do smaller risers. The linear diffusion model predicts a specific relationship between riser height and reduced midpoint gradient, which is dependent on the regional diffusion age and reduced initial gradient, as described by equation (6). The slope offset method compares relationships predicted by the linear diffusion model to patterns in populations of observed riser data (Figure 9). Regardless of the regional diffusion age, the theoretical relationship of reduced gradient to height asymptotically approaches the reduced initial gradient at large riser heights. Therefore, in data sets that include a wide range of riser heights, particularly tall or young risers, this asymptotic trend should be observable (as seen for New Zealand terraces > 30 m high; Figures 9a and 9b), and the reduced initial gradient can be estimated from the reduced maximum gradient of the tallest risers. Characteristic curves can be created from equation (6) using both this derived reduced initial gradient and a range of diffusion ages (Figure 9). The linear diffusion age for an entire terrace population can be estimated by the best fit synthetic curve to the observed data [Pierce and Colman, 1986; Hanks and Andrews, 1989; Pelletier et al., 2006]. This method requires a sufficiently large population of riser measurements in order to define a regional trend and assumes all risers in a population have the same diffusion age and initial angle.

Relative to individual theoretical diffusion age curves, variations in the reduced initial gradient and/or diffusion age will result in a wide scattering of data points beyond that attributed to noise in the field survey data. Consequently, terrace risers need to be grouped according to factors that control the reduced initial gradient and diffusion age. The most influential of these is the age of the riser. For risers of the same age, climatic, compositional, and biological factors can affect reduced initial gradients and diffusion rates. Therefore, risers should be separated based on orientation, due to its effect on incident solar radiation and diffusion rates [Pierce...
and Colman, 1986], compositional texture [Simons and Albertson, 1963; Statham, 1974], and any known biological influences [Black and Montgomery, 1991; Gabet, 2000; Gabet et al., 2003; Yoo et al., 2005]. The consequence of not separating terraces by these influential factors is a larger scatter of data points relative to the predicted curves. In cases where the influence or presence of these factors is unknown, the amount of scatter in the data set may provide information into how much variation due to external factors is present in a population of terrace risers.

29 We applied the slope offset method to north and south facing terraces in both New Zealand and Idaho (Figure 9). The data were separated by region and orientation to account for regional differences in diffusion rates, as well as the influence of incident solar radiation and microclimate on risers of different orientations [Pierce and Colman, 1986]. Riser heights reach up to ∼60 m in New Zealand, whereas in Idaho, the maximum height is ∼13 m. The wide range of terrace heights in New Zealand provides a well-defined relationship between reduced maximum gradient and terrace height (Figures 9a and 9b). Overall, the data show that, as riser heights increase, the reduced maximum gradients asymptotically approach a uniform gradient. For both north and south facing risers in New Zealand, we define the reduced initial gradient to be equal to the average reduced maximum gradient of the largest (>35 m) terrace risers in the region: 0.68 for south facing risers and 0.62 for north facing risers (Figures 9a and 9b). Such gradient differences might be expected based on contrasts in incident solar radiation, which can cause disparities in soil cohesion and moisture content.

30 In Idaho, terrace risers only range up to ∼13 m in height and do not reveal a clear plateau in reduced maximum gradient values (Figures 9c and 9d). Because the initial gradient must be greater than or equal to the current riser gradient, we use the reduced maximum gradient of the steepest and tallest scarp from both orientations as the best estimates for the reduced initial gradients; the terrace risers in Idaho have estimated reduced initial gradients of 0.60 and 0.59 for north and south facing risers, respectively. While acknowledging the limitations of the Idaho data, we suggest that our method for estimating the reduced initial gradient provides a minimum value for the initial riser geometry.

31 In addition to the initial geometry, terrace riser evolution is controlled by the diffusion age. We assume that diffusivity, $\kappa$, remains constant. In this case, the relation of observed data to predicted curves should vary only with differences in formation age. Geomorphic mapping of terraces shows their relative ages (Figures 4 and 5). No correlation exists between riser height and relative age in either study site (Figure 9). If a considerable time difference existed between the formation of the different terrace sets within each region and orientation, then risers of the same height, but different relative ages, should display significantly different reduced maximum gradients because older risers should have evolved to lower gradients than younger risers of the same height. To assess the similarity of reduced maximum gradients for risers of similar heights but different relative ages, we determined the mean and standard deviation of the reduced maximum gradient for all risers of a given relative age in binned height increments of 5 m for New Zealand risers and 1 m for Idaho risers (Figure 10). This analysis allows for
a statistical comparison of reduced maximum gradients for terrace risers of similar heights but of different relative ages. The data show that terraces of the same height, within either region, have similar reduced maximum gradients regardless of the relative age of the terrace risers (Figure 10). Although we do not dispute that suites of terrace risers in both regions were formed incrementally in time, such uniformity in reduced midpoint gradients suggests that all terraces within a given region were formed over a sufficiently short period of time that we cannot resolve systematic temporal effects. Hence, we treat all risers from a given region as having the same formation age.

[32] This analysis of reduced maximum gradients and riser heights serves to improve constraints on initial riser geometries and allows for a quantified comparison of observed data and curves predicted by the linear diffusion equation. For risers of the same age, initial gradient, and diffusivity, we expect the observed data to follow synthetic curves predicted for a given diffusion age. In all four subdivisions of our data, however, the data as a whole define gentler trends than the theoretical curves (Figure 9), suggesting that diffusion age increases with riser height. A few New Zealand risers < 5 m high yield data resembling the patterns predicted by the linear diffusion model (Figures 9a and 9b). When the entire data from a given-aged suite of terrace risers are examined, many riser suites span too narrow a range of heights or have data that are too noisy to reveal whether diffusion ages clearly change. For several riser sets that encompass a broader range of heights, however, diffusion ages clearly become greater for higher terraces (see N facing T10 and S facing T8 profiles in NZ, for example: Figures 9a and 9b). Given that these sets of terrace risers are assumed to be everywhere the same age, these trends require higher degradation rates on higher terraces and, consequently, are indicative of a nonlinear relationship between sediment flux and terrace riser slope. Such nonlinear sediment fluxes result in slope offset patterns whereby larger risers correspond to synthetic curves of greater diffusion age, similar to the data presented here [Pierce and Colman, 1986; Hanks and Andrews, 1989; Hanks, 2000].

3.1.2. Midpoint Slope Inversion Method

[33] The slope offset method uses an entire population of terrace risers to determine the regional degradation parameters (i.e., initial gradient and diffusion age), but does not yield a unique result on a profile-by-profile basis. The midpoint slope inversion method uses the measured riser height, far-field slope of the treads, reduced initial gradient, and reduced maximum gradient of individual risers to calculate a value for diffusion age (equation (7)) [Hanks and Andrews, 1989; Pelletier et al., 2006]. This method allows for analysis and comparison of diffusion age values for individual terrace risers. For risers of the same age experiencing the same external influences, the linear diffusion model predicts that diffusion age should be constant, irrespective of riser height.

[34] In New Zealand and Idaho, we calculate the diffusion age of individual terrace risers from equation (7) (Figure 11) by using the reduced initial gradients determined by the slope offset method. Their different initial geometries require us to subdivide both regions into north and south facing risers. Our calculated diffusion ages reveal a positive correlation between diffusion age and riser height (Figure 11). Due to the large scatter in all data sets in both New Zealand and Idaho, no statistically significant difference exists between north and south facing risers in either region (Figure 11). Nonetheless, all four data sets show an increase in diffusion age over the full range of heights.

[35] As discussed earlier, we argue that our data-based estimates for reduced initial gradients represent a minimum estimate of the true reduced initial gradient. Pelletier et al. [2006] showed that such underestimations would reduce the calculated diffusion ages of large risers from their actual values. Because our diffusion ages increase with riser height, despite using a minimum estimate of the reduced initial gradient, we deduce that this trend is not an artifact of the choice of reduced initial gradient.

[36] Any change in diffusion age with height should result from differences in age, diffusivity, or the relationship of sediment flux to slope. For each region, we have argued that all risers were formed over a short period of time and showed that there is no correlation between age and height. In addition, by subdividing risers according to region and orientation, we assume we have separated risers by equivalent external influences (e.g., climate, insolation, biota), and thus diffusivity values should be similar within each subgroup.

Figure 11. Diffusion age calculated from the midpoint slope inversion method for (a) New Zealand risers (inset shows a more detailed view for risers < 25 m) and (b) Idaho risers. Risers with reduced maximum gradients larger than the estimated reduced initial gradient result in unrealistic, negative diffusion ages and have been omitted from these plots. All data sets show an increase in diffusion age with riser height indicative of nonlinear sediment flux.
Hence, the prominent increase in diffusion age with height for risers of all scales can be inferred to result from a nonlinear relationship of sediment flux to slope.

3.1.3. Full Scarp Modeling

Both the slope offset method and midpoint slope inversion method rely on the terrace riser height and midpoint gradient to determine the regional or individual diffusion age. Morphometric change driven by diffusion is focused on the portion of the riser with the greatest curvature, as described by equation (4), such that changes in surface form start at the intersection of the riser with the upper and lower treads. Only as the riser degrades do changes in surface form migrate toward its center (Figure 3). The full scarp modeling method analyzes the shape of the entire riser profile and compares it to full profiles modeled by the linear diffusion equation [Avouac, 1993; Arrowsmith et al., 1998; Mattson and Bruhn, 2001; Pelletier et al., 2006]. An optimal model fit can be found with respect to either the measured elevation profile or slope profile based on equations (5) or (6), respectively. Here we use the slope profile due to its greater simplicity and the fact that all variables in equation (6) can be measured in the field, except for the reduced initial gradient and diffusion age. Using a parameter search, the best fit to the measured data can be defined as the combination of reduced initial gradient and diffusion age that produces a modeled slope profile fit with the lowest error (Figure 12). The intent of this method is to reduce the bias imposed by estimating or assuming initial conditions or spatially uniform diffusivity. [Mattson and Bruhn, 2001; Pelletier et al., 2006].

[38] The results of the full scarp modeling method for both study sites yield a similar, but far less well defined, relationship between modeled diffusion ages and terrace heights (Figure 13) as the midpoint slope inversion method (Figure 11). Diffusion ages show a general increase with increased riser height, but significant dispersion of diffusion ages exists for all riser populations. Such dispersion limits the ability to define significant trends in the data. No statistically significant difference exists between equator- and pole-facing data in either region (Figures 13a and 13b). The general increase in diffusion age with height contradicts the uniform diffusion age predicted by the linear diffusion model and again implies a nonlinear sediment flux for both study sites. In addition to diffusion age, the full scarp model finds the reduced initial gradient that yields the best fit to the observed data (Figures 12c–12d and 13c–13d). For risers < 20 m in both regions, the modeled reduced initial gradients vary widely over the full range of the parameter search (0.2–1.8). This instability in the modeled reduced initial gradients is in part due to the insensitivity to initial geometric conditions for later stages of riser degradation. This effect has been explained by Hanks and Schwartz [1987], who showed that the reduced maximum gradient of all scarps converges to

![Figure 12. Full scarp modeling of gradient profiles. (a) Black lines show the best modeled fit to the observed data (asterisk). Inset plot shows the corresponding elevation profiles for each example riser. (b–d) Gray scale plots show the RMSE of the model fit in parameter space. Darker colors correspond to lower RMSE and better modeled fits. The white circles identify the combination of diffusion age and reduced initial gradient that produce the best fit to the measured data. Note that only the highest riser has a well-constrained fit.](image-url)
simply low gradients after a significant period of time, regardless of the initial geometry. This evolutionary convergence of all risers limits the ability of any model to differentiate the true initial conditions of highly degraded terrace risers [Hanks and Schwartz, 1987; Hanks, 2000]. Due to their lower volumes, smaller risers reach advanced evolutionary stages faster, where further degradation is independent of the initial conditions. In such cases, the observed reduced gradient profile data can be equally well fit by a range of reduced initial gradient values (Figures 12b and 12c). In contrast, large New Zealand risers (>35 m) show near uniform reduced initial gradient of ∼0.6 (Figure 13), which is in close agreement with the reduced initial gradient determined from the slope offset method. These uniform reduced initial gradients show that large risers in New Zealand are still in an early evolutionary stage and predictions about riser degradation are still sensitive to the reduced initial gradient value. These results also highlight the strong influence of terrace riser evolutionary stage on the model’s ability to assess initial riser geometry. Examination of the best fit RMSE for all profiles in this study (Figures 13e and 13f) shows no systematic difference in the ability of the model to find a reasonably good fit to large or small terrace risers in either region or orientation.

Results of the full scarp modeling indicate that by using parameter searches, we are able to closely match modeled slope distributions to observed data over the entire length of terrace riser profiles. The value of the best fit parameters, however, may be unrealistic in nature, particularly for small or old risers. Diffusion ages for both regions again show an increase with riser height indicative of a nonlinear sediment flux. This method, however, produces wide variability in diffusion ages, due in part to the instability of the determination of the reduced initial gradient for highly degraded risers. Caution should, therefore, be taken when interpreting model results, particularly for highly degraded risers whose profiles may be equally well modeled by multiple solutions to the linear diffusion equation.

3.2. Geometric Scaling Relationships

The methods previously discussed attempt to match the observed geometry of river terrace risers to the geometry predicted by the linear diffusion model. As our results clearly indicate, however, riser degradation in our study sites is not well reproduced by models dependent on a linear sediment flux function. Nash [1980, 2005] developed an alternative method for “morphologically dating” terrace scarps based on
Figure 14. Schematic illustration of the degradation of two geometrically similar, triangular objects. Triangles have illustrative simplicity, but the geometric relations hold true for any geometrically similar objects, such as terrace risers. Two risers of different heights \( H_1 \) and \( H_2 \) degrade from their initial gradients \( \theta_1 \) to some lower gradient \( \theta_2 \) over two different lengths of time \( T_1 \) and \( T_2 \), if diffusivity, \( \kappa \), is the same for both risers. The ratio of the time it takes the two risers to degrade to a given slope, \( \theta_2 \), is proportional to the ratio of cross-sectional area: \( (T_2/T_1) = (H_2/H_1)^2 \). If the time required for both risers to degrade from \( \theta_1 \) to \( \theta_2 \) is the same, the proportional difference in the diffusivity is defined as \( (\kappa_2/\kappa_1) = (H_2/H_1)^2 \) (see text for further discussion).

scaling relationships of geometrically similar hillslopes. The method utilizes ratios of geometric change to produce a ratio of the relative length of time that hillslopes have been degrading. In theory, this method is applicable to all geometrically similar hillslopes composed of unconsolidated or transport-limited material, as long as sediment flux is solely a slope-dependent function, either linear or nonlinear, that is completely independent of time and scale. The advantage of this geometric scaling method is that it does not rely on fitting a model to observed data, but rather uses simple geometric relationships to arrive at proportional differences in degradation times or rates.

[41] The geometric scaling method is based on an ergodic substitution of changes in shape for changes in time or degradation rate. Fluvial terrace risers with the same initial geometry are predicted to evolve through the same degradational phases, if flux is solely proportional to slope [Nash, 2005]. Thus, for a set of terrace risers of the same age, the changes in geometry for risers of different scales (i.e., heights) exactly mimic the changes in geometry with time for a set of risers of a fixed scale. The rate at which a riser evolves through degradational phases, however, is dependent upon the diffusivity, \( \kappa \), and the riser’s scale or size. Because sediment flux represents the volume of material moved per unit contour per time and is proportional to the diffusivity, the relative rate at which risers degrade, or reduce midpoint slopes, is a function of riser volume.

[42] Here we build upon this geometric method in order to compare the degradation of terraces of the same age but within different erosional regimes. Nash’s [2005] analysis was based on a 3-D geometric form, such as a cone, in which the volume increased as the cube of the height, whereas contour length increased linearly with height. Because we are considering fluvial terrace riser profiles in this study, we cast them as 2-D features for which cross-sectional area \( A \) increases as the square of the height \( H \). This transposition from 3-D analysis to 2-D analysis is possible because sediment flux has units of volume per time per contour length, which results in units of area per time. In 2-D analysis, we simply remove the contour length dimension and only consider the cross-sectional profile (Figure 14). Therefore, due to its greater area, a higher riser requires more time than a shorter one to degrade to a lower slope. If two terrace risers have the same diffusivity, \( \kappa \), then because \( \kappa \) is in units of area/time \((A/T)\), we can express their equivalence:

\[
\frac{k_1}{T_1} = \frac{k_2}{T_2} = \kappa.
\]

[43] Rearranging equation (8),

\[
\frac{T_2}{T_1} = \frac{A_2}{A_1}.
\]

Because the ratio of cross-sectional areas is equal to the square of the ratios of terrace heights, \( (H_2/H_1)^2 \), we can rewrite equation (9) as

\[
\frac{T_2}{T_1} = \left( \frac{H_2}{H_1} \right)^2.
\]

This yields a predictable ratio of riser age and height in a regime of uniform diffusivity [Nash, 2005]:

\[
T_1 H_1^{-2} = T_2 H_2^{-2}.
\]

Similarly, if the time of formation, \( T \), of both risers is the same but the diffusion rates, \( \kappa_1 \) and \( \kappa_2 \), differ, equation (8) can be rewritten such that

\[
\frac{\kappa_2}{\kappa_1} = \left( \frac{H_2}{H_1} \right)^2.
\]

These equations permit either a calculation of the ratio of terrace ages, if their diffusivity is known to be equivalent (equation (10)), or a calculation of their diffusivity ratio, if they were formed at the same time (equation (12)). These equations only hold true, however, if the risers being compared are geometrically similar, such that they have the same initial geometry and evolve through the same degradational phases based on the same functional relationship of sediment flux to slope. Notably, individual terrace risers do not degrade in a self-similar manner. Rather, all risers with similar initial conditions, diffusivities, and external inputs will pass through geometrically similar phases of evolution (similar to the triangles in Figure 14).

[44] Each evolutionary phase of degradation is the unique result of specific values of time, height, and diffusivity. The simplest and most commonly used metric of terrace degradation is the maximum slope or midpoint slope. For any set of geometrically similar terraces, semilog plots of the maximum slope versus \( H^{-2} \) should reveal a linear data array if the assumptions of the geometric analysis are met, including spatially and temporally uniform diffusivity and similar initial geometries. For both the New Zealand and Idaho terraces, we have plotted maximum gradient versus \( H^{-2} \) for groups of
Figure 15. Geometric scaling relationships between north and south facing risers in (a) New Zealand and (b) Idaho. (c) Horizontal offsets between trendlines reveal proportional differences in diffusivity or formation time. In both regions, the horizontal offset between equator- and pole-facing risers indicate that equator-facing risers degrade approximately twice as fast as pole-facing risers. Comparison of equator- or pole-facing risers from the different regions reveals that the diffusivity in Idaho is 2 times greater than New Zealand. Notably, the slope of the semilog relationship for all data sets is strikingly similar, suggesting a widely applicable relationship between sediment flux and surface gradient.

north or south facing terrace risers (Figure 15) and then fit logarithmic regressions to the data. In New Zealand, we omitted the highest terrace risers (>35 m) from the regression: they have maximum gradients that are lower than predicted by the trend in the rest of the data (Figure 15a). This mismatch is not surprising, however, because the regression predicts infinite increases in riser gradient with height, whereas in actuality the maximum riser gradient is limited to the angle of repose. The midpoint gradient of these tall risers is still at or near the angle of repose, and simply not enough time has passed to significantly alter the midpoint from its initial slope.

[45] The best fit trends to all data sets are remarkably similar (Figure 15). All four riser populations have best fit trendlines that follow the equation

$$\frac{\partial h}{\partial t_{x=0}} = -0.08 \log(H^{-2}) + C,$$

where $C$ is a constant ranging from 0.06 to 0.17. The uniformity of trendline slope ($-0.08 \pm 0.01$) suggests that the functional relationship between sediment flux and riser gradient is very similar for north facing and south facing risers in both regions. This uniform functional relationship suggests that the fundamental processes degrading all risers in this study may be widely applicable to transport-limited hillslopes.

[46] Because the surveyed risers within each region are interpreted to have formed over a relatively short period of time, regardless of height or orientation, the horizontal offset between regressions through the north and south facing risers can be attributed to differences in diffusivity ($\kappa$), rather than differences in the time of formation [Nash, 2005]. Assuming that north and south facing risers in both regions have similar initial geometry, we can predict the relative differences in diffusivity (equation (13)). Even though north and south facing risers are composed of the same material in each region, differences in microclimate and vegetation due to orientation may cause minor differences in the initial gradient. We expect a certain amount of noise in the natural system, as is evident in the range of maximum gradients for any given height that are on the same order of magnitude as the differences in initial gradients. Based on this signal-to-noise ratio, the assumption that north and south facing terraces have similar initial gradients appears reasonable enough to make first-order estimates of the differences in diffusivity.

[47] In both New Zealand and Idaho, the horizontal offset of the slope-$H^{-2}$ trendlines reveals that risers facing the equator degrade at faster rates than those facing the poles (Figure 15). At both sites, the proportional difference in $H^{-2}$ values is a factor of ~1.9. Thus, following equation (6), we infer that risers facing the equator in both regions degrade ~2 times faster than nearby pole-facing risers.

[48] Another comparison can be made between similarly oriented risers from New Zealand and Idaho. If we assume near-equivalent initial conditions, as suggested by the slope offset method, and a similar functional relationship between sediment flux and slope, as suggested by the similar trendline slope in semilog space; then we can approximate the relative differences in degradation between the two regions. If we assume the New Zealand and Idaho terraces were formed at similar times, then offsets in the geometric scaling method would yield the proportional difference in regional diffusivities. Conversely, if diffusivity were equivalent in the two regions then horizontal offsets would be attributed to proportional differences in formation age. If neither age nor diffusivity can be constrained, however, differences in horizontal offset reveal proportional differences in diffusion age, $kt$.

[49] Comparisons between regions of equator-facing and pole-facing risers indicate that, for both orientations, trends in Idaho riser populations are ~2.1 times greater than those in New Zealand (Figure 15c). Therefore, based on the
assumptions outlined above, either Idaho risers are degrading twice as fast as New Zealand risers, Idaho risers are twice as old, or some combination of age and diffusivity differences result in Idaho diffusion ages that are twice those of New Zealand.

Some limits can be placed on the potential age differences between the sites. Formation ages are constrained to 13–18 ka in New Zealand and 11–19 ka in Idaho, as discussed above. The New Zealand terraces are unlikely to be younger than ~13 ka, and some of them should be close to 18 ka, when incision of the T2 (Tekapo) terrace began. The Idaho terraces should be no older than 19 ka, according to the existing dates [Pierce and Colman, 1986]. If all of the New Zealand and Idaho terraces were formed in a burst of incision at 13 ka and 19 ka, respectively, the ratio of their ages would be ≤ 1.5. This extreme interpretation is unlikely and their ages are probably more equivalent. If so, the primary cause of the offsets between the two data sets (Figure 15) should be a difference in diffusivity. Even assuming the extreme age scenario, some contrast in regional diffusivity is required to account for the > twofold difference in their diffusion ages. Our interpretation of the important role of diffusivity (rather than age) is reinforced by the analogous contrasts in diffusivity based on orientation in each area. Within each site, we know that the terrace ages are the same. Therefore, contrasts in diffusivity must underpin the observed differences between risers of different orientations. Nonetheless, improved age control is needed to place more reliable constraints on the magnitude of the regional diffusivity difference. In addition, detailed process-based studies are needed to tell what combination of factors (biota, climate, insolation, composition) modulates rates of diffusion in each setting.

Overall, this method helps to quantify the effect of terrace orientation: equator-facing risers in both regions degrade twice as fast pole-facing risers. Moreover, risers in both regions appear to be degrading following a widely applicable functional relationship between sediment flux and slope. Although age uncertainties preclude placing tight constraints on diffusivity between the two regions, the geometric scaling method clearly shows that diffusion age is twice as great in Idaho as in New Zealand.

4. Discussion

Through our focus on similarly aged terrace risers developed in consistent materials and under comparable climatic conditions, this study reduced some of the sources of uncertainty that are common in many similar studies. The relatively large number of surveyed terrace risers (320), their broad range of heights (1–60 m), and their pole- and equator-facing orientations allowed us to explore broad, but statistically robust, trends in the degradational evolution of terrace risers.

By using three analytic methods based on the linear diffusion equation, we are able to test the applicability of the linear diffusion model and assess the validity and applicability of these oft used techniques. All three analyses methods based on the linear diffusion equation show increases in diffusion age with height, suggesting that a nonlinear equation describing the relationship between sediment flux and slope is needed to accurately model hillslope processes. Although the data sets in their entirety show nonlinear trends, examination of small (<5 m) low-gradient risers using the slope offset method and midpoint slope inversion methods reveal a close correspondence between predicted and observed diffusion age values (e.g., Figures 9a and 9b). This correspondence suggests that the linear model may be applicable for low-gradient risers where linear and nonlinear diffusion models are indistinguishable.

The slope offset method proved to be a valuable tool, both to assess the validity of the linear diffusion model, as well as to provide a quantitative method for estimating reduced initial gradients. Additionally, when used in concert with the midpoint slope inversion method, significant morphologic information can be obtained for assessing riser degradation. Although downslope sediment transport appears nonlinearly related to slope, these two methods can still be used for analysis of small, low-slope risers, for comparisons of risers or fault scarps of similar height, and for a first-order assessment of general trends within large populations of risers. Both of these methods based on midpoint slope characteristics have the advantage of utilizing easily obtained field measurements and requiring relatively simple analysis and computational techniques. Additionally, these simple methods appear more reliable than the more complex full scarp method.

Although the full scarp modeling method was able to match the form of observed gradient profiles, the modeled values commonly represented best fit parameters that would not occur in nature. The wide dispersion of diffusion ages, even among risers of similar heights, and the instability in determination of reduced initial gradients raises serious concerns with using this method to analyze riser degradation. Therefore, caution needs to be taken when applying this method because the best numerical fit may have little applicability to real landscapes. Ultimately, however, based on the results of this study we find no advantage to using this method over the simpler midpoint slope based methods.

The geometric scaling method provides an alternative means of determining proportional differences in riser age and diffusivity that are not based on the linear diffusion model. Results of this method reveal a consistent relationship between gradient and downslope sediment flux that may be widely applicable to all transport-limited hillslopes. Most notable in this study is that risers facing the equator degrade approximately twice as fast as risers facing the poles. This result emphasizes the importance of riser orientation on degradation rates. Additionally, the geometric scaling method estimates that diffusion ages of Idaho risers are more than those of New Zealand risers. Unfortunately, because of the limited constraints on riser chronologies, we can place only loose limits on interregional differences in diffusivities. These proportional differences, however, are still provocative from a local surface processes perspective, and they emphasize the need to quantify actual rates in order to improve understanding of the physical processes and influences of external factors on hillslope sediment transport. Future work examining scaling relationships may help lead to a process-based equation that more accurately describes downslope sediment transport.

Finally, we note that analysis of our New Zealand data with its broad range of terrace heights suggests that initial, pole-facing riser slopes are steeper (by ~2.5°) than equator-facing initial slopes. Assuming that this contrast is real and
not an artifact of limited or noisy data, this difference violates the geometric scaling method assumption of geometrically similar initial conditions for all risers. On the other hand, this difference suggests that the same processes and external conditions that control contrasts in diffusivity with respect to orientation also influence the angle of repose that is achieved in the earliest stages of riser formation. Thus, not only do biotic, climatic, and insolation parameters influence diffusivity, but they may also influence the angle of repose that forms in the decades or centuries following terrace incision.

5. Conclusion

[58] In this study, we tested the ability of the linear diffusion model to accurately describe terrace riser degradation, and we made comparisons between equator- and pole-facing terrace risers from two latitudinally antipodal study sites in order to assess the relationship between sediment flux and slope and to determine what factors contribute to differences in degradation rates. Using dense arrays of surveys on terrace risers, we explored similarities and contrasts between temperate sites in the northern and southern hemispheres. Our findings suggest that, in both New Zealand and Idaho, downslope sediment flux is nonlinearly proportional to slope and that the linear diffusion equation does not accurately describe terrace degradation, except for low-angle risers where differences between linear and nonlinear models are indistinguishable. Instead, we find a systematic increase in diffusion age with increasing riser height. These results indicate that, in order to accurately model hillslope processes, a nonlinear transport equation is needed. By utilizing a geometric scaling method that does not rely on a specific transport equation model, we show that degradation in both New Zealand and Idaho is governed by the same functional relationship of sediment flux to slope, which may be widely applicable to transport-limited landscapes. The nature of this relationship, however, remains unknown. The geometric scaling method also allows us to compare proportional rates of degradation and reveals that risers facing the equator degrade approximately twice as fast as risers facing the poles. We conclude that hillslope orientation plays an important role in controlling rates of degradation. Moreover, regional comparisons reveal that diffusion ages are more than twice as great in Idaho compared to New Zealand. We argue that a distinct difference in diffusivity exists between these regions, but without better dating control, only loose limits can be placed on the magnitude of this difference. Overall, the large quantity of new data analyzed here suggests that the linear diffusion model does not reliably characterize hillslope degradation on transport-limited slopes above angles of ~5°–10°. Nonetheless, geometric scaling relationships do indicate that downslope sediment flux is governed by a widely applicable, yet still undetermined, sediment transport equitation.

Notation

\( h \) height, m.
\( x \) distance, m.
\( q_s \) sediment flux, m\(^2\)/ka.
\( \kappa \) diffusivity, m\(^2\)/ka.
\( S_c \) threshold gradient.

\[ t \] time.
\[ a \] initial riser gradient.
\[ b \] far-field gradient.
\[ (a - b) \] reduced initial gradient.
\[ 2a \] riser height, m.
\[ \kappa t \] diffusion age, m\(^2\).
\[ A \] riser cross-sectional area, m\(^2\).
\[ T \] degradation time, a.
\[ H \] riser height, m.

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References

Gilbert, G. K. (1877), "Pleistocene episodes of alluvial deposition," in *Quaternary Geology*.  
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