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Hanging valleys in fluvial systems: Controls on occurrence and implications for landscape evolution

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[1] We document and characterize hanging valleys in a fluvially eroded landscape in eastern Taiwan. Our conceptual model for the initiation of hanging valleys builds on a recently proposed model of bedrock incision in which erosion actually becomes less efficient on very steep channel gradients. If a pulse of incision in the main stem outpaces the tributary response, the gradients at tributary mouths may therefore pass a threshold value beyond which erosional efficiency declines, giving rise to a mismatch between trunk and tributary erosion rates. This mismatch is expected at junctions with small tributaries, where a step function decrease in drainage area also leads to sharp contrasts in water and sediment flux between trunk and tributary channels. The occurrence of hanging valleys in actively uplifting fluvial landscapes such as the Central Range of Taiwan suggests that the most common parameterizations of bedrock erosion, which typically assume a monotonic positive correlation between channel gradient and incision rate, may be violated in very steep channels. In addition, hanging valleys could greatly increase the response time of landscapes to tectonic perturbations since catchments above these tributary mouths will be insulated from these perturbations until a new suite of processes (e.g., weathering and rock mass failure) wear through the hanging valley lip. The results of this study underscore the need for a more complete understanding of bedrock erosion processes and the incorporation of process transitions and threshold conditions into landscape evolution models.

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1. Introduction

[2] To quantify the feedbacks among climate, tectonics, and surface processes, we require a set of testable, process-based rules to describe how fluvial networks respond to external forcing. In general, fluvial networks in a transient state or those containing spatially variable tectonic forcing provide the best opportunity to test these rules, since the concave-up form of steady state river profiles is inherently nonunique in its reflection of dominant erosive process [*Howard et al.*, 1994; *Whipple and Tucker*, 2002; *Willgoose et al.*, 1991]. In a few cases, field sites experiencing transient responses and nonuniform forcing have been used to calibrate the parameters in fluvial erosion laws assuming a stream power or shear stress control on erosion rate [*Bishop et al.*, 2005; *Crosby and Whipple*, 2006; *Howard and Kerby*, 1983; *Kirby and Whipple*, 2001; *Rosenbloom and Anderson*, 1994; *Snyder et al.*, 2000; *Tomkin et al.*, 2003; *van der Beek and Bishop*, 2003]. While these studies have had some success, the generality of such an approach requires simplified formulations of erosional process that clearly cannot capture all of the underlying physics [*Whipple*, 2004]. In particular, the suggestion that thresholds in shear stress, transport stage, or sediment supply are important in controlling the transient response of landscapes has only begun to be evaluated [*Gasparini*, 2003; *Sklar and Dietrich*, 1998; *Sklar and Dietrich*, 2004; *Snyder et al.*, 2003; *Tucker*, 2004] and studies exploring these effects in field settings are even more rare [*Crosby and Whipple*, 2006]. Further work in field settings where simple models of landscape evolution fail may provide an important opportunity to improve our understanding of landscape response.

[3] In this paper, we describe hanging valleys in the Eastern Central Range of Taiwan, and suggest that non-monotonic relationships among transport stage, drainage area and erosion rate may lead naturally to the formation of these features. We begin with a review of fluvial scaling in natural systems, using the network geometry to predict the distribution of channel gradients if simple shear stress or unit stream power erosion rules are invoked. We then turn to a field example from the San Gabriel Mountains of southern California, where the scaling relationships predicted by such erosion rules provide a reasonable estimate of the transient channel geometry. The San Gabriel analysis serves as a counterpoint to our Taiwan example and thus helps define the conditions required for hanging valley formation. Next,

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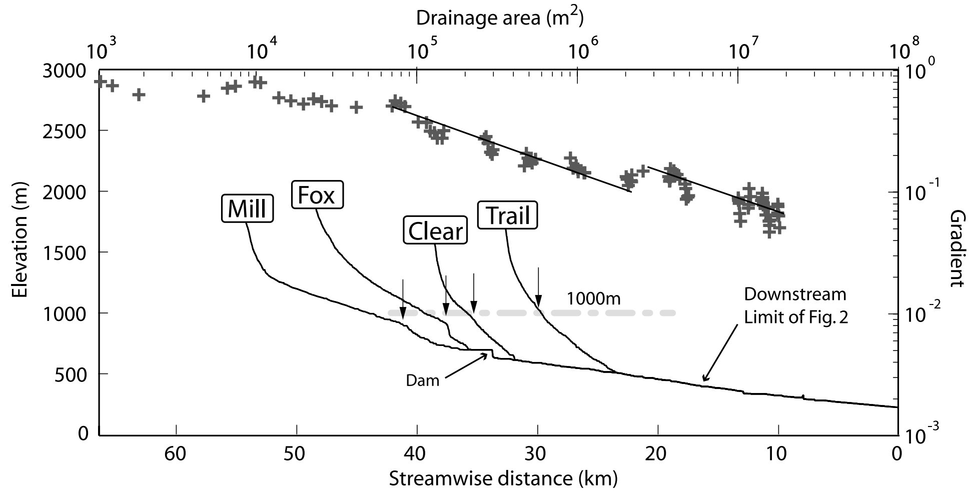

Figure 1. Longitudinal profiles (lines, left and bottom axes) for Mill Creek and three tributaries and slope-area data (crosses, right and top axes) for Trail Canyon in the Big Tujunga basin of southern California. Linear fits to slope-area data are shown with forced concavity of θ_{ref} = 0.45. Note that knickpoints on tributaries (vertical arrows) all lie near 1000 m elevation, consistent with a constant vertical knickpoint migration rate (e.g., equation (3)). Large step on trunk stream between Fox and Clear Creeks is an engineered dam. Shift in slopes at a drainage area of $\sim 3 \times 10^6$ m^2 corresponds to knickpoint on Trail Canyon at $\sim$1000 m elevation.

we examine the distribution of channel gradients in three basins in northeastern Taiwan, where the steepest portions of the fluvial network are almost always found at tributary mouths. At many of these tributary mouths, channel gradients are significantly oversteepened relative to gradients predicted from simple river incision models. We classify these basins as hanging valleys, since the oversteepened gradients at their mouths limit the communication of erosional signals upstream, resulting in a disequilibrium between rock uplift and river incision. Using this classification, we examine the distribution of hanging valleys in the fluvial network relative to tributary drainage area, trunk to tributary drainage area ratio, and proximity to lithologic boundaries. Guided by fluvial erosion models that incorporate a nonmonotonic relationship between transport stage and erosion rate [*Sklar and Dietrich*, 1998, 2004], we suggest that such nonmonotonic erosion rules may help to explain the formation of hanging valleys in fluvial systems. Finally, we discuss the implications of our observations for landscape evolution in Taiwan, and for landscape evolution models, response timescales, and the attainment of steady state conditions.

2. Background

2.1. Scaling in Fluvial Systems

[4] Longitudinal profiles from rivers around the globe commonly yield a scaling in which channel gradient is a power law function of contributing drainage area:

$$S = k_s A^{-\theta} \tag{1}$$

Here, S is the local channel gradient, A is the upstream drainage area, θ is the concavity index, and k_s is the steepness index. The concavity index θ typically falls in a narrow range between 0.3 and 0.6, and appears to be independent of the rate of rock uplift based on empirical data [*Kirby and Whipple*, 2001; *Tucker and Whipple*, 2002; *Whipple*, 2004; *Wobus et al.*, 2006]. At steady state, the steepness index k_s has been shown to be a function of the rock uplift rate [*Snyder et al.*, 2000; *Wobus et al.*, 2006], but other factors such as substrate erodibility, channel geometry, sediment properties, and climatic variables can also be expected to influence k_s [*Whipple*, 2004]. Note that "steepness" as defined here is the channel gradient normalized to the contributing drainage area, and should not be confused with the channel gradient itself.

[5] The form of equation (1) predicts that zones with spatially uniform rock uplift should be manifested as linear arrays on logarithmic plots of slope versus drainage area. Shifts in these linear arrays are expected where the rock uplift rate (or other influences on k_s, as listed above) is spatially variable [*Kirby and Whipple*, 2001; *Wobus et al.*, 2006]. Shifts in these arrays also occur where pulses of incision are sweeping through the fluvial network [*Snyder et al.*, 2002; *Whipple and Tucker*, 1999, 2002] (see Figure 1). In the case of a transient pulse of incision, the upstream-migrating boundary between the adjusting and relict portions of the landscape is defined as a knickpoint, most commonly manifested as a convexity on the longitudinal profile associated with a sudden change in the channel steepness index [*Crosby and Whipple*, 2006].

[6] Entirely on the basis of geometric considerations and the assumption that the concavity index is independent of the rock uplift rate, the horizontal rate of knickpoint migration (celerity) during the adjustment of a fluvial profile to a change in uplift rate can be expressed as a simple function of the local channel gradient and the vertical incision rate [*Niemann et al.*, 2001]:

$$Ce_H = -\frac{1}{S_1\left(1 - {}^{S_2}/_{S_1}\right)}\frac{dz}{dt} \tag{2}$$

Where Ce_H represents the horizontal celerity, S is the local channel gradient, dz/dt is the local incision rate, and subscripts 1 and 2 represent the initial and final states, respectively. Substituting equation (1) into equation (2), we can then relate the horizontal celerity to drainage area as:

$$Ce_H = \frac{U_1 - U_2}{k_{s_1} - k_{s_2}} A^{\theta} \tag{3}$$

Equation (3) suggests that knickpoints should migrate upstream at an ever decreasing rate proportional to the contributing drainage area [see also *Bishop et al.*, 2005; *Rosenbloom and Anderson*, 1994; *Whipple and Tucker*, 1999].

[7] Noting that the vertical celerity is simply the horizontal celerity multiplied by the local channel gradient, we can express the vertical rate of knickpoint migration following a change in uplift rate as follows:

$$Ce_V = \frac{U_1 - U_2}{k_{s_1} - k_{s_2}} k_{s_2} \tag{4}$$

Equation (4) can be derived without making any assumptions about the form of the erosion law: we have simply utilized the geometry of the system, and the empirical observation that channel gradient is a power function of contributing drainage area with a concavity index that does not vary with rock uplift rate (i.e., equation (1)).

[8] If we further assume that the local erosion rate scales with shear stress or stream power, the steady state channel gradient in equation (1) can be written in terms of the rock uplift rate and drainage area as follows [*Snyder et al.*, 2000; *Whipple and Tucker*, 1999]:

$$S = \left(\frac{U}{K}\right)^{1/n} A^{-m/n} \tag{5}$$

where m and n represent the exponents on area and slope in the stream power or shear stress erosion rule, and K is a coefficient representing erodibility parameters such as rock type, channel geometry, sediment properties, climate, and vegetative cover. Noting the similarities in the form of equation (5) and equation (1) and substituting for k_s in equation (4), the vertical celerity can then be expressed as a function only of the rock uplift rate and the slope exponent n [*Niemann et al.*, 2001]:

$$Ce_V = \frac{U_1 - U_2}{U_1^{1/n} - U_2^{1/n}} U_2^{1/n} \tag{6}$$

where for n = 1, we find $Ce_v = U_2$.

[9] In general, assuming a monotonic relationship between erosion rate and channel gradient (i.e., a constant value of n), equation (6) predicts that the rate of vertical translation of knickpoints is a constant that is uniquely determined by the initial and final rock uplift rates, U_1 and U_2. This result predicts that migrating knickpoints created by a change in rock uplift rate should lie along a single contour line at any point in time. Natural systems in which knickpoints separating adjusting and relict portions of the landscape adhere to this spatial pattern would indicate that the scaling in equation (5) may be adequate for describing the evolution of these systems. Since equation (5) can be derived from any parameterization of fluvial erosion in which incision is a power law function of slope and area alone, adherence to the spatial pattern predicted by equation (5) would further suggest that in these settings simple stream power rules might be sufficient for describing the catchment-scale dynamics of fluvial systems. Such behavior will be shown in the following section using an example from the Big Tujunga basin in the San Gabriel Mountains of California.

2.2. Example: Big Tujunga River, California

[10] The San Gabriel Mountains of southern California have been subject to spatially and temporally variable rock uplift rates through the late Cenozoic, as a result of a restraining bend in the San Andreas fault and its interaction with the San Jacinto fault [*Blythe et al.*, 2000, 2002; *Lave and Burbank*, 2004]. The Big Tujunga river drains the northwestern end of the San Gabriel Mountains immediately to the north of Los Angeles, and contains a spatial pattern of knickpoints that appears to be consistent with equation (4). The basin is small enough that climatic conditions are relatively uniform throughout [*Spotila et al.*, 2002], and the bedrock is characterized by a combination of coarse grained anorthosite and granitic intrusive bodies. While normalized steepness indices in channels draining the granites are commonly slightly higher (~30%) than those in the anorthosites, none of the knickpoints discussed here correspond to lithologic boundaries, suggesting that lithology is not a first-order control on knickpoint location.

[11] We analyzed 31 stream profiles from the Big Tujunga basin, using a 10 m USGS digital elevation model (DEM). Methods used in stream profile extraction and analysis followed those of *Snyder et al.* [2000] and *Wobus et al.* [2006]. For each profile, data collected along the length of the stream included elevation, streamwise distance from the outlet, contributing drainage area, and local slope calculated over a 12.2 m vertical interval (corresponding to USGS 40' contours). Following the extraction of these raw data, elevations were smoothed with a 250 m moving window and plots of log(S) versus log(A) were created [*Wobus et al.*, 2006]. With the exception of abrupt changes in steepness associated with knickpoints and dams, equation (1) explains all of the data well with a uniform concavity index between 0.4 and 0.5 (Figure 1). Steepness indices (k_{sn}) normalized to a concavity of 0.45 [e.g., *Kirby et al.*, 2003; *Snyder et al.*, 2000; *Wobus et al.*, 2006] were calculated along the length of each channel profile by regressing on the slope-area data in short segments corresponding to a half kilometer of channel length. Color-coded plots of these normalized steepness indices can then be used to objectively evaluate the distribution of channel gradients in the basin (Figure 2).

[12] Normalized steepness indices in the Big Tujunga basin range from ~90 to ~240 for a reference concavity of 0.45. Slope-area data from channels spanning the entire range of elevations are well approximated by two parallel linear segments separated by a single step, with high steepness indices downstream and lower steepness indices upstream (Figure 1). This pattern of steepness values is consistent with a transient condition in which the lower

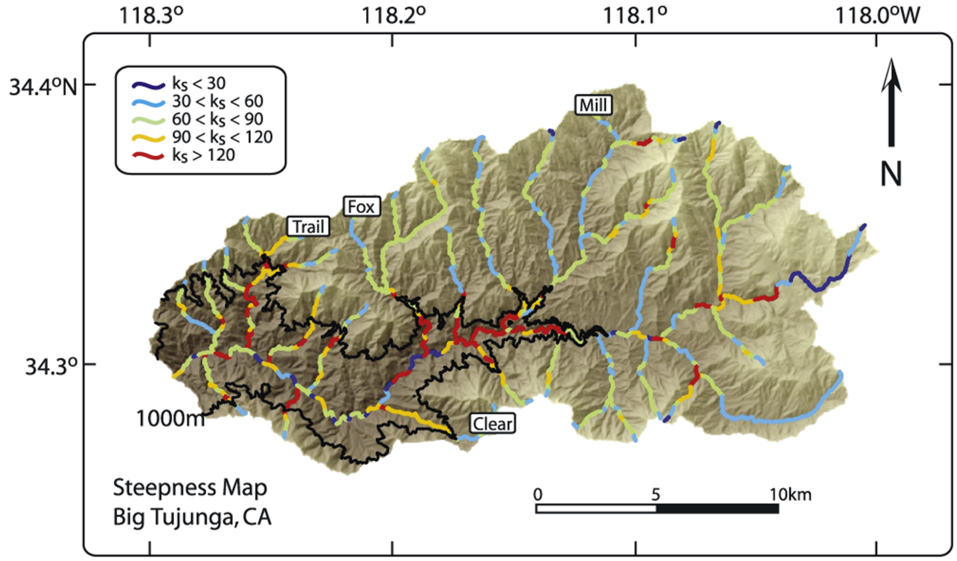

Figure 2. Map view of normalized steepness indices (θ_{ref} = 0.45) in the Big Tujunga basin. The boundary between high and low steepness values lies close to the 1000 m contour, and the highest steepness indices are generally confined to the lowermost portions of the drainage basin, consistent with a model of basin-wide knickpoint retreat. High k_{sn} reaches upstream of 1000 m contour line represent minor perturbations to smooth, low-gradient channel profiles and may be related to localized lithologic heterogeneities, landsliding, or boulder rapids over short channel reaches.

reaches of the basin are adjusting to an increase in rock uplift rate and the upper reaches have not yet responded to this tectonic perturbation. Furthermore, the boundary between the "adjusting" (high k_{sn}) and "relict" (low k_{sn}) channel reaches lies very close to a constant elevation of ~1000 m above sea level (Figure 2), while the drainage areas of tributaries upstream of this boundary vary widely. This spatial pattern suggests that the knickpoints in these channels are in the process of migrating upstream at a nearly constant vertical rate, rather than being stalled at a critical drainage area where erosional efficiency is hindered [e.g., *Crosby and Whipple*, 2006].

[13] The Big Tujunga generally follows the expected behavior of a drainage basin in a transient state if commonly used parameterizations for fluvial erosion (i.e., stream power) are adequate: channels are adjusting to their new conditions in their lower reaches, but upstream of the knickpoints they remain temporarily insulated from perturbation. With the exception of locally extreme gradients created by manmade dams, steepness indices calculated for knickpoints throughout the channel network fall between the "adjusting" and "relict" k_{sn} values of ~90 and ~240 [*Wobus et al.*, 2006]. Furthermore, the relatively constant elevation of the knickpoints suggests a spatially and temporally constant vertical knickpoint migration rate, consistent with a fluvial erosion rule based on shear stress or unit stream power.

[14] In detail, the distribution of steepness indices in the Big Tujunga basin has some complications: in particular, the upper reaches of the basin include a few anomalously steep, but short channel segments that are clearly unrelated to the transient condition migrating headward from the mouth of the network. These anomalously steep channel segments are barely perceptible at the scale of Figure 2 and may be related to lithologic heterogeneities, localized inputs of boulders from landslides or debris flows, or even noise in the digital topographic data. In addition, field observations at a finer spatial scale than allowed by our DEM indicate the presence of waterfalls at some of the smaller tributary junctions and multistepped knickpoints downstream of those described here. Despite these minor perturbations, however, the general pattern of steepness indices in which channel gradients are systematically steeper in the lower reaches of the basin is clearly not an artifact of our methodology nor of the quality of our digital topographic data. This general pattern suggests that the simplified rules for transient channel response outlined in equations (3)–(6) are adequate for describing this system at the scale of our digital topographic data. With this background, we now turn to the Central Range of Taiwan, where there is a clear breakdown in the scaling predicted by these simplified rules, leading to a very different pattern of channel gradients across the landscape.

3. Hanging Valleys in Taiwan

3.1. Geologic Setting

[15] The mountainous landscape of Taiwan is a result of oblique convergence between the Luzon arc, riding on the Philippine Sea plate, and the Eurasian continental margin (Figure 3a) [*Teng*, 1990]. This collision has progressed southward through time, such that there is a rough space for time substitution from north to south [*Suppe*, 1984; *Willett et al.*, 2003]: in the south, the collision has just begun and the orogen is correspondingly young, while in the north the orogen has already begun to collapse due to extension behind the Ryukyu trench. Within the greenschist grade metamorphic core of the orogen, corresponding to the physiographic Eastern Central Range, the landscape is characterized by rapid denudation and bedrock incision,

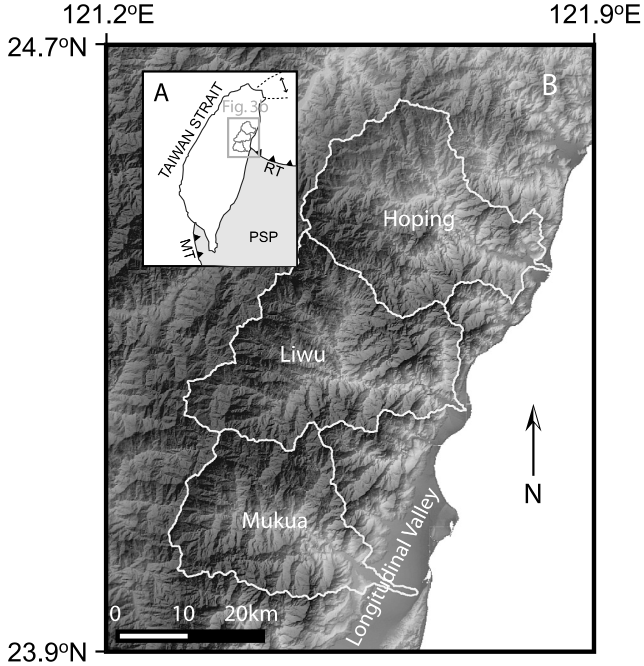

Figure 3. Map of study area in northeastern Taiwan. (a) Tectonic setting. PSP, Philippine Sea Plate; MT, Manila Trench; RT, Ryukyu Trench. Arrows in northeast corner of map show zone of extension behind Ryukyu Trench. Box outlines extent of Figure 3b. (b) Physiography of eastern Taiwan with outlines of the three basins studied.

driven by extremely steep topography and a humid, subtropical climate [*Dadson et al.*, 2003; *Hartshorn et al.*, 2002; *Schaller et al.*, 2005]. Average annual rainfall in the basins we analyzed ranges from ~2 to 4 m/yr, with the highest values associated with orographically enhanced precipitation near the crest of the Eastern Central Range [*Dadson et al.*, 2003].

[16] Erosion and exhumation rate data for Taiwan are available for a variety of timescales. Exhumation rates range from 3 to 6 mm/yr in the metamorphic core of the orogen based on fission track dating of apatites; Holocene bedrock incision rates derived from ^{14}C dating of strath terraces approach 10 mm/yr along the eastern margin of the island; and a 30 year record of sediment yield data indicates basin-averaged rates locally exceeding 30 mm/yr [*Dadson et al.*, 2003]. Measurements of cosmogenic ^{21}Ne within the steep-walled canyons of the Liwu basin suggest extremely high incision rates (up to 26 mm/yr), although these estimates have apparently been compromised by temporary aggradation events and lateral retreat of the canyon walls [*Schaller et al.*, 2005]. Finally, repeat high precision measurements of the evolving microtopography on bedrock ribs in the Liwu basin yield local incision rates between 2 and 6 mm/yr over annual timescales [*Hartshorn et al.*, 2002]. While erosion rates measured over different timescales yield different results, the very broad agreement among erosion and exhumation rate estimates, an approximate balance between estimates of long-term tectonic mass influx and erosional efflux, and approximate invariance in both range width and crest height in the northern half of the Central Range have been used to support the hypothesis that Taiwan has achieved both a topographic and exhumational steady state [*Suppe*, 1981; *Willett and Brandon*, 2002; *Willett et al.*, 2003]. Nonetheless, regional geomorphic studies document the presence of substantial convexities and knickpoints within the fluvial network, suggesting that the topography may be far from steady state at geomorphically relevant spatial and temporal scales [*Slingerland and Willett*, 1999; *Willemin and Knuepfer*, 1994].

[17] Our original analysis examined eight basins spanning the entire eastern side of Taiwan. Channel morphologies suggestive of transient conditions were most common in the three northernmost basins we analyzed, and we therefore focus our analysis here on these three basins: the Hoping, Liwu, and Mukua (Figure 3b). These three drainages lie within the zone of maximum exhumation rates defined from apatite fission track thermochronology [*Dadson et al.*, 2003]. Furthermore, the physiography of these basins suggests rapid denudation throughout the drainage network: trunk streams are steep and narrow, and hillslopes are nearly linear with steep ($\geq 35°$) gradients [*Hovius et al.*, 2000]. Bedrock in these basins comprises greenschist-facies metasedimentary rocks dominated by metapelites, with locally significant marbles and gneisses along the easternmost side of the study area. Foliations generally trend north-northeast, with major trunk streams approximately orthogonal to this dominant foliation.

3.2. Methods and Results

[18] Longitudinal profile data for 182 rivers were extracted from the three drainage basins in northeastern Taiwan, using a 40 m resolution DEM. As in the example from the Big Tujunga basin, we generated plots of channel longitudinal profiles and log(S) versus log(A) for each stream, and created a map of normalized steepness indices for each drainage basin by regressing on half kilometer segments of the slope-area data with a reference concavity, θ, of 0.45. We also recorded the drainage areas in the trunk and tributary basins at each tributary junction. Using all of the data, we classified each tributary channel as either adjusted, linear, transient (containing knickpoints) or hanging (Figure 4).

[19] Adjusted tributary channels are those in which the profiles are smooth, concave-up, and graded to the tributary mouth, with steepness values comparable to those in the trunk stream (Figure 4a). Channels classified as linear have concavity values near zero, possibly representing erosion by nonfluvial agents such as debris flows [*Montgomery and Foufoula-Georgiou*, 1993; *Stock and Dietrich*, 2003] (Figure 4b). Channels placed in the generalized "knickpoint" category are distinguished from those classified as "hanging" by the form of their slope-area data: channel gradients downstream of knickpoints are commensurate with k_s values in the adjusting portion of the trunk stream profile (Figure 4c), while hanging tributaries contain reaches that are significantly oversteepened relative to the trunk stream (Figure 4d). Note that these classifications are largely qualitative; however, the basins unambiguously classified as hanging valleys are characterized by pronounced convexities on longitudinal profiles and a characteristic spike in slope-area data, as shown schematically in Figure 4d.

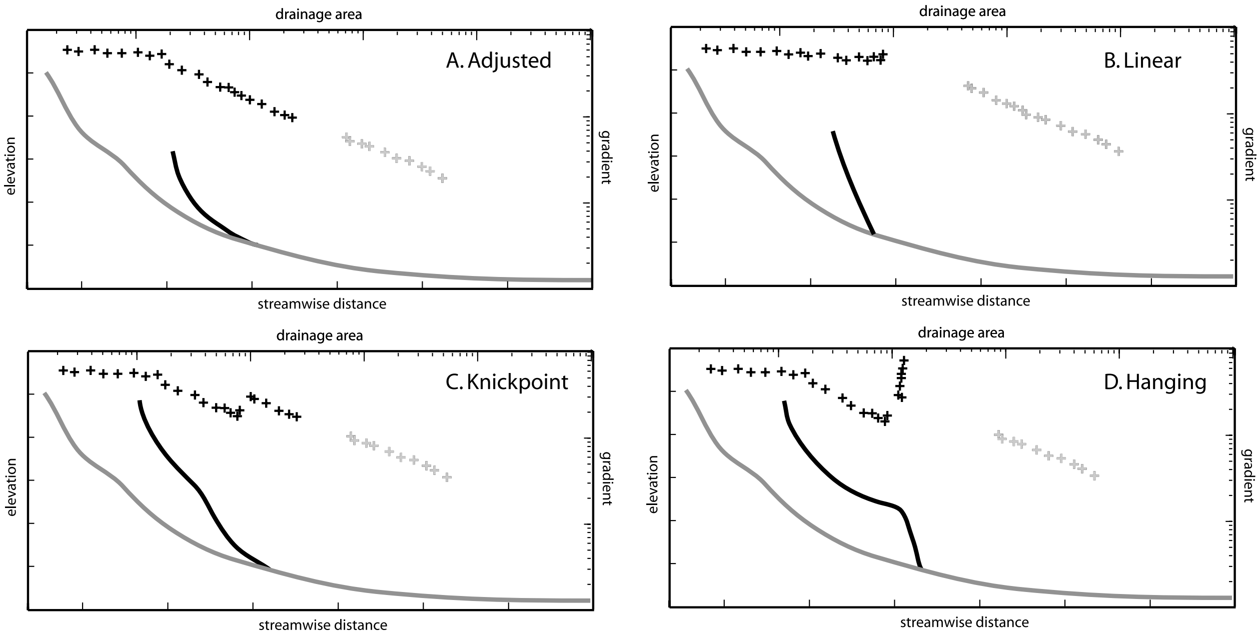

Figure 4. Schematic showing idealized examples of the four categories of longitudinal profiles identified in northeastern Taiwan. Trunk stream profiles and slope-area data are shown in gray (shown only for reaches downstream of tributary junction); tributary data are shown in black. (a) Adjusted profile. Note smooth transition and consistent steepness indices between tributary and trunk streams. (b) Linear profile. Concavity is near zero from the tributary channel head to its mouth. (c) Knickpoint in longitudinal profile. The tributary channel has a significant convexity along its course, but the steepness index below this knickpoint is commensurate with the adjusting portion of the trunk stream. (d) Hanging valley. The tributary channel has a significant convexity near its mouth, and the steepness index is much higher than that found in the trunk stream.

[20] Plan view maps of reach-averaged steepness indices in Taiwan reveal more complex patterns of landscape adjustment than those found in the Big Tujunga catchment. In the Liwu basin, for example, all of the highest k_{sn} values are found at tributary mouths (Figure 5). The presence of these high-k_{sn} zones suggests a transient landscape, but the spatial distribution of these zones indicates that landscape adjustment in this basin is not achieved simply by knickpoints sweeping through the channel network at a predictable rate (e.g., equation (6)). Instead, knickpoints appear to have either formed, stalled, or become exaggerated at tributary mouths, which are found at a range of elevations (Figure 6). Channel gradients immediately downstream of the convexities in these tributary profiles are commonly much higher than those typical for mountain streams (up to 85%, or 40°), and the steepness indices in these reaches are substantially higher than those in the trunk streams they enter. All of these observations suggest that the relationship between steepness index and rock uplift rate can be more complicated during transient adjustment than implied by equation (5) [e.g., *Gasparini et al.*, 2006].

[21] Our field observations are limited to those collected during a reconnaissance trip along the Liwu basin in 2003. However, the field observations we do have suggest a transition from simple bedrock abrasion and plucking in streams with abundant gravel cover to waterfall plunge-pool erosion, boulder jams, and extensive bedrock exposure at many tributary mouths (Figure 7). This transition in the erosive regime suggests that the mechanisms responsible for transmitting transient conditions upstream are no longer described by simple rules for bedrock erosion such as the well-known stream power incision model. The clustering of steep channel gradients near tributary mouths and the field observation that many of these channels have become waterfalls further suggests that local bedrock incision rates are much slower at the tributary mouths than in the trunk streams. Such a disconnect between erosion rates in the tributary and trunk streams indicates that these oversteepened tributary mouths temporarily insulate the basins upstream from main stem incision, and can therefore be classified as hanging valleys.

3.3. Conceptual Model for Hanging Valley Formation

[22] Recent work by *Sklar and Dietrich* [1998, 2001, 2004] suggests that for erosion by bed load abrasion, the highest transport stages (defined as the ratio of nondimensional shear stress to the critical shear stress required to mobilize bed load (τ^*/τ^*_c)) may actually be less erosive than more moderate transport stages. The decreasing erosion rate with increasing transport stage in their model results from a decrease in the frequency of bed load impacts on the bed. At low transport stages, for example, fluid velocities are low and bed load may be just above the threshold of motion. These transport conditions lead to low erosion rates since there is very little excess energy available to erode the bed. As slopes increase, both the mean shear stress and the turbulence increase at the bed. At these moderate slopes, saltation hop lengths are short, and the

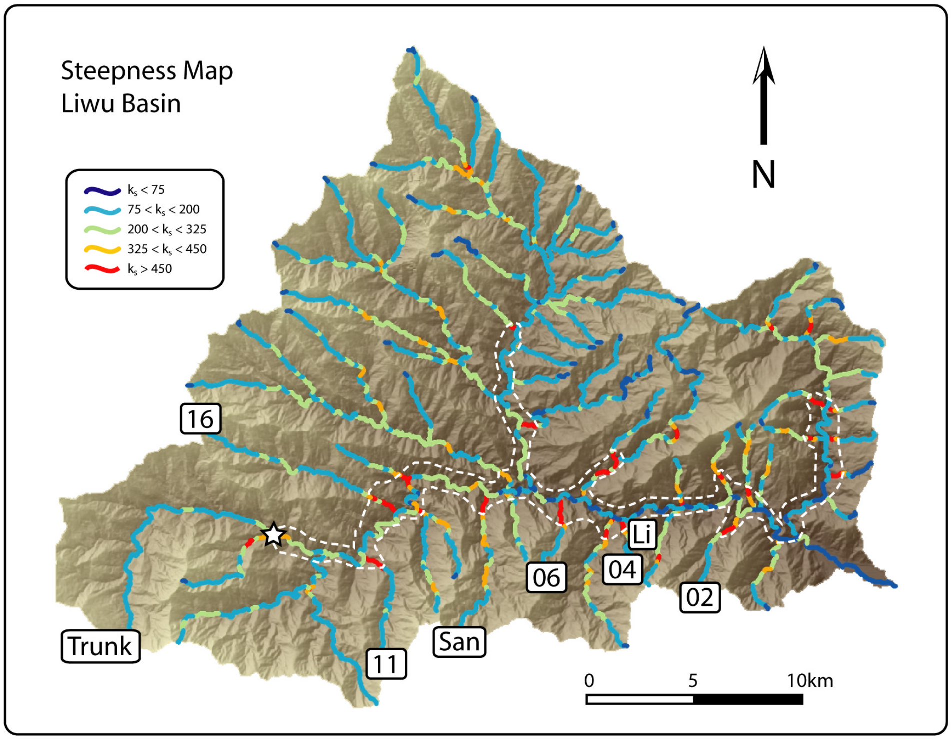

Figure 5. Map view of normalized steepness indices (θ_{ref} = 0.45) for the Liwu basin in Taiwan, calculated over 500 m channel segments. Note that the highest steepness indices are almost all found in short segments at tributary mouths. Boundary between "adjusting" and "relict" landscape is shown by dashed white line, with a star marking upper limit of high steepness values in trunk. This boundary does not fall along a constant contour as in the example from the San Gabriel Mountains (e.g., Figure 2).

high frequency of impacts from saltating bed load results in high erosion rates [*Sklar and Dietrich*, 1998; *Wiberg and Smith*, 1985]. Beyond some threshold value, however, further increases in saltation hop lengths and the resulting decrease in the frequency of bed load impacts outpace the increase in kinetic energy from higher saltation trajectories, leading to a decline in erosion rate at high channel gradient (Figure 8). Such behavior is not, however, unique to the *Sklar and Dietrich* [2004] saltation-abrasion model. For example, similar behavior would be expected for other erosive processes (e.g., suspended load abrasion, plucking), since the efficiency of kinetic energy transfer to the bedrock surface should decrease at very high channel gradients.

[23] Because there may be alternative explanations and because the *Sklar and Dietrich* [2004] analysis is limited to bed load abrasion as the only operative process, considers

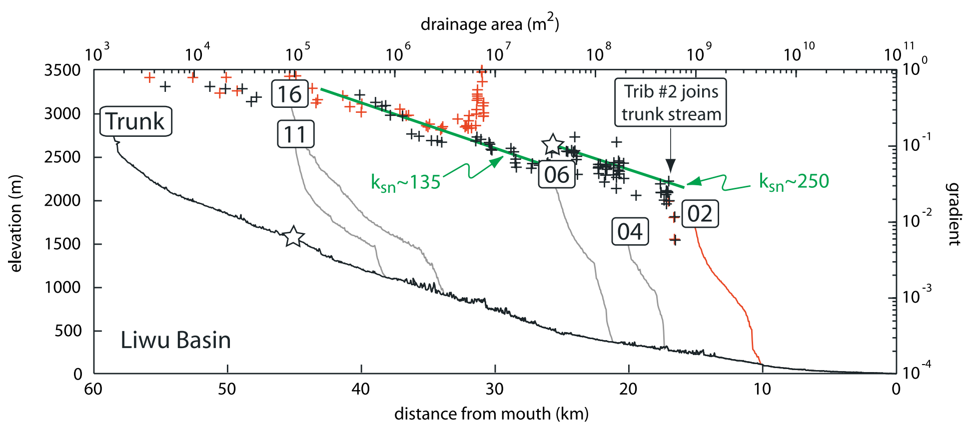

Figure 6. Long profile view of five hanging valleys in the Liwu basin, with slope-area data from the trunk stream (black crosses) and from tributary 2 (red crosses). Green lines show, for reference, the average steepness values below $k_{sn} \approx 250$ and above $k_{sn} \approx 135$, the knickpoint on the trunk stream (star). Note that the channel gradient at the mouth of tributary 2 is much higher than would be predicted on the basis of the gradients in the trunk stream it enters. Compare to Figure 4d.

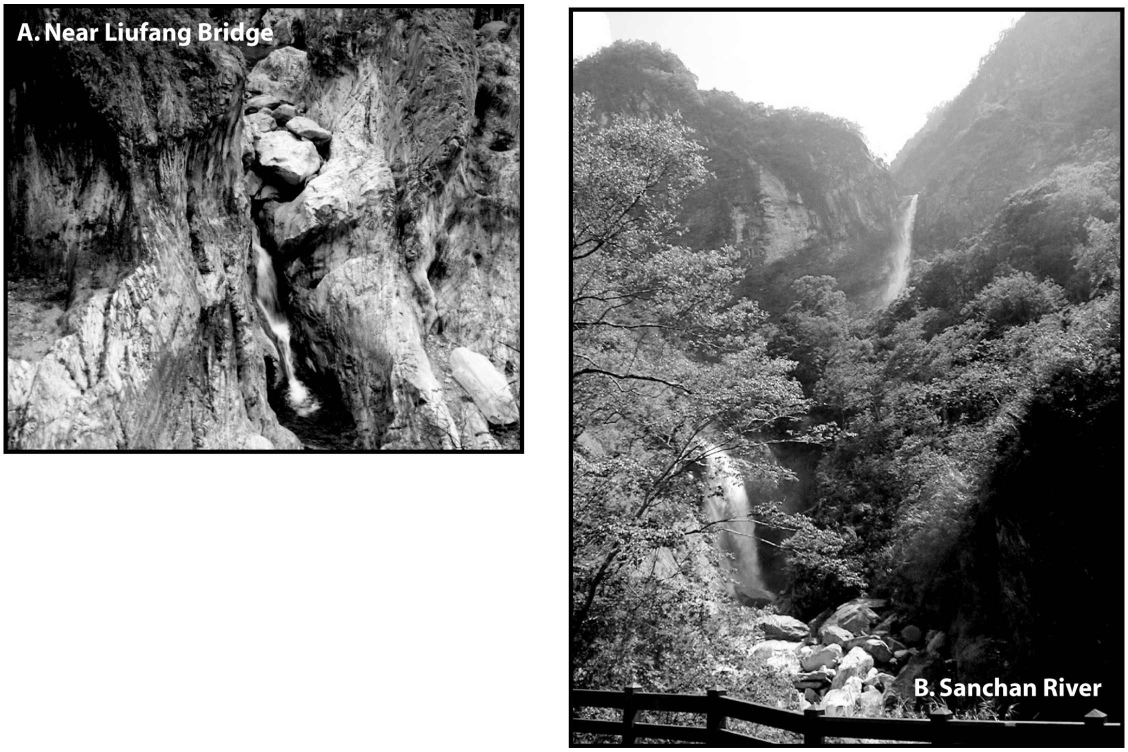

Figure 7. Photographs of two tributary mouths classified as hanging valleys in the Liwu basin. (a) Small tributary near Liufang Bridge ("Li" on Figure 5). (b) Sanchan River ("San" on Figure 5). Note the presence of waterfall plunge pool erosion in both channels. Upstream knickpoint migration rate should therefore be limited by the erosion rate at the waterfall lip, rock face stability, plunge pool scour, and the ability of these rivers to remove large boulders downstream of the plunge pool.

only a uniform-sized bed load supply, and is written only for a planar bed morphology, it is difficult to determine quantitatively what combinations of channel gradient, sediment supply, and flow rate might be sufficient to cross the threshold to decreasing erosion rates in nature. However, since channel gradient maps directly into transport stage for a given discharge and sediment grain size, we might expect channel reaches with extremely steep gradients to erode at a lower rate than more moderate gradients. Such steep gradients might be expected to initiate at the mouths of small tributary channels, where upstream-migrating pulses of incision along the main stem can lead to a rapid drop of the local base level at the tributary mouth. In the limiting case of an instantaneous lowering of the tributary junction, for example, the tributary mouth will become vertical, and a process transition from bedrock abrasion and plucking to focused plunge pool erosion will occur. At this point, the rate of migration of a wave of incision into the tributary basin might well be more strongly influenced by the rock strength of the substrate than by the transport conditions in the channel [e.g., *Weissel and Seidl*, 1998]. Such a decoupling of erosion rate from the transport conditions in the channel may explain the spatial pattern of oversteepened reaches in Taiwan: once a threshold transport stage is exceeded, knickpoint migration rate is no longer a simple function of upstream drainage area (e.g., equation (3)) allowing the observed oversteepened channel reaches to stall and perhaps grow near the tributary mouths.

[24] We suggest that the rapid increase in tributary channel gradient required to initiate a hanging valley may be driven by a wave of incision migrating headward in the main stem. If the fluvial network generally responds to perturbation in a manner consistent with equation 3, a wave of incision initiated near the basin mouth will propagate upstream at an initially rapid rate determined by the drainage area of the entire basin. When this wave of incision passes a small tributary valley, there will be a substantial mismatch between the rates of knickpoint migration in the trunk and tributary systems, driving a rapid steepening of the tributary mouth (Figure 9). If this steepening increases

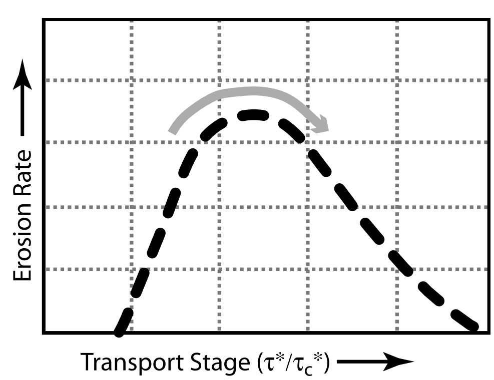

Figure 8. Schematic showing the expected relationship between transport stage and erosion rate based on the work of *Sklar and Dietrich* [2004]. This relationship predicts that erosion rates will begin to fall as channel gradients increase, driving transport stage above a critical value.

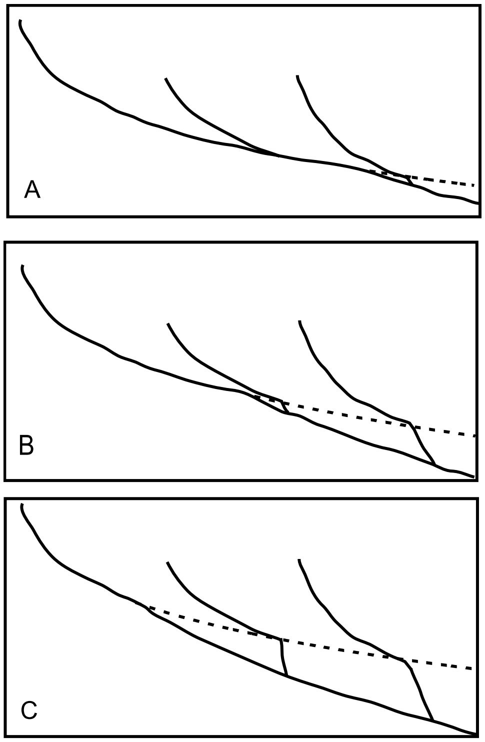

Figure 9. Schematic showing the growth of hanging valleys through time, in extreme case with no response of tributary upstream of the knickpoint. (a) Pulse of incision on the main stem oversteepens the tributary mouth sufficiently such that erosion rates fall. (b and c) Once this threshold condition has been exceeded at a tributary mouth, further incision of the main stem increases the height of the hanging valley through time. Compare to Figure 6.

the transport stage enough, erosion rates in the oversteepened tributary mouth will actually decrease (e.g., Figure 8), eventually leading to a waterfall instability in the tributary as lowering continues in the main stem. Since sediment supply and all other transport conditions in the tributary basin remain at their unperturbed values, the tributary channel makes no internal adjustment to these new conditions. The oversteepened mouth of the tributary therefore remains at a new, lower erosion rate while further lowering in the main stem increases the elevation drop across the hanging valley through time (Figure 9). *Crosby et al.* [2005] have begun exploration of this hypothesis for hanging valley formation in the context of a landscape evolution model that incorporates sediment-flux-dependent river incision rules [e.g., *Gasparini et al.*, 2006].

[25] Because the formation of hanging valleys should depend on the incision rate in the main stem, the rock strength at the tributary mouth, and the transport conditions in the tributary channel, all of which will be unique to a given drainage network, we cannot directly compare the threshold conditions needed to form hanging valleys between two different landscapes. However, the fact that hanging valleys are relatively common at the scale of our DEM in Taiwan but are not observed at a similar scale in the San Gabriels suggests that the tectonic and/or climatic perturbation giving rise to the transient condition in Taiwan may be more extreme than that leading to the transient in southern California. As such, our example from Taiwan might expose the failings of simple ''stream power'' descriptions of fluvial erosion, while the example from the San Gabriels remains consistent with the predictions of these simplified rules. Alternatively, there may be important differences in the dominant erosional processes between the two basins that account for the differing response.

[26] Finally, while we do not know what tectonic or climatic event might have given rise to the wave of incision in Taiwan, we can use the height of the hanging valleys to speculate on the timing of this perturbation. For example, assuming a long-term rock uplift rate of ~5 mm/yr [*Dadson et al.*, 2003] and a complete decoupling between erosion in the main stem and the hanging valleys, the approximate height of the hanging valleys above the trunk stream (~500 m) suggests ~100 ka since perturbation. We stress that this is a minimum timescale, since we have assumed zero erosion in the hanging valleys once the wave of incision has passed.

4. Discussion

4.1. Conditions of Formation

[27] We suggest that the formation of hanging valleys is controlled by two threshold conditions. First, as suggested by *Sklar and Dietrich* [2004], there must be a threshold transport stage beyond which erosion rates begin to decrease with further increases in channel gradient (e.g., the peak in Figure 8). And second, there must be a threshold main stem lowering rate (or size of base level drop) beyond which tributary mouths become oversteepened sufficiently to exceed this critical transport stage. The first threshold should be controlled by the flow conditions in the tributary channel, including the dominant erosive process, sediment supply, and sediment transport capacity. Changes in channel gradient, driven by local base level lowering as pulses of incision sweep past the tributary junction in the main stem, will alter these flow conditions as the system adjusts. The second threshold should be controlled by the size of the tributary basin, or by the ratio of drainage areas in the tributary and trunk streams [*Crosby et al.*, 2005], since we expect the relative rates of transient adjustment to scale with the contributing drainage areas in each basin [*Crosby and Whipple*, 2006; *Niemann et al.*, 2001; *Whipple and Tucker*, 1999] (equation (3)). In either case, position in the basin will be an important control on where hanging valleys are found: we expect to find hanging valleys only in those portions of the tributary network that have been exposed to pulses of incision in the main stem. By examining the channel gradient and drainage area data for tributaries downstream of prominent knickpoints in the trunk streams, we can begin to place some constraints on the necessary conditions for hanging valley formation in this landscape.

[28] The first threshold condition, the transport stage required to drive a reduction in erosion rate at a tributary mouth, can be evaluated based on the gradients observed in the oversteepened reaches of hanging valleys. For the fifteen tributaries we classified as hanging valleys, these reach-averaged channel gradients range from 0.28 to 0.85, with a mean of 0.46 (~25°) (Figure 10). The highest

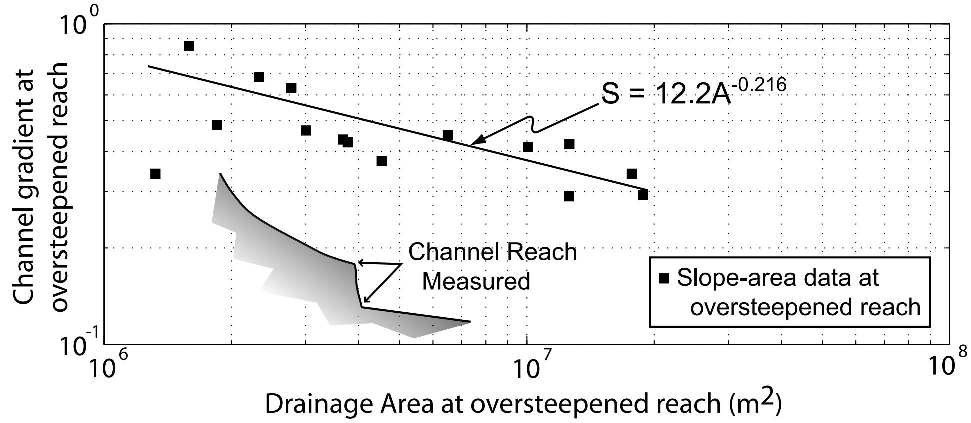

Figure 10. Plot of channel gradient versus upstream drainage area for oversteepened reaches at the mouths of tributary channels in the Liwu, Mukua, and Hoping basins. Drainage area dependence of channel gradient for these oversteepened reaches suggests that the larger streams maintain a greater capacity to erode despite the process transition at the tributary mouth.

gradients are generally associated with the smallest drainage area basins, and the lowest gradients occur in tributaries with larger drainage areas. This observed drainage area dependence suggests that erosion rates at the tributary mouths are not completely decoupled from the transport conditions in the tributary channel: larger tributaries have lower gradients along their oversteepened reaches presumably because they have more erosive power.

[29] The second threshold condition, the critical drainage area needed to develop a hanging valley in this landscape given the recent rate of main stem incision, can also be evaluated using our data. Figure 11a summarizes all of the trunk and tributary drainage area data from the Hoping, Liwu, and Mukua basins, along with the classification of each tributary as adjusted, linear, containing knickpoints with gradients commensurate with those in the trunk stream, or hanging. Note that all of the channels classified as hanging valleys occur at a small tributary drainage area (less than ~20 km^2), supporting a model in which there may be a threshold drainage area required to generate a hanging valley [*Crosby and Whipple*, 2006]. In addition, nearly all of the hanging valleys are also found at a high trunk to tributary drainage area ratio (≥10:1), lending support to a model in which drainage area ratio may be the relevant control on hanging valley development. Although we do not have enough data to accurately determine the absolute values of drainage area or drainage area ratio that might be required to generate a hanging valley, the patterns revealed by our data set support a conceptual model in which trunk and tributary drainage areas, which control the relative rates of knickpoint migration as a wave of incision passes a tributary mouth, play an important role in the formation of hanging valleys.

[30] We restrict our discussion here to basins which enter trunk streams downstream of prominent knickpoints, and therefore lie within the portion of the landscape that appears to be adjusting to tectonic or climatic perturbation. In order to help frame our discussion, we also focus on tributaries with a trunk:tributary drainage area ratio greater than 10:1. However, we stress that this value is chosen only as a baseline, and our intention is not to imply that this value represents a physically meaningful threshold. Figure 11b summarizes the data from all of these tributaries, focusing on a drainage area less than 20 km^2.

[31] While our data indicate that drainage area may be an important variable in controlling hanging valley formation, they also indicate that other local conditions play an important role in determining which tributaries will hang. For example, among the tributaries entering the adjusting portion of the trunk stream with a trunk:tributary drainage area ratio greater than 10:1, only ~15% were categorized as hanging valleys. The remaining tributaries were placed in other categories, indicating a variety of response mechanisms at high trunk:tributary drainage area ratio. Most commonly (~45% of the time), tributaries with a trunk: tributary drainage area ratio greater than 10:1 were classified as linear, suggesting erosion by debris flow processes [*Montgomery and Foufoula-Georgiou*, 1993; *Stock and Dietrich*, 2003]. These profiles show no indication of a transient response to main stem incision, suggesting either an insensitivity to incision rate or simply fast response times. Approximately 25% of channels with a trunk:tributary drainage area ratio greater than 10:1 have smooth, steep profiles with steepness indices commensurate with the steep lower "adjusting" reach of the main stem. These tributaries appear to have fully adjusted to the new main stem incision rate. The remaining channels (~30%) exhibit clear signs of a transient response to accelerated incision. Of these, we classify about half as distinctively hanging valleys, where channel gradients have dramatically oversteepened in response to main stem incision, in some cases forming waterfalls. The relevant question, then, is why some tributaries with a large trunk to tributary drainage area ratio become hanging valleys, while others do not.

[32] As noted above, the largest number of the tributaries with a trunk:tributary drainage area ratio greater than 10:1 have linear morphologies, consistent with erosion by debris flow, rather than fluvial incision processes [*Montgomery and Foufoula-Georgiou*, 1993; *Stock and Dietrich*, 2003]. None of these linear profiles contain knickpoints or hanging morphologies, and none of the channels containing knickpoints or hanging morphologies are linear upstream of the

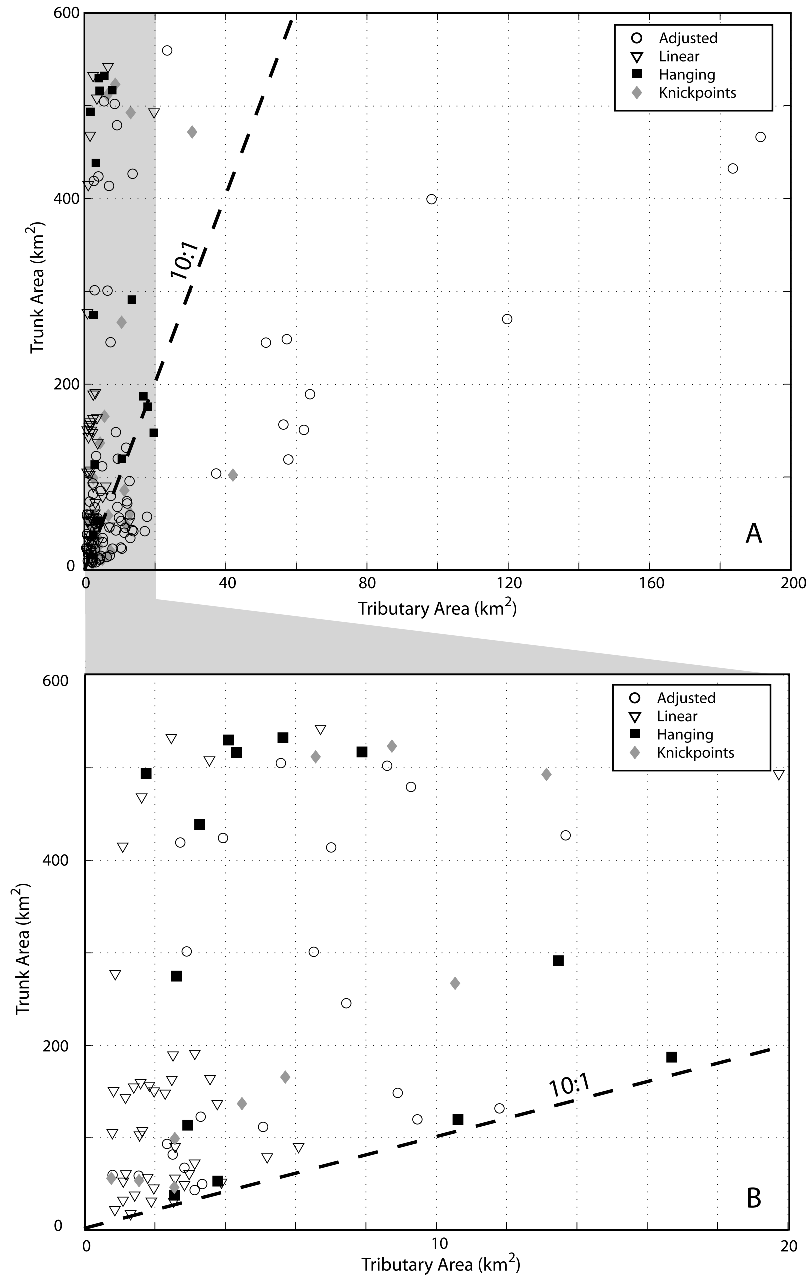

Figure 11. Plot of tributary versus trunk stream drainage area at each classified tributary junction for the Mukua, Liwu, and Hoping basins. Symbols represent the style of tributary adjustment based on observations from long profile and slope-area data. Thick dashed lines show trunk to tributary drainage area ratio of 10:1. (a) Data from all of the basins analyzed. Note that all tributaries classified as "hanging" occur at small drainage area. (b) Data from all tributaries entering trunk streams within "adjusting" portion of the landscape with a trunk:tributary drainage area ratio >10:1 and contributing drainage area < 20 km^2. Note that many of the "false positives" in Figure 11b have linear morphologies, possibly reflecting a process transition to debris flow erosion (see text).

knickpoint. While we have only a small data set to draw from, the observation that linear profiles do not hang suggests that channels dominated by debris flow incision are not susceptible to the same negative feedback as those dominated by fluvial incision processes, and hence these tributaries may be more likely to keep pace with main stem lowering driven by tectonic or climatic forcing. This observation suggests that debris flow incision becomes an important mode of landscape response in steep mountain catchments [*Stock and Dietrich*, 2003], which may have important implications for the style and duration of transient landscape response in these settings.

[33] Most of the remaining "false positives," tributaries with high trunk:tributary drainage area ratios but exhibiting adjusted or knickpoint morphologies, appear to reflect either differing responses to perturbation due to local conditions,

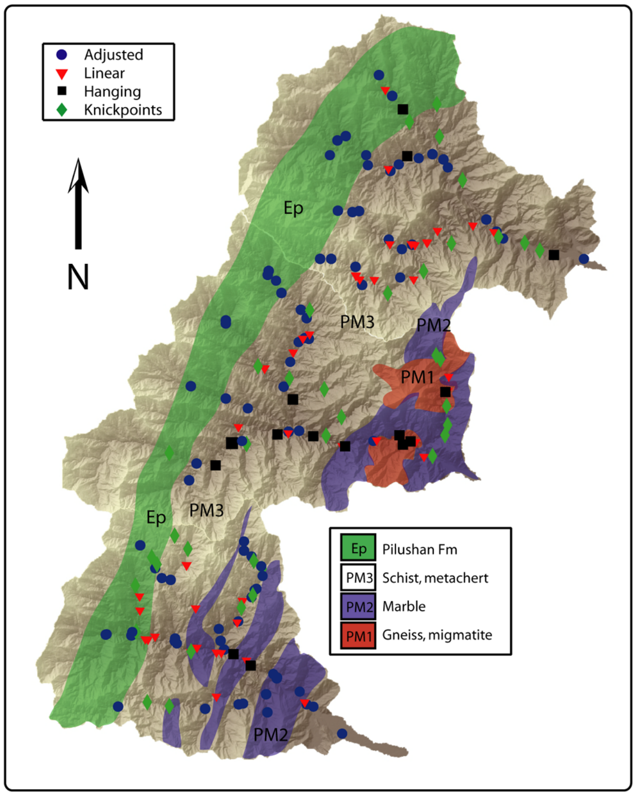

Figure 12. Map of tributary junction classifications superimposed on a geologic map of Taiwan. Note that hanging valleys are found in all mapped lithologies within the study area, suggesting that the development of these features is not strongly controlled by local lithology.

or morphologies whose classifications were ambiguous due to the limited resolution of our digital topographic data[1]. For example, most of the ''adjusted'' tributaries with high trunk:tributary drainage area ratios have uniform steepness indices comparable to those in the lower reaches of the trunk streams, suggesting that their adjustment to tectonic or climatic perturbation has been completed without an over-steepening of the tributary mouth. Local differences in water or sediment flux, rock strength, or erosional process may have allowed these profiles to keep pace with main stem lowering during transient adjustment despite the mismatch between potential erosive power in the trunk and tributary basins. Differences in the morphology of adjacent tributaries subject to the same base level history have also been observed in the Red River of Yunnan, China, suggesting that subtle differences in local substrate or hydraulic conditions can drive substantial differences in the transient response of a tributary catchment [*Schoenbohm et al.*, 2004].

[34] Many of the tributary mouths classified as ''knickpoints'' have gradients that appear to be somewhat oversteepened relative to the main stem, but not dramatically so. Given the limitations of our topographic data and lack of field observations, however, we have been intentionally conservative in classifying tributary basins as ''hanging.'' Thus it is possible that several of these ''knickpoint'' tributaries would be more properly labeled as hanging valleys. Definitively distinguishing between these two similar profile morphologies would require field observation and/or a higher resolution digital topographic data set. We hope our preliminary analysis and interpretation will motivate further research on this problem, including a more detailed, field-based analysis of the drainage basins discussed here.

[35] On the basis of the above observations, it seems likely that local conditions will commonly play a role in controlling the transient morphology of tributary basins, suggesting a sensitivity to subtle differences in local geography, substrate properties, incision history, or other variables. As one example of local geographic control, nearly all of the hanging valleys identified from our initial analysis of eight eastern Taiwan catchments were found in the three basins discussed here, and most were found in the Liwu and Hoping basins. Because of the rough north-south space for time substitution along the eastern margin of Taiwan, these basins lie within the most rapidly uplifting portion of the Taiwan orogen, between the ongoing arc-continent collision in the south and its extensional collapse in the north [*Dadson et al.*, 2003; *Willett et al.*, 2003]. This setting might give rise to the strong tectonic forcing necessary to isolate tributary catchments from upstream-migrating waves of incision. Furthermore, the Liwu and Hoping rivers empty directly into the sea, where a steep continental shelf [*Lee et al.*, 1997] would make both catchments sensitive to knickpoint development driven by eustatic forcing [*Snyder et al.*, 2002]. In contrast, many of the other basins along the eastern margin of Taiwan are insulated from eustatic variations by the north-south trending Longitudinal Valley (see Figure 3). It is possible that the basins in northern Taiwan are simply ideally situated in space, which has enabled us to capture a number of knickpoints and hanging valleys within these basins during our snapshot in time.

[36] Another possible local control on the development of hanging valleys is lithology. Most of the hanging valleys described here are from the Liwu river basin, whose lower reaches comprise resistant marbles, gneisses and migmatites (Figure 12). These resistant lithologies would be expected to transmit waves of incision upstream in a relatively intact, ''detachment-limited'' manner [*Crosby and Whipple*, 2006; *Whipple and Tucker*, 1999, 2002]. As these coherent knickpoints pass tributary mouths, the tributary channels would therefore steepen quickly, favoring the creation of hanging valleys as described in our conceptual model. While field observations indicate that the lowermost reaches of the Liwu river are filled with alluvium which could potentially diffuse these coherent knickpoints [*Whipple and Tucker*, 2002], these alluviated reaches are likely to be quickly excavated during a base level fall, perhaps forcing detachment-limited erosive behavior.

4.2. Implications for Landscape Response

[37] The presence of hanging valleys in the eastern Central Range of Taiwan challenges the notion that this landscape is in an approximate steady state balance between erosion and tectonic uplift [*Suppe*, 1981; *Whipple*, 2001; *Willett and Brandon*, 2002; *Willett et al.*, 2003], or at least

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/jf/2005jf000406.

motivates the question of what spatial and temporal scales are relevant in assessing the steadiness of an orogenic system. Because waves of incision are frequently stalled at tributary junctions, erosion rates along the eastern Central Range are likely to vary significantly on opposite sides of these junctions. This suggests a pattern of erosion rates that is highly variable in space, and uncorrelated with the positions of major tectonic structures. At the scale of individual drainage basins, then, a balance between rock uplift rate and erosion rate is unlikely to be achieved. In addition, while the distribution of cooling ages in Taiwan can be interpreted as evidence for an exhumational steady state over million year timescales [*Willett et al.*, 2003], hanging valleys may be important in prolonging stochastic perturbations away from this steady form, such as those resulting from oscillatory changes in climate state [*Whipple*, 2001]. Depending on the spatial and temporal scales of interest, then, models which invoke a steady state hypothesis for Taiwan, or indeed for any orogen, should be interpreted with caution.

[38] For a well-behaved system in which erosion rate scales predictably with parameters such as channel gradient and drainage area, theoretical considerations suggest that the minimum timescale for landscape response can be easily estimated [*Whipple*, 2001; *Whipple et al.*, 1999; *Whipple and Tucker*, 2002]. The possibility that hanging valleys may form in purely fluvial systems reinforces the notion that these theoretical estimates are minima, and that landscape response timescales in real systems will always exceed these estimates, since much of the landscape lags behind in its response to tectonic perturbation. This in turn reinforces the argument that steady state conditions will rarely be achieved in real orogens [*Whipple*, 2001]. Incorporating into landscape evolution models a nonmonotonic relationship between channel gradient and erosion rate, and a description of other processes that become important at tributary junctions when thresholds are exceeded (e.g., plunge pool erosion, weathering, mass wasting, etc), may help us to make more accurate predictions about the timescales of landscape response and enhance our ability to make robust interpretations of tectonic events from study of landforms.

5. Conclusions

[39] Our analysis of the eastern Central Range of Taiwan indicates that hanging valleys can develop in purely fluvial networks, and that these hanging valleys can temporarily insulate the catchments above them from tectonic perturbations migrating up the trunk streams. While our conceptual model remains preliminary, we propose that hanging valleys can be explained by incorporating a nonmonotonic relationship between transport stage and erosion rate into existing bedrock erosion rules [e.g., *Sklar and Dietrich*, 2004]. This important modification to existing erosion rules allows the rate of erosion to fall once a channel gradient exceeds a threshold value. On the basis of our observations from hanging valleys along the northeastern coast of Taiwan, it appears that a small contributing drainage area in the tributary and/or a large ratio between trunk and tributary drainage areas may be necessary, but not alone sufficient, conditions for the formation of hanging valleys. Our conceptual model for hanging valley formation highlights the important first-order effects that thresholds in bedrock channel incision processes can have on landscape form, and underscores the value of studying transient landscape response to test geomorphic transport and incision rules. Recognition of process transitions at threshold conditions, and better physically based rules describing those distinct processes, will greatly improve our ability to simulate landscape response to external forcing. In turn, incorporation of these more comprehensive erosion rules into landscape evolution models will help us to better predict landscape response timescales, understand the nature of the coupling among tectonics, climate and landscape form, and interpret landforms in terms of their tectonic and climatic history.

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