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Hillslope response to knickpoint migration in the Southern Appalachians: implications for the evolution of post-orogenic landscapes

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ABSTRACT: The southern Appalachians represent a landscape characterized by locally high topographic relief, steep slopes, and frequent mass movement in the absence of significant tectonic forcing for at least the last 200 Ma. The fundamental processes responsible for landscape evolution in a post-orogenic landscape remain enigmatic. The non-glaciated Cullasaja River basin of south-western North Carolina, with uniform lithology, frequent debris flows, and the availability of high-resolution airborne lidar DEMs, is an ideal natural setting to study landscape evolution in a post-orogenic landscape through the lens of hillslope–channel coupling. This investigation is limited to channels with upslope contributing areas >2.7 km^2, a conservative estimate of the transition from fluvial to debris-flow dominated channel processes. Values of normalized hypsometry, hypsometric integral, and mean slope vs elevation are used for 14 tributary basins and the Cullasaja basin as a whole to characterize landscape evolution following upstream knickpoint migration. Results highlight the existence of a transient spatial relationship between knickpoints present along the fluvial network of the Cullasaja basin and adjacent hillslopes. Metrics of topography (relief, slope gradient) and hillslope activity (landslide frequency) exhibit significant downstream increases below the current position of major knickpoints. The transient effect of knickpoint-driven channel incision on basin hillslopes is captured by measuring the relief, mean slope steepness, and mass movement frequency of tributary basins and comparing these results with the distance from major knickpoints along the Cullasaja River. A conceptual model of area–elevation and slope distributions is presented that may be representative of post-orogenic landscape evolution in analogous geologic settings. Importantly, the model explains how knickpoint migration and channel–hillslope coupling is an important factor in tectonically-inactive (i.e. post-orogenic) orogens for the maintenance of significant relief, steep slopes, and weathering-limited hillslopes. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: transient phenomena; channel–hillslope coupling; knickpoint migration; post-orogenic landscape evolution; Southern Appalachians

Introduction

The southern Appalachian Mountains of North Carolina west of the Blue Ridge escarpment (BRE) sustain relatively high relief (*ca* 1 km) and are prone to numerous and frequent mass-wasting events (Wooten *et al.*, 2006, 2008). Given that most researchers agree that this region has been tectonically inactive since at least the Late Triassic (Oyarzun *et al.*, 1997), we ask the question how do these landscapes maintain such high relief and steep slopes that are prone to frequent mass wasting events. The primary objectives in this investigation are to gain insight into the fundamental driving forces behind the long-term maintenance of topographic relief and concomitant steep and unstable slopes in post-orogenic landscapes.

Many studies have investigated knickpoint migration through fluvial networks (Gardner, 1983; Whipple, 2001; Harbor *et al.*, 2005; Crosby and Whipple, 2006; Crosby *et al.*, 2007; Hayakawa and Oguchi, 2006, 2009), and the transient hillslope response to upstream knickpoint propagation (Weissel and Seidl, 1997; Bishop *et al.*, 2005; Bigi *et al.*, 2006; Korup and Schlunegger, 2007); however, the relationship between knickpoint migration, hillslope response and its control on long-term slope stability remains poorly understood. We propose that the active upstream migration of knickpoints through fluvial networks along the eastern flank of the tectonically inactive southern Appalachian Mountains has resulted in the development of transient hillslope response to local channel steepening, where both measures of local relief and slope steepness are increasing in the absence of evidence for bedrock uplift.

The past several decades have seen a concerted effort to understand the physical processes responsible for the incision of steams into bedrock (Seidl and Dietrich, 1992; Merritts *et al.*, 1994; Howard, 1998; Pazzaglia *et al.*, 1998; Sklar and

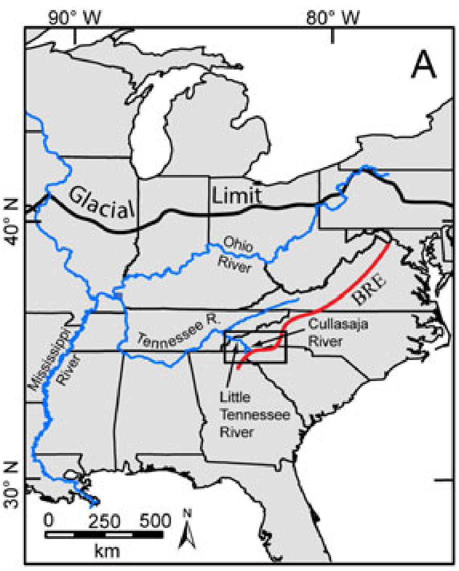
Dietrich, 1998; Weissel and Seidl, 1998; Whipple and Tucker, 1999, 2002; Tucker and Whipple, 2002). Gilbert (1877) realized that the rate at which streams are able to lower the elevations of their beds through incision into bedrock is a fundamental control on the erosion of adjacent hillslopes, and by extension is the dominant process governing the local and regional pace of landscape evolution. Knickpoint migration is one mechanism by which streams are able to incise into rock, and from which changes in baselevel are transmitted from the channel to slopes and ultimately to drainage divides. Conceptually, the time-transgressive upstream migration of knickpoints through a fluvial network will impact adjacent hillslope properties and processes (e.g. gradient and mass wasting frequency). Analog and numerical models have been used to demonstrate how upstream propagating channel incision may force hillslope response in time and space (Culling, 1960; Howard, 1994; Fernandes and Dietrich, 1997; Bigi *et al*., 2006); however, studies of these linkages in natural settings are limited because direct correlations between channel and hillslope processes are often confounded owing to complexities within and between geologic, geomorphic, and hydrologic systems (Carson and Kirkby, 1972; Bull, 1991; Mudd and Furbish, 2007; Norton *et al*., 2008). A natural laboratory was identified in the southern Appalachians where it is possible to directly investigate coupling between fluvial channels and hillslopes driven by knickpoint retreat.

Located west of the Blue Ridge escarpment in Macon County, North Carolina, the Cullasaja River basin (Figure 1) is an ideal location to investigate the coupling between channel incision and concomitant hillslope response in a tectonically inactive landscape for several important reasons. First, numerous historic mass wasting events have occurred in the basin (e.g., the 2004 Peeks Creek debris flow) and relict landslide deposit are widespread, both proof that basin hillslopes are prone to gravitational failure. Second, basin relief of nearly 1 km, steep slopes (up to 73° and a mean of 20° ± 9°), and high intensity and duration precipitation events associated with subtropical cyclones are conducive to the continued failure of slopes by debris flows and other mass wasting mechanisms (Liebens and Schaetzl, 1997), as attested to by basin-wide slope stability mapping results (Wooten *et al*., 2006, 2008). Third, relatively uniform bedrock geology with similar rock-mass strength (Burton, 2007), implies that lithologic variability is of limited importance to knickpoint formation and migration (Figure 2). Fourth, the Cullasaja River and its tributaries contain multiple prominent knickpoints, representing a time-transgressive record of southern Appalachian landscape evolution (Figure 3A–3C). And finally, the availability of high-resolution (6 m horizontal and 0.1 m vertical) airborne lidar digital elevation models (DEMs) for the entire basin permit detailed topographic analyses.

Geologic and Geomorphic Setting

The 240 km^2 Cullasaja River basin is located in the southern Appalachians of western North Carolina (Figure 1). Sitting west of the Eastern Continental Divide along the Blue Ridge escarpment, basin headwaters (>1500 masl) begin near the town of Highlands, NC and flow north and west for 43 km before reaching the confluence with the Little Tennessee River at Franklin, NC (600 masl). Numerous waterfalls are located along the Cullasaja River and its tributary streams, including Cullasaja, Quarry, Dry, Kalakaleskies, and Bridal Veil falls (Figures 2 and 3).

The predominantly bedrock channels of the Cullasaja River and its tributaries are cut into the Neoproterozoic Ashe Metamorphic Suite of the Eastern Blue Ridge geologic province. The Ashe suite is composed of biotite-muscovite gneiss, metamorphosed quartz diorite to monzonite and minor meta-ultramafic rocks (Dicken *et al*., 2005; Burton, 2007; Thigpen and Hatcher, 2009; Figure 2b). The last orogenic event to effect the southern Appalachians was the Carboniferous-Permian (~320–260 Ma) Alleghanian orogen and it is believed that this portion of the mountain range has been tectonically quiescent since the end of Mesozoic rifting (~200 Ma; Oyarzun *et al*., 1997; Hatcher, 2002; Spotila *et al*., 2004). Fluvial bedrock incision and shallow landsliding on adjacent hillslopes dominates the present-day evolution of this landscape. Identifiable geomorphic surfaces within the Cullasaja River basin vary between nearly flat, alluvium-draped floodplains and river terraces to steep hardwood-forested slopes. Bedrock is exposed on many slopes and both hillslopes and valley bottoms develop and maintain only thin soil mantles, with



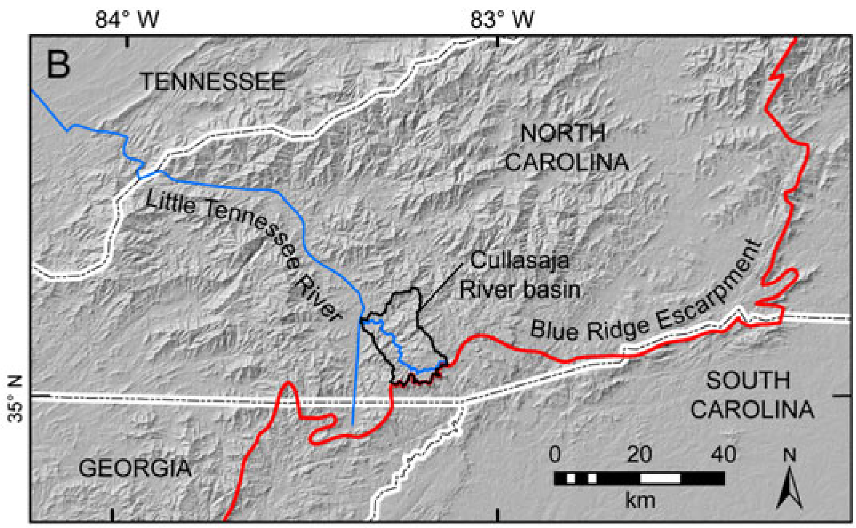


Figure 1. (A) Map of the eastern United States showing major rivers, the Blue Ridge Escarpment (BRE), and the southern limit of continental glaciation (Thelin and Pike, 1991) in relation to the Cullasaja River. The black rectangle overlying the upper Little Tennessee River basin is enlarged in B. (B) Hillshade image of southwestern North Carolina and adjacent states from SRTM digital topography; study area outlined in black. Note the absence of ridge relief west of the Blue Ridge Escarpment (solid thick line). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

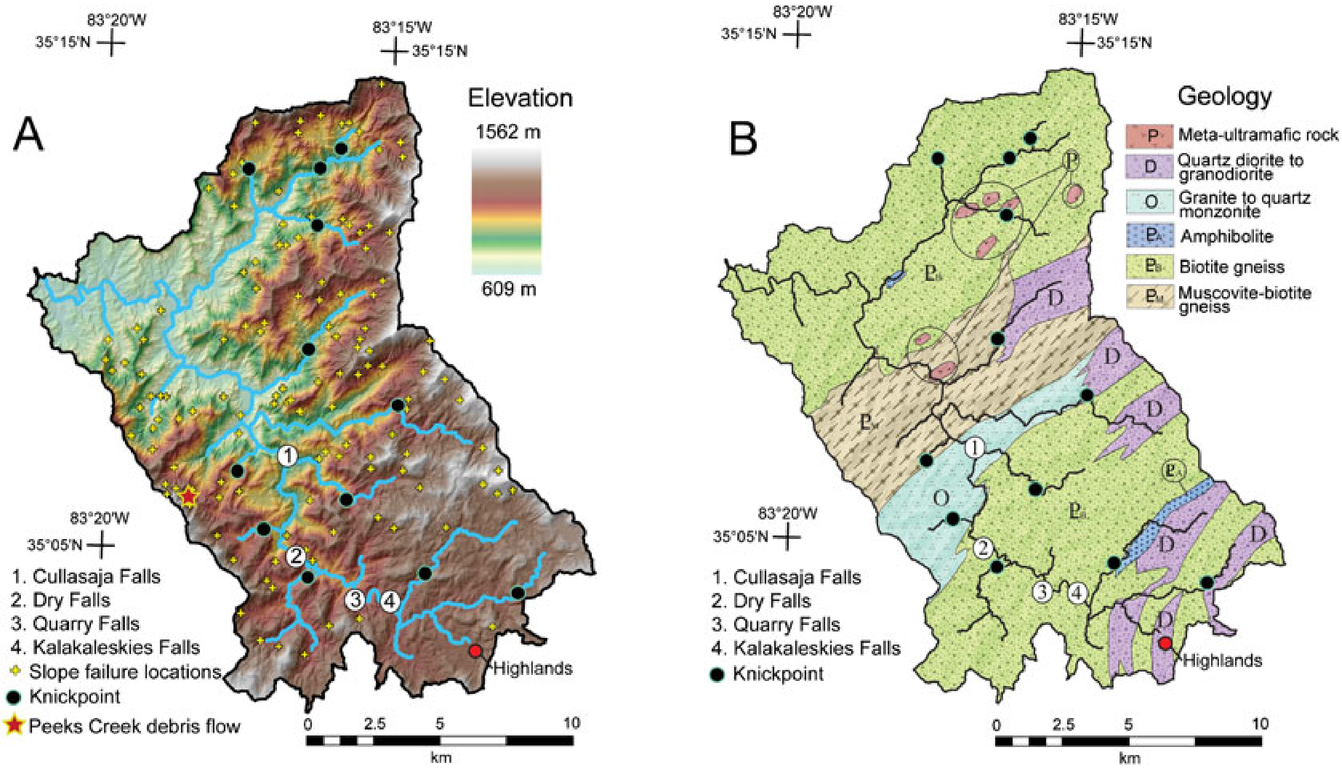


Figure 2. The Cullasaja River basin. The basin's fluvial network is defined by channels draining areas greater than 2.7 km^2. (A) Shaded relief map with locations of mapped slope failure locations from Wooten *et al.* (2006). (B) Geologic map of the Cullasaja River basin (North Carolina Geological Survey, 1985). The relative consistency of rock types suggests that lithology is not a first-order control on slope stability or knickpoint location. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

thicknesses ranging from <50 cm along ridgetops to >1 m beneath stream terraces, except for those areas where recent shallow landslides and debris flows have produced steep debris fans at tributary mouths. Shallow landsliding has stripped many upper hillslope segments to bedrock (Liebens and Schaetzl, 1997; Eaton *et al.*, 2003). The landscape as a whole is weathering-limited.

Baselevel fall and knickpoint formation

Studies demonstrate that upstream knickpoint migration plays a dominant role in initiating stream channel adjustment to changes in both regional and local baselevel (Gardner, 1983; Schumm *et al.*, 1987; Seidl and Dietrich, 1992, 1994; Weissel and Seidl, 1997; Zaprowski *et al.*, 2001; Bishop *et al.*, 2005; Crosby and Whipple, 2006). Regional controls on baselevel fall, such as eustasy and tectonic uplift, are not likely to be responsible for the knickpoints observed in the Cullasaja River basin. As shown by Schumm (1993), channel elevation perturbations from eustatic fluctuations are likely to be confined to the lower reaches of the Mississippi River, and almost certainly would not have propagated *ca* 1500 km upstream from the Gulf of Mexico to the Eastern Continental Divide. Moreover, most investigators agree that the southern Appalachians have not undergone significant tectonic forcing for more than 200 Ma (Oyarzun *et al.*, 1997; Spotila *et al.*, 2004). Furthermore, modeling of the contribution of mantle flow to surface topography predicts that the eastern USA overlies a zone of negative dynamic topography or subsidence (Steinberger, 2007; Forte *et al.*, 2010). The broad wavelength and slow rate of surface change probably preclude dynamic topography as a forcing mechanism for distinct bedrock knickpoints in the Appalachian headwaters of streams draining to the Gulf of Mexico (Braun, 2010).

The southern Appalachians were not glaciated (Carson *et al.*, 1974) and the Cullasaja River basin lies >500 km south of the terminal position of the last glacial maximum (LGM) Laurentide ice sheet; therefore, long-wavelength glacial isostatic adjustments are expected to be far-field to our study area, imparting only a minimal and uniform regional effect on surface elevations, if any. Modeling and stratigraphic studies suggest, however, that regional baselevel fall and valley incision on the eastern flank of the Appalachians may have its origin in the Cenozoic unroofing of the Appalachians, driven in large part by sediment loading onto, and subsidence of, the Atlantic coastal plain and shelf (Pazzaglia and Gardner, 1994). Subsidence of the US Atlantic margin may have resulted in isostatically-driven lithospheric response at a wavelength commensurate with the width of the modern topographic expression of the Appalachians (Pazzaglia and Brandon, 1996); however, the amount of surface uplift resulting from episodic lithospheric flexural isostatic forces modulated by eustatic sea level fluctuations and sedimentation rate on the Atlantic continental shelf should decrease in a westward direction away from the Eastern Continental Divide, and as such is an unlikely driving mechanism for eastward migrating knickpoints in west-draining streams. At present the exact mechanism(s) responsible for the genesis of knickpoints on west-draining southern Appalachian streams is unknown and is an area of needed research. With that said, we envision that local controls on baselevel and river incision into bedrock, such as stream capture (Zaprowski *et al.*, 2001), lithologic variability (Miller, 1991; Alexandrowicz, 1994; Harbor *et al.*, 2005), and stream power contrasts at tributary junctures (Crosby and Whipple, 2006), perhaps modulated by autogenic processes (Limaye and Lamb, 2010) or late Cenozoic climate unsteadiness (Hancock and Anderson, 2002; Reusser *et al.*, 2004, 2006; Ward *et al.*, 2005; Hancock and Kirwan, 2007) might represent a more likely explanation for the formation and upstream propagation of the prominent knickpoints in the Cullasaja Basin.

Figure 3. Field photographs (A – C) of Cullasaja River knickpoints (from http://www.panaramio.com). (A) Cullasaja Falls. (B) Dry Falls. (C) Quarry Falls. (D) Photograph of the upper portion of the September 15, 2004 Peeks Creek debris flow track, triggered by excessive precipitation from the remnants of Hurricanes Francis and Ivan. This debris flow destroyed 15 homes and took five lives and is a reminder of the mass wasting hazard potential in the southern Appalachians (Wooten *et al.*, 2008). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Methods

A geographic information system (GIS) was used to perform a variety of hillslope and stream channel analyses on a 6 m resolution (horizontal) airborne lidar DEM (North Carolina Division of Emergency Management, 2006). The surface hydrographic network of the Cullasaja River basin was defined by generating flow direction and flow accumulation models from the DEM in ArcGIS. The high frequency of debris flows within the Cullasaja basin is expected to influence channel morphology, especially along the upper reaches of a river basin, which may complicate longitudinal profile analysis (Wobus *et al.*, 2006). As such, a conservative minimum drainage area threshold of 2.7 km^2 was used to define channel initiation points, as this may represent the approximate up-basin drainage area needed to separate channels dominated by fluvial processes from those dominated by hillslope-debris flow processes in this environment (Montgomery and Foufoula-Georgiou, 1993). A total of 14 major tributaries were delineated from their confluence with the Cullasaja River up to the watershed divide using this method (Figures 2 and 4).

Longitudinal profiles of the Cullasaja River and its tributaries were extracted from the confluence with the Little Tennessee River to their respective drainage divide using the StreamProfiler tools package (http://geomorphtools.org) within ArcGIS and Matlab. Prior to analysis, each longitudinal profile was smoothed using a 100 m sampling window in order to remove pre-processing artefacts and random noise embedded in the DEM that might otherwise interfere with subsequent visual identification of knickpoints. Knickpoints were defined as

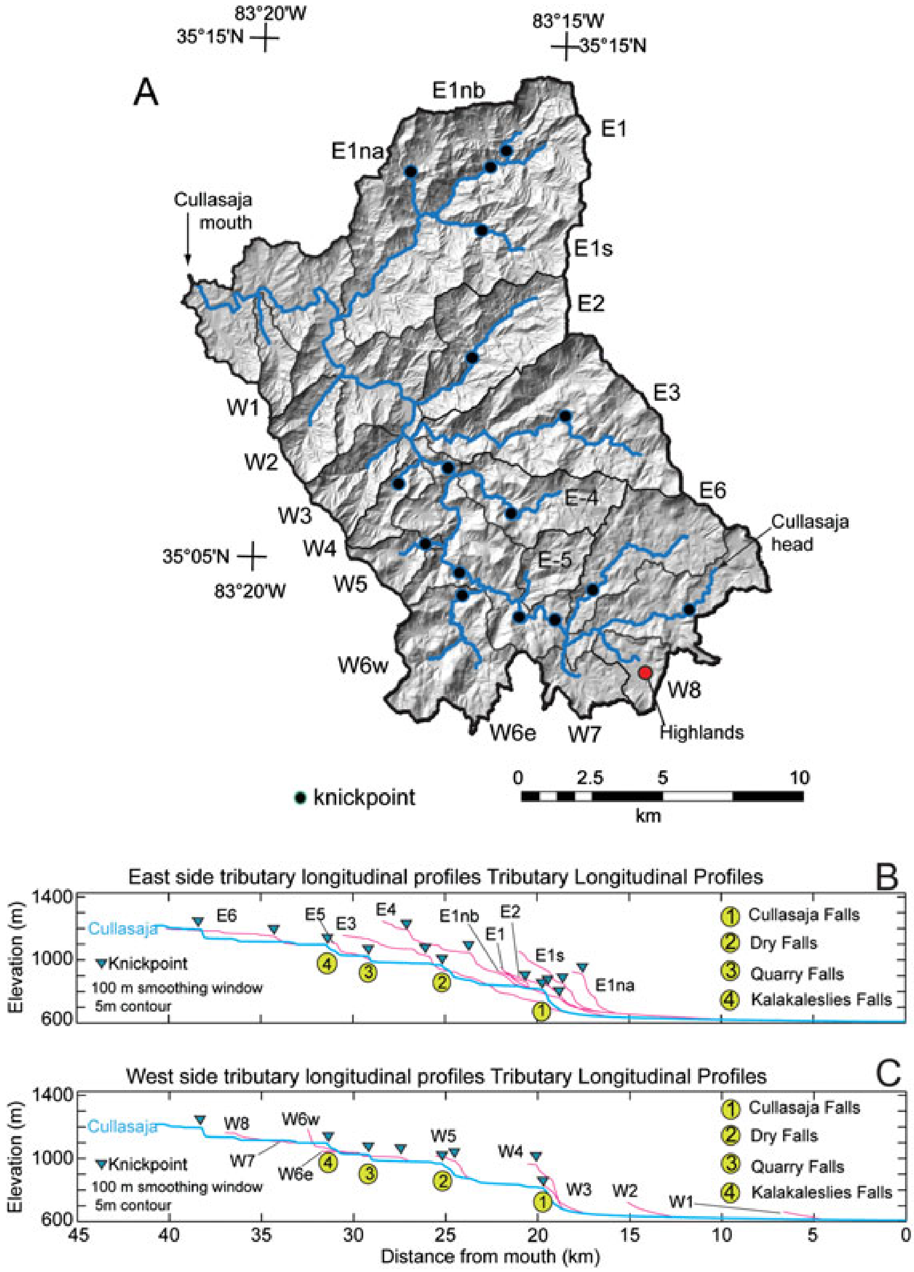


Figure 4. Distribution of elevation, knickpoints, and longitudinal profiles for the Cullasaja River and its major tributaries. (A) Airborne lidar digital elevation model (6 m) of the Cullasaja River basin. West- and east-side tributary basins discussed in the text are labeled sequentially beginning with the most northerly (e.g. E1, W1, etc.) and delineated by black lines. Knickpoints (black circles) were identified from longitudinal profiles as convex channel reaches dropping a minimum of 15 m in 0.5 km (gradient ≥ 0.3). (B and C) Channel longitudinal profiles of the Cullasaja River (heavy line) and tributaries (thin lines) draining areas greater than 2.7 km^2 as a function of distance from the basin mouth. A total of 16 prominent knickpoints (triangles) were identified within the basin, five along the Cullasaja trunk channel, four of which correspond to prominent waterfalls (1 – Cullasaja Falls; 2 – Dry Falls; 3 – Quarry Falls; and 4 – Kalakaleskies Falls). Tributary basins with more than one channel have lower case letters denoting geographic position of the channel within the sub-basin (north, **n**; south, **s**; east, **e**; west, **w**). Lowercase letters **a** and **b** are used when more than one channel exists within a given quadrant of the tributary basin. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

pronounced convex upward perturbations on otherwise smooth concave-up longitudinal profiles with channel elevations that dropped at least 15 m per 500 m of bed length (gradient ≥ 0.03). In total, 16 knickpoints were identified using this method including all of the named waterfalls along the Cullasaja River (Figures 2, 3, and 4).

The spatial distributions of elevation, relief, and slope were quantified by constructing a swath profile along the approximate trend of the Cullasaja River valley. The swath profile consists of five lines spaced at 500 m intervals and sampled every 100 m from the digital elevation, relief, and slope models (Figure 5). The topographic relief model was generated by passing a 500 m circular radius focal range window over the original DEM (Figure 5B). To characterize slope variations at the sub-basin scale a mean slope model was constructed by passing a 500 m circular radius focal mean window across a basic slope model derived from the original DEM (Figure 5C). The mean relief and mean slope for each of the 14 sub-basins were calculated by averaging the relief and basic slope layers, respectively, over the entirety of each sub-basin. In addition, the density of naturally occurring mapped landslides per km^2 from Wooten *et al.* (2006) was calculated for each tributary drainage basin (Figure 6).

To evaluate landscape transients imparted by upstream migration of knickpoints hypsometric (proportion of area vs elevation) and mean slope vs elevation plots were produced

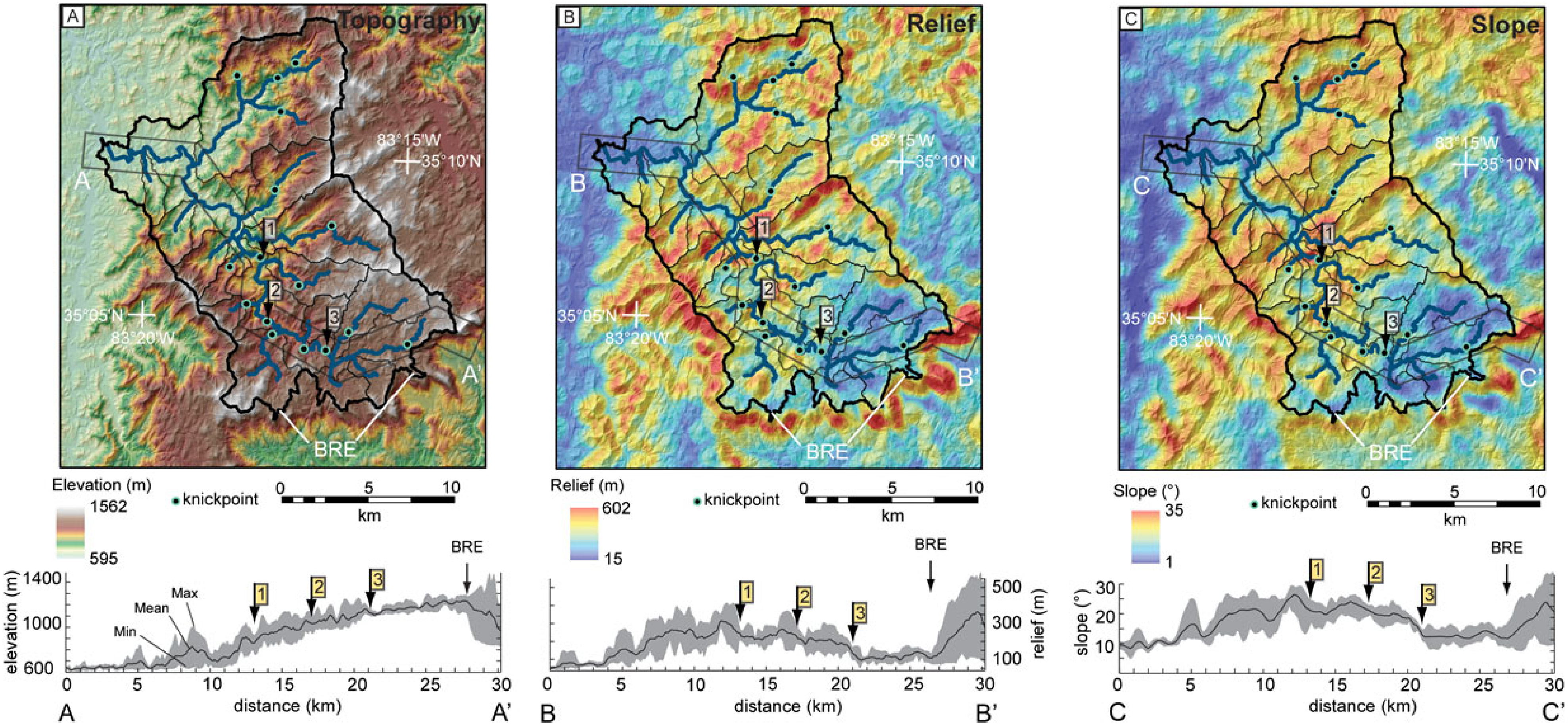


Figure 5. Swath profiles of maximum, mean, and minimum values of elevation, relief, and slope taken along the approximate trend of the Cullasaja River valley, each ~30 km long by 2 km wide. (A) Topographic swath extracted from the 6 m resolution lidar DEM. (B) Relief swath derived from a 500 m focal range analysis of the DEM. (C) Slope swath extracted from a 500 m focal mean analysis of a slope map generated from the original topographic DEM. On the profiles below the maps the position of the Blue Ridge Escarpment marks the upper limit of the Cullasaja River basin, and the numbers *1*,*2*, and *3* correspond to the location of Cullasaja Falls, Dry Falls, and Kalakaleskies Falls, respectively. Note the arc of increasing mean relief and mean slope beginning at Kalakaleskies Falls (3) that then begins to decay downstream of Cullasaja Falls (1).

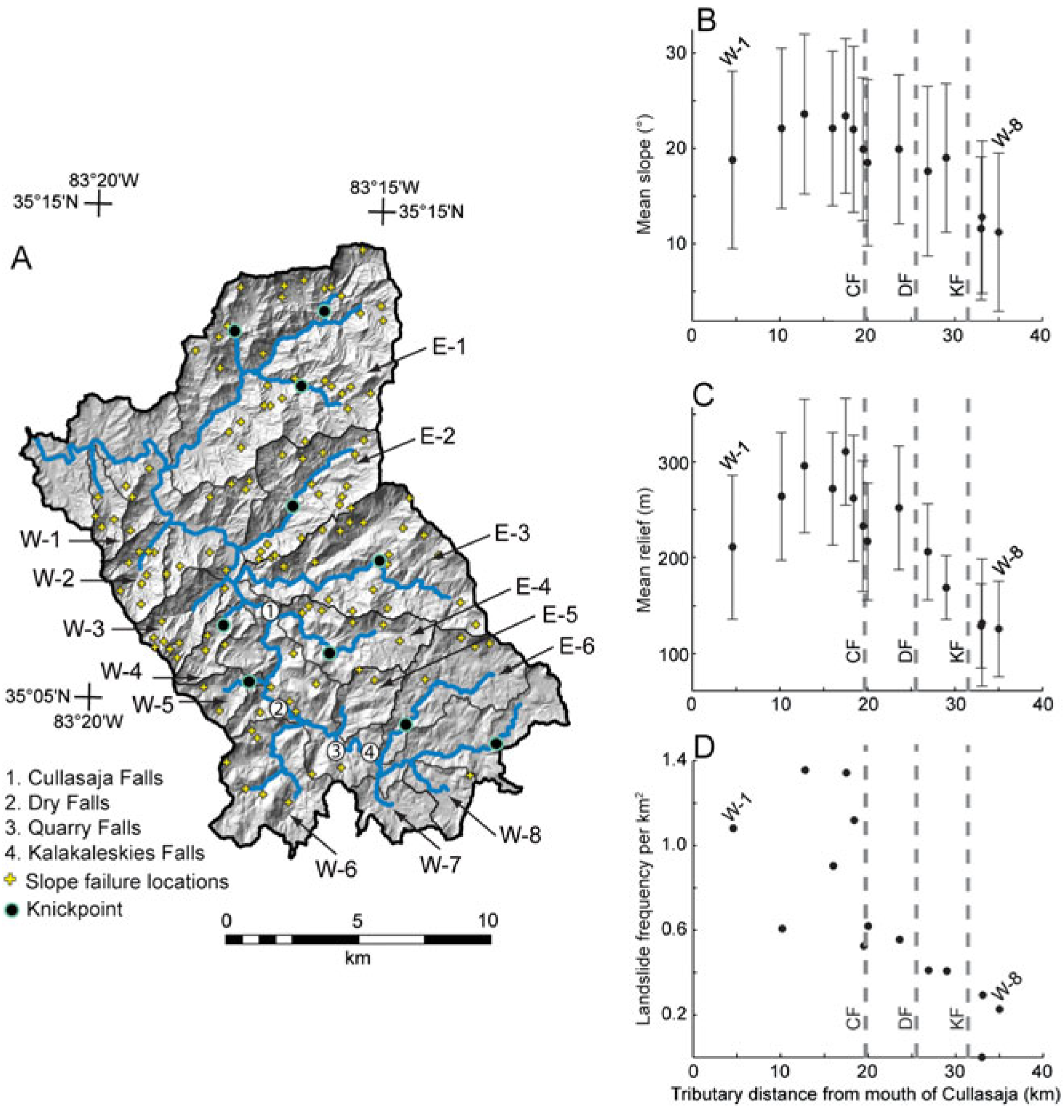


Figure 6. Values of mean slope, relief, and landslide frequency as a function of tributary basin position along the Cullasaja River. (A) Shaded relief map highlighting the main tributary basins and mapped landslides (Wooten *et al*., 2006) within the Cullasaja River basin. (B and C) Values of mean slope, relief, and their associated standard (1σ) errors as a function of tributary confluence distance from the mouth of the Cullasaja River. (D) The frequency of mapped landslides for each tributary basin. Note the overall increase in observed mean slope, relief, and landslide frequency downstream of Cullasaja Falls. The locations of Cullasaja (CF), Dry (DF) and Kalakaleskies (KF) falls are denoted by vertical dashed lines. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

for each of the 14 tributary drainage basins (Figure 7). The hypsometric dataset was generated for individual sub-basins by summing the pixel frequency within individual 25 m elevation bins. Determination of the hypsometric integral (HI) for sub-basins was estimated by:

$$HI = (Z_0 - Z_{min})/(Z_{max} - Z_{min}) \quad (1)$$

where Z_0, Z_{min}, and Z_{max} are the mean, minimum and maximum elevations, respectively, for the entire sub-basin.

Results

Knickpoints and topographic metrics

Metrics derived from swath profiles of topography, relief, and slope exhibit discernible changes along the length of the river basin between three of the prominent knickpoints, Cullasaja Falls, Dry Falls and Kalakaleskies Falls located ~13, 17, and 21 km, respectively, from the beginning of the swath profile near the basin mouth (Figure 5). Small increases in mean elevation, mean relief, and mean slope are observed immediately downstream from each of these waterfalls (Figure 5). The largest changes in the measured metrics are between the major Cullasaja knickpoints, from just below Cullasaja Falls to Kalakaleskies Falls. Specifically, the mean elevation of the river valley increases rapidly from just downstream of Cullasaja Falls at ~10 km to Kalakaleskies Falls at ~21 km along the swath profile (Figure 5a). Mean relief and mean slope progressively increase from ~5 km along the swath profiles to Cullasaja Falls at ~17 km. After which they show a generally decreasing trend to ~21 km at Kalakaleskies Falls, with the exception of small increases downstream of Dry Falls and Kalakaleskies Falls (Figure 5A and 5B). From a distance of 21 km along the swath profile to the Blue Ridge escarpment mean elevation, mean relief, and mean slope all remain relatively constant and with minimal variability (Figure 5).

Knickpoints and landslides

Each of the 14 tributary sub-basins of the Cullasaja River was investigated in order to quantify variations between hillslope

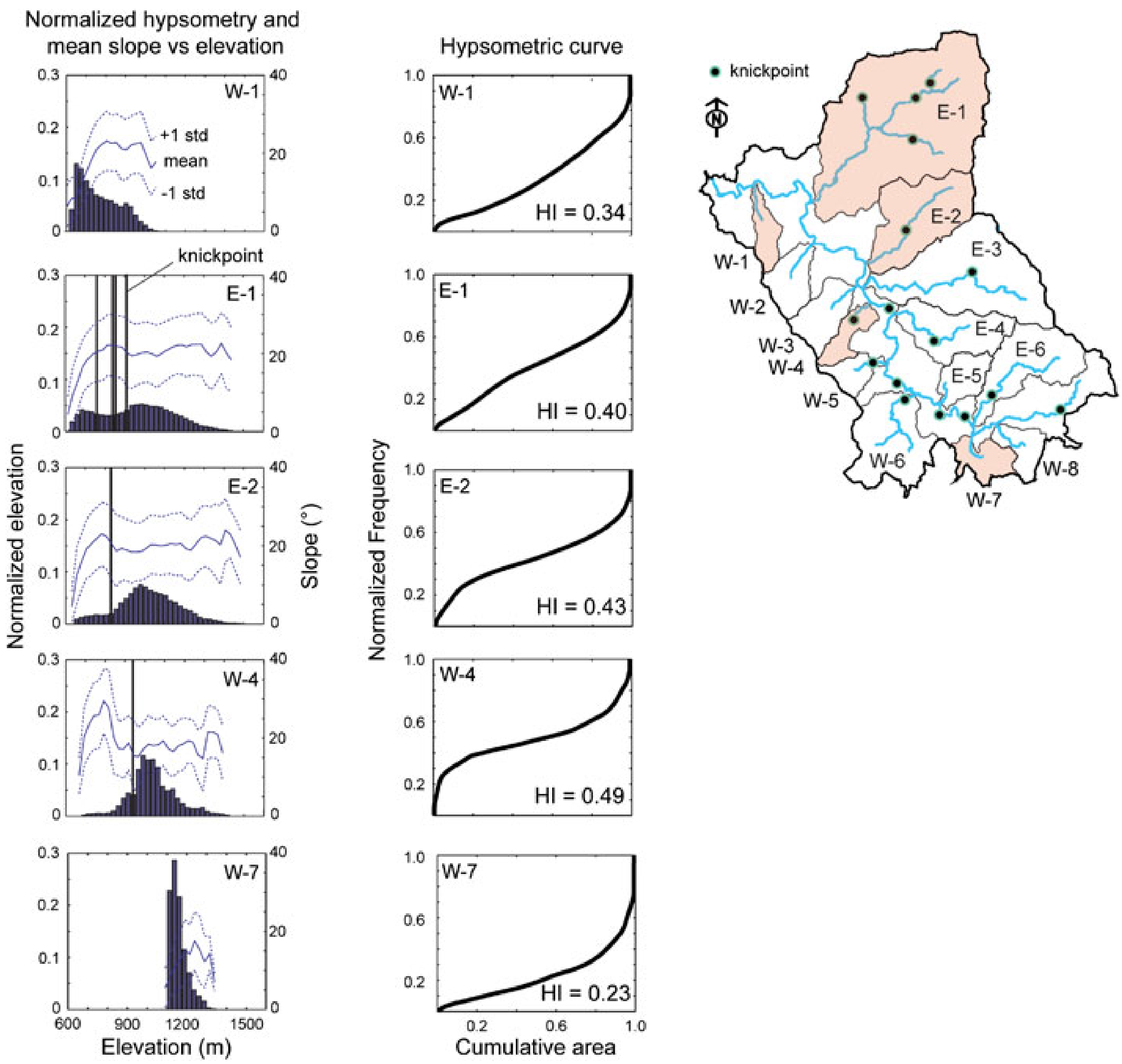


Figure 7. Spatial distribution of normalized hypsometry, mean slope, and individual hypsometric curves for representative tributary basins along the Cullasaja River. Vertical black lines on the normalized hypsometric plots show the elevation of identified knickpoints. Each plot shows tributary basins in different stages of landscape development. The spatial distribution of hypsometry and mean slope exhibits time-transgressive variations interpreted to result from knickpoint migration and concomitant hillslope response. Dispersion statistics for each hypsometric plot are provided in Table I. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

metrics, landslide distribution and tributary confluence distance from the mouth of the Cullasaja (Figure 6). Clear patterns are observed in mean slope, mean relief, and landslide frequency. Tributary basin mean slope and mean relief are lowest near the headwaters of the Cullasaja, both increasing until ~7 km downstream of Cullasaja Falls, after which they decrease (Figure 6B and 6C). The frequency of tributary basin landslides per unit area generally increases from the headwaters of the Cullasaja to its mouth (Figure 6D). The highest values for all of these parameters are found downstream of Cullasaja Falls.

Hypsometric evolution

The hypsometric and mean slope versus elevation relationships extracted from the 14 tributary basins fall into three broad groups of which representative examples are shown in Figure 7 (Table I). The first group (tributary basins W-1, W-7, W-8 and E-6) is characterized by positively skewed hypsometry with high peakedness and steeper mean slopes at high elevation and low hypsometric integrals relative to the other basins. Basins characterized by this type of elevation distribution are generally found farthest from the waterfalls both up and downstream (Figure 7; W-7 and W-1). The second group (W-3,

Table I. Distribution statistics of hypsometric plots derived from the 14 tributary sub-basins and the Cullasaja River basin

Tributary basin	Skewness	Peakedness	Modes	Hypsometric integral
E-1	0.0849	2.228	2	0.4
E-2	0.0171	2.935	1	0.43
E-3	−0.2142	2.474	1	0.51
E-4	−0.4545	2.387	1	0.54
E-5	−0.0772	2.168	1	0.49
E-6	1.2371	5.623	1	0.32
W-1	0.5225	2.184	1	0.34
W-2	0.4899	2.512	2	0.36
W-3	0.0902	2.629	1	0.45
W-4	0.351	3.76	1	0.49
W-5	0.4355	2.361	1	0.49
W-6	0.3956	2.406	1	0.39
W-7	1.1806	4.213	1	0.23
W-8	1.0483	4.512	1	0.28
Cullasaja	−0.3713	2.1393	2	0.43

W-4, and E-2) exhibits a near normal hypsometric distribution with moderate to low peakedness, and steeper mean slopes at elevations above and below the hypsometric maxima and the highest hypsometric integrals. Basins that follow this pattern are found in close downstream proximity to Cullasaja and Dry Falls (Figure 7; W-4 and E-2). The third group (E-1 and W-2) shows a weakly defined bi-modal hypsometric distribution with low peakedness and steeper mean slopes constrained to elevations between the hypsometric peaks and the upper elevations of the tributary basin and have intermediate hypsometric integrals relative to other sub-basins. This grouping of basins is found downstream of the prominent main-stem waterfalls (Figure 7; E-1).

Discussion

Results suggest that a spatial relationship exists between migrating knickpoints, topographic change and debris flow frequency within the Cullasaja River basin. However, before accurate interpretations can be made regarding landscape evolution in this setting we must assess factors that may convolute the linkage between fluvial channels and the surrounding landscape.

Critical drainage area

Knickpoints need fluvial-driven shear stress to propagate upstream. We attempted to limit the investigation to channels dominated by fluvial processes; however, the large frequency of mapped and historic debris flows within the Cullasaja River basin (Wooten *et al.*, 2008) implies that they are important contributors to the formation of channels in this setting (Eaton *et al.*, 2003). Mass wasting (i.e. shallow-rapid landslides and debris flows) becomes increasingly important in channel incision and modification at higher reaches of drainage basins (Brocklehurst and Whipple, 2002; Stock and Dietrich, 2003; Whipple, 2004). In an effort to avoid analytical complications introduced by debris-flow-dominated channels the study was constrained to channels dominated by fluvial erosion that we define as those channels draining a critical area (A_{CR}) $\geq 2.7\ km^2$. The spatial position of this channel-process transition was not field-verified, however, it is believed that this A_{CR} is a conservative estimate by which to discriminate between debris-flow-dominated and fluvial-dominated channels in this setting, as applied by previous investigators (Harbor *et al.*, 2005). While we are fairly confident that the $2.7\ km^2$ A_{CR} closely approximates the extent of the fluvial network within the Cullasaja River basin, drainage area is not the only factor influencing the upstream migration of knickpoints in the system.

Lithologic controls

Variations in bedrock lithology and rock mass strength are common controls on knickpoint nucleation and spatial position (Gardner, 1983; Goldrick and Bishop, 1995; Weissel and Seidl, 1997; Frankel *et al.*, 2007). Two lines of evidence, however, suggest that bedrock does not serve as a first order control on the development and propagation of knickpoints in the Cullasaja basin. First, the study area is underlain by more or less uniform bedrock that varies minimally between biotite gneiss and muscovite-biotite gneiss (Thigpen and Hatcher, 2009). Rock mass strength measurements of bedrock exposed along the Cullasaja River and its tributary channels were not collected for this study. Qualitative assessments of rock hardness variability, however, indicates that the minor amounts of metamorphosed granite, quartz monzonite, and meta-ultramafic rocks that crop out along the Cullasaja River channel are unlikely to have significantly different rock mass strength from that of the dominant gneisses (Burton, 2007; Thigpen and Hatcher, 2009). The only lithology that may yield slightly greater rock mass strength than the majority of the bedrock within the basin are spatially limited exposures of Devonian quartz diorite to granodiorite (Figure 2B). However, these units are present only at the surface in the upper reaches of the drainage basin, above the highest of the identified knickpoints and thus cannot have influenced knickpoint formation or propagation. Second, the Cullasaja River and its tributary channels cut orthogonally across regional strike rather than along strike between differing rock types (Figure 2B). We interpret these observations as further evidence in support of the assessment that bedrock variation is not responsible for knickpoint nucleation and stagnation within the Cullasaja River basin.

Landscape metrics

Swath profiles

The largest knickpoints within the drainage basin are found along the Cullasaja River and their upstream propagation should force adjustment of adjacent hillslopes. Topographic swath profile analysis conducted along the length of the Cullasaja River supports this assertion (Figure 5). Combined, the swath profiles for topography, mean relief, and mean slope demonstrate a clear landscape response to knickpoint passage downstream of Cullasaja Falls, Dry Falls and Kalakaleskies Falls. The first-order trends show that this series of knickpoints increases mean relief and the mean gradient of adjacent hillslopes, as observed in Figure 5B and 5C, where both values exhibit a progressive downstream increase from ~21 km at Kalakaleskies Falls to just below Cullasaja Falls at ~12 km along the swath profile. Downstream of Cullasaja Falls, mean relief and mean slope decrease progressively towards the mouth of the basin. Second-order trends observable in the valley swath profile further support the knickpoint–hillslope connection where small, but significant increases in mean relief and mean slope are observed immediately downstream of all three knickpoints (Figure 5B and 5C). These trends suggest that the passage of each knickpoint lowers local baselevel, and in so doing forces adjacent downstream hillslope relief and steepness to progressively increase. As a result, hillslope potential energy increases, priming them for enhanced transient rates of denudation that will ultimately drive the lowering of mean relief and slope steepness. We do not yet have denudation rates for the study area, however, the decrease in both of these metrics observed downstream of Cullasaja Falls supports the assertion that those lower reaches once had greater amounts of relief and slope steepness following the wave of knickpoint-induced channel incision and transient hillslope response that has since decayed. The analysis shows that topographic metrics can reveal the generation, maintenance, and decay of relief in the absence of absolute bedrock erosion rate data. The small local changes in mean relief and mean slope below each waterfall suggest that hillslopes begin to adjust to channel forcing fairly quickly. Interestingly, if this is in fact true and rates of knickpoint retreat can be measured we can begin to determine the response time of hillslopes to channel forcing in this and similar environments.

Tributary drainage basins

The generally increasing trend of tributary basin mean slope, mean relief, and landslide frequency per unit area from the

Cullasaja River's headwaters to its mouth is perhaps best explained by the progressive introduction of a series of new local baselevels brought on by the migration of knickpoints (Figure 6). It is intuitive that a reduction in local baselevel in a tributary basin will increase relief and slope steepness within that basin and as such increase the likelihood of mass wasting. We suggest that this broadly increasing trend represents progressive stages of baselevel lowering induced by the propagation of the major knickpoints along the Cullasaja River. A decreasing trend is observed in tributary basin mean slope and mean relief beginning at about 7 km downstream of Cullasaja Falls (Figure 6B, 6C). We take this as evidence that the hillslopes of these tributary basins have begun to equilibrate to the series of imposed local baselevel conditions brought on by knickpoint migration. This hypothesis is supported by the increase of landslide frequency in tributary basins downstream of Cullasaja Falls, implying that greater hillslope denudation is occurring within tributary basins downstream of this large knickpoint than those upstream. From this, it follows that the tributary drainage basins closest to the mouth of the Cullasaja River (Figure 6; basins W-1, E-1) have more land area adjusted to the new local baselevel, specifically at lower elevations, than tributary basins farther upstream and closer to the large main stem knickpoints. Importantly, the swath profiles exhibit a very similar build up and decay of mean relief and mean slope (Figures 5 and 6), suggesting that there is a real transient landscape response that is observable along adjacent hillslopes and tributary basins below the uppermost Cullasaja River knickpoint.

The variation in tributary basin mean slope, mean relief, and landslide frequency implies that each basin is in varying stages of development. This pattern of landscape evolution is clearly observed in the plots of normalized tributary basin hypsometry and slope vs mean elevation and in the hypsometric curves and integrals (Figure 7; Table I). Basins downstream of, and closer to, major knickpoints generally exhibit more convex hypsometric curve and a larger hypsometric integral (e.g. basins W-3 through W-5 and E-2 through E-4). In contrast, the tributary drainages farthest from the main stem knickpoints exhibit progressively more concave hypsometric curves and lower hypsometric integrals (Figure 7; Strahler, 1952; Pike and Wilson, 1971; Miller *et al.*, 1990). We interpret this pattern as evidence that the knickpoint-proximal tributary drainage basins are in greater disequilibrium than those that are farther away from the waterfalls in both the up and downstream directions along the Cullasaja River. Plots of tributary basin hypsometry and mean slope versus elevation likewise appear to capture the transient and progressive drainage basin evolution as controlled by proximity to the Cullasaja River knickpoints (Figure 7).

Before a local baselevel drop induced by the propagation of a knickpoint, the hypsometry of a given tributary drainage basin will be positively skewed, and have high peakedness, as the steepest mean slopes will be concentrated in the upper elevations (Table I; Figure 7). We suggest that this combined hypsometric and mean slope versus elevation distribution is diagnostic of a drainage basin that has fully equilibrated to an imposed baselevel condition. Examples of tributary basins that exhibit this hypsometric and mean slope versus elevation distribution are found near the mouth of the Cullasaja River (Figure 7; basin W-1) as well as for those tributary basins that at present are above the highest of the major Cullasaja River knickpoints, and thus still preserve the relic upland landscape (Figure 7; basins W-7). As knickpoints migrate upstream through the Cullasaja River they are transferred at stream junctures to tributary basins (Bishop *et al.*, 2005; Crosby and Whipple, 2006). While the newly formed knickpoint migrates up the tributary basin, more land area is reduced to lower elevations and hillslope gradients immediately downstream steepen. The corresponding skew and peakedness of the normalized tributary basin hypsometry will be reduced, resulting in a more normally distributed hypsometry with an affiliated local maximum in mean slope steepness observable at elevations just below that of the passing tributary knickpoint (Table I; Figure 7; basins E-2, W-3, W-4). As the knickpoint migrates farther upstream the skew in hypsometry increases, peakedness is reduced in favor of a bimodal hypsometric distribution, and a maximum in slope steepness is observed in the elevations between the two bimodal peaks that correspond to the elevation just below the knickpoint (Figure 7; basin E-1). When an individual knickpoint reaches its upstream propagation terminus, which is controlled by the A_{CR}, the landscape will return to an 'equilibrium' state as defined by positively skewed hypsometry with high peakedness and steep mean slopes that are concentrated in the upper elevations of the landscape (Figure 7; basin W-1). We speculate that knickpoint migration rates slow and may stall around the A_{CR} threshold (~2.7 km^2) and are eventually removed from the landscape by the repeat occurrence of debris flows, common to the southern Appalachians, however with the current lack of evidence this assertion remains speculative (Eaton *et al.*, 2003). A key observation of this analysis is that of all of the tributary basins containing knickpoints the elevations of these knickpoints are located just above peaks in mean hillslope steepness (Figure 7; E-1, E-2, and W-4). This finding strongly suggests that channel incision via knickpoint migration is forcing the surrounding downstream hillslopes to steepen, thereby reducing the long-term slope stability of these reaches. If this hypothesis is true for individual tributary basins of the Cullasaja River then it should also apply to the basin as a whole.

Basin wide analysis

To determine the state of landscape evolution for the entire Cullasaja River basin the same hypsometric and mean slope versus elevation analysis was performed as was carried out for the tributary basins (Figure 8). The hypsometric curve for the entire basin is slightly convex and the hypsometric integral is similar to those from tributary basins that are located downstream of Cullasaja Falls and Dry Falls and also contain prominent knickpoints in their channels (Figure 7; Table I). We interpret this finding as evidence that the Cullasaja River basin is actively adjusting to local baselevel fall driven by knickpoint propagation. The hypsometric and mean slope versus elevation analysis reveals that the entire basin contains a bimodal distribution of elevation as a function of area with steeper mean slopes in the trough between the two modal peaks (Figure 8B). When the elevations of Cullasaja Falls and Dry Falls are plotted relative to both the basin hypsometry and mean slope the relationship between these waterfalls and changes in the landscape becomes evident (Figure 8B). The two waterfalls lie within the trough in the hypsometric distribution and are at elevations just above the steepest mean slopes (Figure 8B), showing that a spatial relationship exists between knickpoints in the fluvial channel and hillslope gradient. We interpret this observation as evidence for a strong coupling between hillslopes and transient channel perturbations.

In an effort to gain insight into the spatial distribution of steepened hillslopes in relation to knickpoint locations we isolated the envelope of elevation (725 m to 950 m) containing the highest mean slopes in proximity Cullasaja Falls and Dry Falls, the two largest knickpoints, and overlaid them on a shaded relief map of the Cullasaja River basin (Figure 8A). All of the major knickpoints identified in an earlier analysis fall within this envelope of steep hillslopes. The zone of steeper slopes

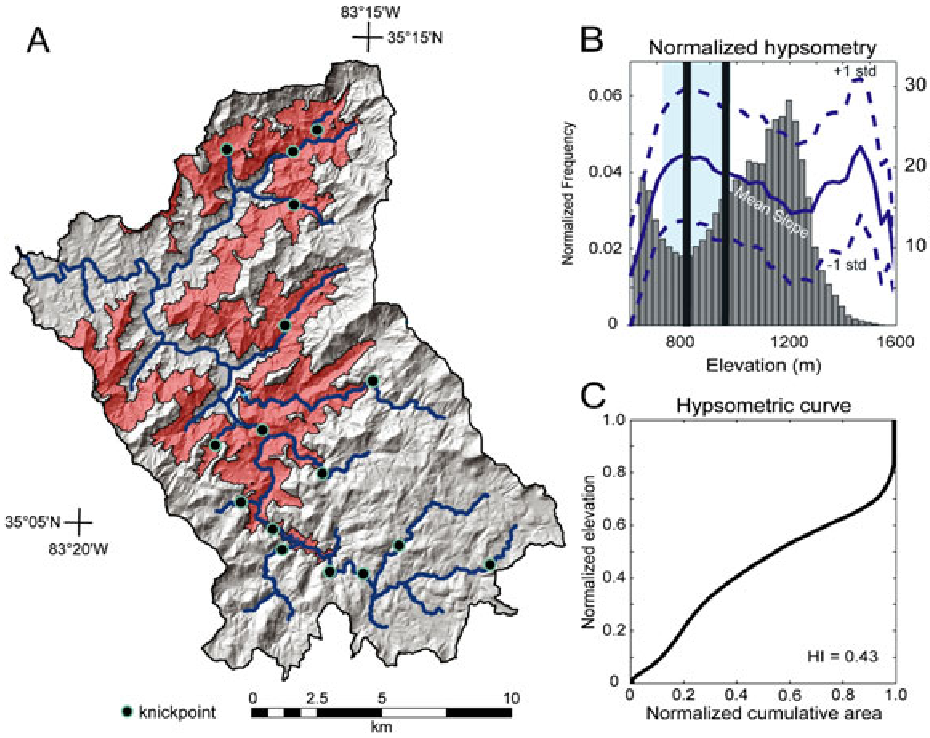


Figure 8. Landscape metrics for the entire Cullasaja River basin. (A) The shaded relief map highlights (darker tone band of topography) steeper slopes located between 750 and 975 m in elevation, corresponding to the shaded elevation band in part B. (B) Plot of hypsometry and mean slope versus elevation. Note the bimodal hypsometric distribution and peak in mean slope steepness at lower elevations in the basin. The solid black bars correspond to the elevations of Cullasaja Falls (~810 m) and Dry Falls (~965 m). (C) Cullasaja basin hypsometric curve exhibiting a convex profile with a hypsometric integral of 0.43, suggesting that this drainage basin is in disequilibrium. See Table I for hypsometric dispersion statistics. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

encompasses only 26% of the area of the Cullasaja basin; however 42% of the basin's mapped landslides initiated within this steeper-slope envelope (Wooten *et al.*, 2006, 2008). We interpret this as further evidence that in the hinterland of post-orogenic mountain ranges, knickpoint propagation may be the fundamental driving force responsible for maintaining relatively steep slopes prone to significant mass wasting potential.

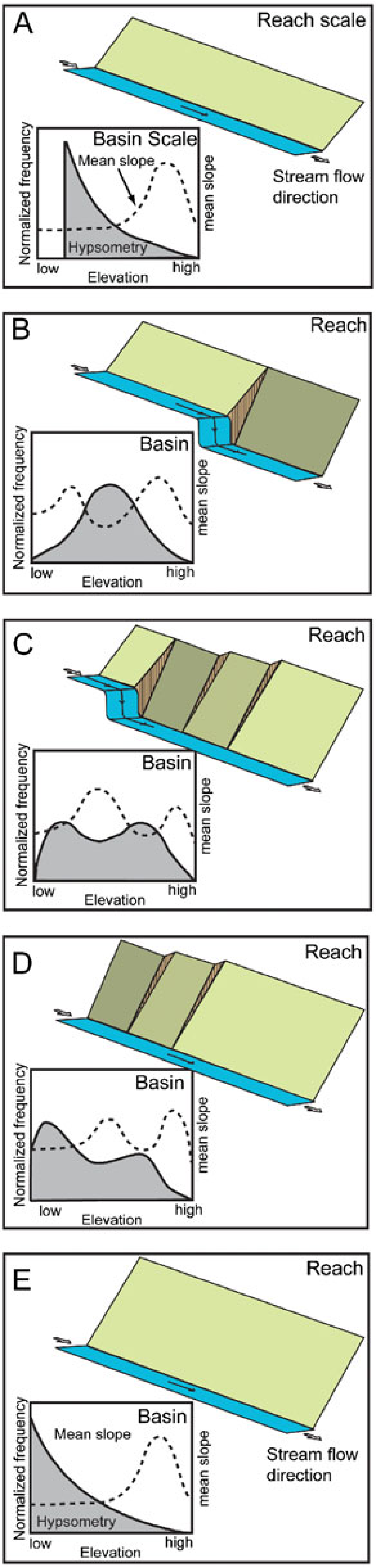
Conceptual model

Bigi *et al.* (2006) investigated hillslope response to knickpoint migration using analog sandbox models, and confirmed a significant (3σ) spatial and temporal relationship between migrating knickpoints and mass wasting on experimental hillslopes. These authors presented a conceptual model in which migrating knickpoints increase mass wasting frequency by undercutting and destabilizing the toes of adjacent hillslopes. The conceptual model of Bigi *et al.* (2006) is applied to the natural environment, and extended to the basin scale. Observations suggest progressive stages of drainage network development in the tributary sub-basins of the Cullasaja River, a progression seen clearly in the hypsometric and mean slope versus elevation analyses that highlight the utility of this method (Figure 7). We envision an initial drainage basin development model (Figure 9) where hillslope gradient and basin elevations are equilibrated to channel gradient, upstream basin area decreases exponentially with increases in elevation, and steeper mean hillslope gradients are distributed along the high elevation ridge crests (Figure 9A). A). When a knickpoint enters the channel it progressively steepens adjacent lower elevation hillslopes and increases the relief of the channel and basin (Figure 9B). This increase in potential energy is stored in hillslopes downstream of the knickpoint. Hillslopes respond to the transient passage of a knickpoint by increased rates of mass wasting that result in a long-term increase in basin denudation ultimately followed by the reduction of elevations within the basin (Figure 9C and 9D). This continues until the knickpoint has reached its terminus in the landscape and the hillslopes have once again equilibrated to the new local baselevel (Figure 9E).

Implications for post-orogenic landscape evolution

The hypsometric analyses used in this study help determine varying stages of landscape evolution. While, hypsometric curves and hypsometric integrals are capable of capturing stages of landscape equilibrium (e.g. S-shaped hypsometric curves and higher hypsometric integrals signify a landscape farther from equilibrium; Strahler, 1952), they cannot be used to determine whether or not that landscape is waxing or waning. In other words, these analyses are limited because they cannot distinguish if a landscape is moving farther away from, or returning to a state of equilibrium. Figures 7 and 9 show that the combined use of hypsometric and mean slope versus elevation analyses allow for the determination of different evolutionary stages in the continuum of landscape development. This is important because these topographic analyses can be used to provide a more detailed assessment of landscape evolution than with the use of hypsometric curves and integrals alone and are particularly useful in similar post-orogenic settings where the conceptual model is applicable.

The Cullasaja River basin can be used as a model for the development and evolution of many portions of the southern



Appalachians. Drainage basins throughout the eastern Blue Ridge province cut into meta-igneous and meta-sedimentary rock units similar to the Neoproterozoic Ashe Metamorphic Suite that underlies the Cullasaja River basin. Moreover, it has been shown that debris flows are important contributor to hillslope erosion in similar geologic settings (Eaton *et al.*, 2003; Wooten *et al.*, 2008). As such we believe that the conceptual model provides a good explanation for post-orogenic landscape evolution in locations where either climatic variations over late Cenozoic timescales or local internal autogenic processes within eroding drainage basins are the primary driver of channel incision and strong variations in lithology and differential tectonic uplift/subsidence are generally absent. If correct, the model suggests that the steepening of hillslopes and increases in relief follow in the wake of the transient propagation of local baselevel perturbations, and that this important process is responsible in part for the long-term maintenance of the rugged topographic expression of the southern Appalachians. The transmission of the baselevel signal to the hillslopes provides the necessary potential energy to increase locally the rate of hillslope denudation. The model makes specific predictions about zones within a drainage basin that should have increased rates of channel incision and sub-basin-scale denudation, as well as fluvial terrace formation and preservation downstream of knickpoints. These predictions await field-based tests in the Cullasaja River and other similarly suited settings.

Conclusions

The Cullasaja River basin is located in the post-orogenic southern Appalachian Mountains. Despite tectonic inactivity in this region since the Late Triassic opening of the Atlantic basin, significant relief (~1 km), steep mean slopes (20° ± 9°), and frequent slope-clearing mass wasting events (0.684 per km^2) persist. All three of these characteristics are at least in part related to the continued migration of knickpoints through the Cullasaja River fluvial network. We have shown that in this basin prominent knickpoints and hillslopes are closely linked by the spatial relationship between knickpoint position and slope gradient below and above these channel perturbations. The pattern of drainage basin modification within the tributary network of the Cullasaja River basin (Figure 7) is evidence that knickpoint migration is responsible for transient maintenance of valley relief and relatively steep mean slopes in the absence of tectonic forcing (Figure 9).

Figure 9. Schematic conceptual model for the progressive development of post-orogenic landscapes in response to knickpoint migration. Block diagrams show the migration of a knickpoint through a channel and the transient hillslope response at the reach scale. The inset hypsometric and mean slope versus elevation plots show the idealized evolution of a drainage basin in which knickpoints are migrating. (A) Undisturbed/equilibrated drainage basin. (B) The entrance of a knickpoint forces base-level adjustment of the fluvial channel, resulting in the steepening of downstream hillslopes. (C to D) Upstream knickpoint migration causes additional downstream steepening of the tributary channel in its wake. The resulting increase in potential energy downstream from knickpoints causes a rise in long-term hillslope erosion rates. Downstream from the knickpoint, hillslope gradient and the mean basin elevation are reduced as hillslopes adjust through increased rates of denudation on over-steepened slopes. (E) Basin hillslopes finally adjust to the imposed new local baselevel conditions following knickpoint migration through the reach; a new state of equilibrium is obtained. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Moreover, this study highlights an apparent relationship between knickpoint migration, hillslope evolution and the spatial distribution of mass wasting in post-orogenic landscapes. Specifically, we observe enhanced relief, steepened hillslopes and a greater concentration of landslide per km^2 in tributary basins immediately downstream of major knickpoints; hillslope relief and steepness decay and mass wasting becomes less frequent at distances farther away from major knickpoints. We put forth a model for drainage basin evolution in this and similar post-orogenic settings that relies upon analyses of basin hypsometry and mean slope versus elevation for the qualitative identification of differing stages of drainage basin maturity and general mass wasting potential. In this model knickpoints migrate upstream steepening the hillslopes in their wake. This has the effect of increasing the potential energy and thereby the rate of denudation from adjacent hillslopes, ultimately resulting in the reduction of basin elevations as a function of time elapsed since knickpoint passage. The proposed model, coupled with data from the Cullasaja River basin, demonstrates how hypsometric and mean slope versus elevation analyses are useful tools in the elucidation of fundamental mechanisms responsible for drainage basin development and in assisting in identifying specific regions of drainage basins that may be persistently susceptible to slope failures at human timescales. More importantly, the model and data sets illustrate that, while precipitation is the main driving force in the evolution of post-orogenic landscapes, local baselevel fall and knickpoint migrations are important transient hillslope forcing mechanisms that function in shaping the topography. These transient signals have the effect of increasing local relief, slope gradient, and hillslope denudation rates, and by extension help explain the rugged appearance of the southern Appalachian landscape.

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