Geogr. Fis. Dinam. Quat.
28 (2005), 23-36., 9 figg.

DAVID HARBOR (*), AMY BACASTOW (*), ANDREW HEATH (*) & JACKSON ROGERS (*)

CAPTURING VARIABLE KNICKPOINT RETREAT IN THE CENTRAL APPALACHIANS, USA

ABSTRACT: HARBOR D., BACASTOW A., HEATH A. & ROGERS J., *Capturing variable knickpoint retreat in the central Appalachians, USA.* (IT ISSN 1724-4757, 2005).

In the upper James River basin (Virginia, USA), topography includes incised valleys in limestone uplands, high-elevation low-relief surfaces, and knickpoints/knickzones in resistant and nonresistant rocks. Mainstream and tributary profiles are irregular and stepped. Some have obvious floodplain abandonment and strath terrace formation at the heads of bedrock knickpoints. Although stream knickpoints can be compared on log-distance-downstream plots, the ability to correlate tributary knickpoints with those on the confluent stream is limited. Automated mapping of the entire drainage network using deviation from a predicted area-slope relationship identifies landscape knickzones. These diffuse zones of incision connect steep stream segments with sometimes distant, steep valley sidewalls. Computing area-slope curves requires significant smoothing to remove the effects of random error and contour interval stepping of streams in 30 m DEMs. Random error is addressed using a median value filter. Comparison of stream profiles yields variability in the distance of knickpoint retreat from the basin outlet. In the folded sedimentary rocks of the Valley and Ridge, bedrock resistance, sediment character, and possibly, alignment of streams to structural orientation cause this change of retreat. Substantial changes of rock type from shale or limestone to sandstone significantly retard the retreat. The extreme case of increased rock resistance in structurally-repeated quartz arenite strata leads to foreshortening of the distance between knickzones as they collapse into a singularly high profile convexity. The abundance or absence of abrasive sediment load promotes or retards knickpoint retreat for streams in carbonate bedrock and changes the shape of the retreating knickpoint.

KEY WORDS: Knickpoint, DEM, Stream power, Fluvial erosion.

INTRODUCTION

The profiles of bedrock rivers are increasingly the object of study regarding landscape evolution over time and transient responses to changes of base level, climate, and tectonics (Whipple, 2004). River incision rate into bedrock determines, in part, the relief of hillslopes and hence the sediment production to alluvial lowlands and coastal regions, and has clear linkages with the ongoing deformation of plate margins, active and passive. Moreover, enhanced or diminished erosion rate is propagated along river profiles (Whipple, 2001) and through positive feedback can be integral to the stability of the landscape as more rapidly incising basins capture drainage area from more slowly eroding basins (e.g., Harbor, 1997). Informed largely by a stream power conception of stream erosion rate (e.g., Hack, 1957, Howard & Kerby, 1983, Whipple & Tucker, 2002), theoretical descriptions of river erosion have depended largely on the shape of the river profiles because of the comparative lack of understanding of river width and other responses to changing incision rate. Analyses of river segments have shown the sensitivity of profile shape to uplift rate (Kirby & Whipple, 2001), orographic precipitation (Roe & *alii*, 2002), and even unmapped fault offset (Kirby & *alii*, 2003). However, the history of river incision is a more problematic question. Whipple (2004) cautions that transient responses to river base level fall and knickpoint migration render meaningless any comparison of modern stream profiles and incision rates when they are determined from terraces. In settings with multiple bedrock types or a complex erosion history, river profiles are not likely to fit well the theoretical log downstream decrease of slope of Hack (1957). How much information is stored in the convexities apparent in these profiles? Knickpoints (Penck, 1925), referred to as knickzones when broad (Zaprowski & *alii*, 2001), are abrupt, steep sections of rivers produced by variability in bedrock resistance (Penck, 1925), localized uplift (Harbor, 1998, Kirby & Whipple, 2001)) or differential erosion due to changed uplift rate (Whipple & Tucker, 1999). Knickpoints can remain stationary when pinned on resistant lithology or differential uplift. Others migrate upstream following a change of base level or other perturbation to the profile.

(*) *Geology Department, Washington and Lee University, Lexington Virginia 24450 USA.*

Funding for this project was provided to us by Washington & Lee University through RE Lee Research Scholarship and Glenn Faculty Grant programs. The manuscript was significantly improved by two anonymous reviews.

River profile analyses have their origin in the assumption of a graded profile wherein slope decreases as basin area and river discharge increase. Hack (1973) developed the «stream gradient index» to compare downstream changes of power in relation to sediment size. Using this same reasoning to differentiate the types of knickpoints, Goldrick & Bishop (1995) employ log-linear plots of distance downstream vs. elevation to extend knickpoint heights downstream. Knickpoints on two streams that project to the same elevations at the confluence are assumed to be generated by a shared base level fall. Two knickpoints with differing relative relief at the confluence are instead thought to be the result of lithologic differences. Most studies emphasize the stream power (or bed shear stress) control of bedrock channel erosion rate (e) as

$$e = K A^m S^n \quad (1)$$

where A is basin area, S is stream gradient, K is the coefficient of rock erodibility, and m and n are exponents reflecting the relative importance of discharge and slope in erosion rate. Using Hack's (1957) relationship between distance and area, this relationship (1) reduces to

$$S = k_s A^{-\theta} \quad (2)$$

where k_S is the steepness index and θ is the concavity index (see Kirby & Whipple (2001) for one example of this kind of analysis). An important assumption of this methodology using stream profiles is that the profile is in equilibrium, or steady state.

Dynamic or migrating knickpoints are transient responses to base level lowering or increased uplift rate (e.g., Whipple & Tucker, 1999, 2002), which are now modeled using variations of the stream power law (Howard & Kerby, 1983) applied to bedrock or mixed channels (Whipple, 2001, Neimann, 2002). In alluvial channels knickpoints are thought to diffuse as they retreat (Begin, 1988) because of the stream power dependence on slope. However, if the stream power exponent for slope (n) is less than or equal to 1, knickpoints translate by parallel retreat with a sharp break at the bottom or top respectively (Tucker & Whipple, 2002). It has become clear that several processes including knickpoint-generated bedrock exposure in otherwise alluvial channels (Seidl & *alii*, 1994, Howard, 1998) can cause channel steps to retreat long distances in a way that was not appreciated by experimental studies of homogeneous materials (Gardner, 1983) or in alluvial channels.

Few attempts have been made to use knickpoints to assess the perturbations to a drainage network, including uplift, drainage capture, or base level lowering (e. g., Zaprowski & *alii*, 2001). However, the basin-wide distribution of knickpoints offers a means to evaluate bedrock erodibility as well as the mechanisms of stream erosion beyond those implied in profiles and drainage basin area (stream power). Thus, the goal of this analysis is to define numerically the sections of river that could be considered too steep for local conditions of rock type and drainage area. These sections can then be correlated using degree of deviation from a theoretical profile or height above base level. Correlation of the knickpoints permits the evaluation of incision wave speed models (Whipple & Tucker, 1999) as well as rock resistance effects in heightened erosion cases.

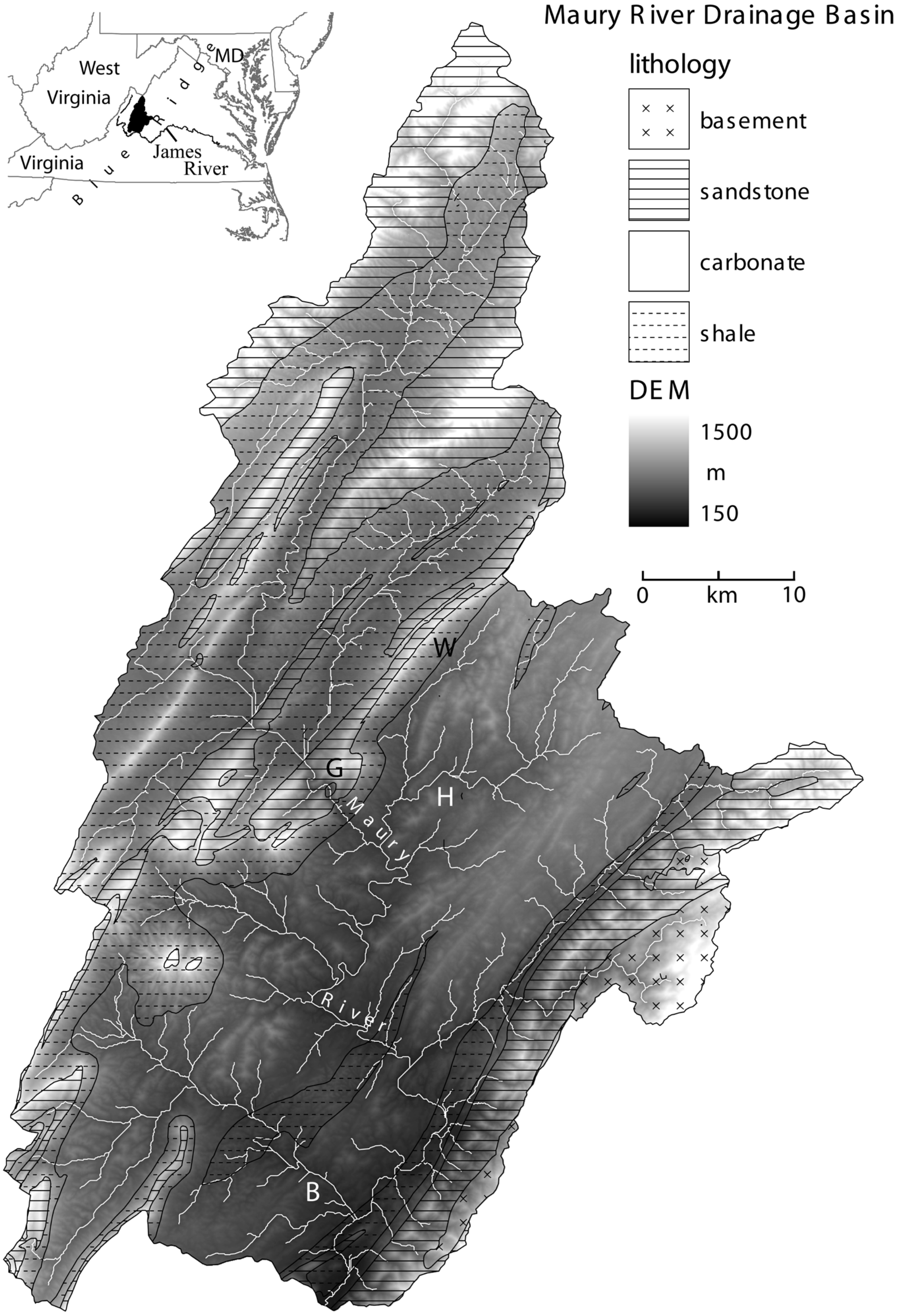
METHODS

The study area is the Maury River drainage basin of the central Appalachian Mountains of Virginia (fig. 1). The Maury River is tributary to the James River, which is the southernmost transverse river draining large sections of the Valley and Ridge through the crystalline Blue Ridge province. Drainage rearrangement associated with continental divide migration into Appalachian interior (Harbor, 1996) has resulted in rates of erosion that may be 6-10 times greater than surrounding basins (Harbor & *alii*, 1999) fueling incision and headward growth and capture (Bank & *alii*, 1999). The basin is underlain by crystalline rocks to the southeast and a series of early-mid Paleozoic sedimentary rocks of varying resistance for the bulk of the basin to the northwest. Linear ridges adjacent to the crystalline rocks and in the middle to upper basin are underlain by orthoquartzite whereas valleys are underlain by limestone (central valley) and shale (northwestern portion). Pronounced convexities interrupt the concave profiles of the James River and its major tributary, the Maury River (fig. 2A), including lithologically-controlled knickzones associated with outcrops of crystalline rocks at the Blue Ridge and sandstones farther upstream, plus the enigmatic Fall Zone knickzone near sea level. In addition to these static knickpoints, dynamic knickpoints are propagating upstream (e.g., the base of the Maury River profile, fig. 2A). Migration continues through all rock types and locally generates strath terraces that project to upstream floodplains. Extensive mapping and dating have yet to produce a coherent terrace chronology and correlation, in part because of these knickzones.

The goal of the method presented below is to find numerically and correlate knickpoints or knickzones, and to show that one can use the correlations to assess the dynamics of knickpoints and the relative erodibility under different rock types and sediment load conditions. The steps outlined below include 1) obtaining the channel network and basin attributes from ArcGIS, 2) smoothing the profiles in Matlab using median filters and splines, 3) regression of channel slope against drainage area, accounting for variation of channel margin resistance due to lithology, 4) use of the deviation from the regressed AS relationships to locate knickpoints and determine the deviation from theoretical profile shape. The resulting map positions of the knickpoints are analyzed in terms of the distance of travel.

Numerous methods have been employed to derive channel profiles from DEM data, most of them resulting in reproducible channel gradients on the order of contour crossings of topographic mapping at a comparative scale (approx 1:25,000 for 30 m grid spacing). Snyder & *alii* (2000) smooth the DEM-generated profile (with long stretches of zero slope created by pit-filling GIS routines)

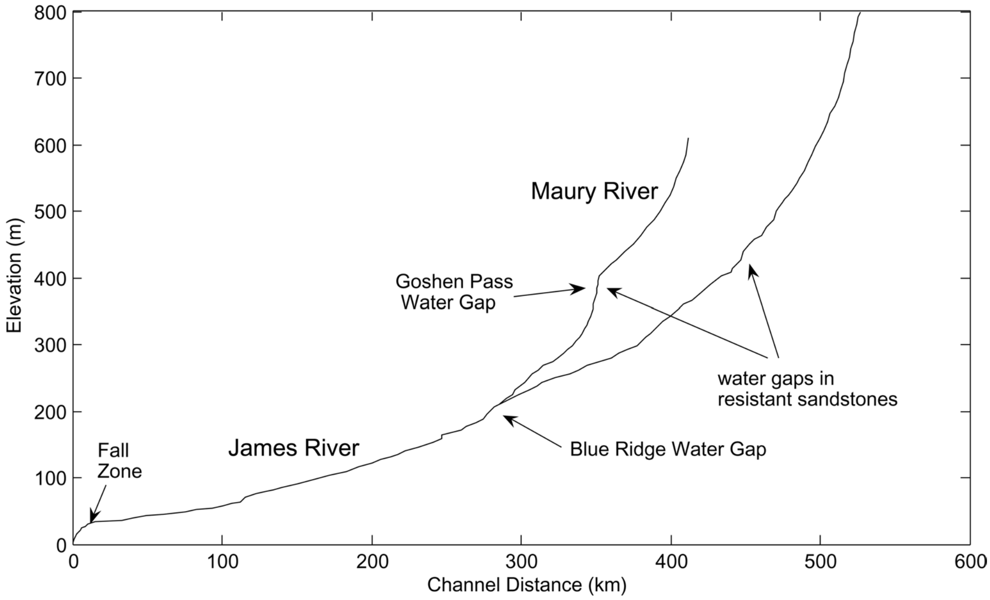
FIG. 1 - Location map showing topography (1" DEM), simplified geology (based on VDMR, 2003), DEM-derived drainage network (2.7 km² threshold), and locations discussed in the text; B - Buffalo Creek G - Goshen Pass water gap, H - Hayes Creek, W - Walkers Creek.



on a regular elevation basis, to equally weight sections of the profile. Montgomery and Blanco (2003) assign arbitrary low slopes to zero and adverse slope section of DEM generated profiles.

DEM data (30 m, USGS) were processed using drainage extraction routines in RiverTools leading to 30 m raster GIS layers describing elevation, basin area, stream distance, and channel network. The geologic units were also incorporated from the 1:500,000-scale geologic map of Virginia (VDMR, 2003), generalized to just 4 units. Channels were created above of threshold drainage area of 2.7 km² (3000 cells), which is approximately the limiting area between fluvial profiles and profiles influenced by hillslope processes such as debris flows (Montgomery & Fou-

A



B

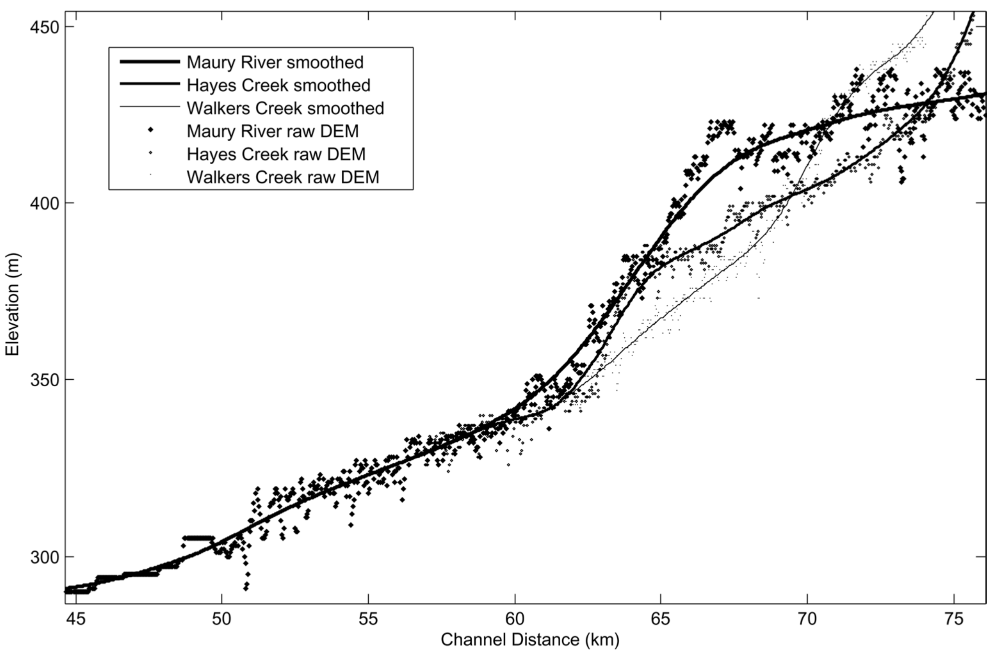


FIG. 2 - Knickpoints at several scales along the James and Maury River. A: Longitudinal profile drawn from 1:24000 scale topographic quadrangles with a contour interval of 6-12 m (20 or 40 ft). B: knickpoint-rich profile of the Maury River and two major tributaries showing the raw DEM data points and the results of the smoothing procedure. Note the difference between the DEM data for the downstream end of the Maury River reach, which was generated by digitizing map contours, versus the photogrammetric methods used in the rest of the profile.

foula-Georgiou 1993). Note that the scale of the raster DEM influences both the drainage area, slope, and river network lengths (Finlayson & Montgomery, 2003). Because the drainage extraction routine utilize a «pit-filling» routine to produce a connected drainage network, the processed DEM has significant «stepping» and is disregarded in favor of the raw DEM data in further analyses. We determined that the newer reprocessed and mosaiced DEM data available online (http://seamless.usgs.gov) contain a greater number of arbitrary steps, and thus were not used. The DEM data also have a variety of errors and artificial steps introduced by photointerpretative methods and digitizing of map contours, respectively.

The next step is to produce a smooth profile preserving majors change of slope while eliminating localized errors. The channel network was searched from the outlet upstream to find tributaries of maximum basin area and a long profile of segments is created. Subsequent profiles start with the next-largest tributary, continuing until all channel segments are part of a profile. In the smoothing routine, the mainstem is smoothed first and any smaller tributaries are forced to join the main channel at the smoothed elevation. As channel size increases, slope decreases and the expected wavelength of slope change increases. Therefore, the smoothing routine first creates a regular series of points that decrease in spacing upstream according to the square root of distance downstream, as follows

$$x_m = \frac{\sqrt{x}}{\sqrt{10^5}} \times 2000 + 500 \qquad (3)$$

where x_m is the spacing of median points (m) and x is the distance downstream (m). Thus the smallest spacing was 500 meters and the spacing at 100 km downstream is 2500 m. The elevation value at each x_m was created using the median value for all DEM values between adjacent median values. The median rather than the mean was used because of the non-normal nature of the deviation in the DEM. A spline was fit to these median values. Rare sections with adverse or zero slope are iteratively erased by incrementally lowering the downstream point and raising the upstream smoothing point. The profile at the cell scale of the DEM is then sampled from the spline curve at each cell center.

We begin the analysis of the river shape using the relationship of basin area (A) and channel gradient (S, fig. 3). Because of the strong lithological contrasts in the basin, the AS relationship was recalculated for each of the generalized geologic units (A-D, fig. 3). The regression of slope on area was computed from the mean of log slope in each 0.1 bin of log drainage area, because the most of the data points are from small basins. The steepness and concavity of the basement rock type were significantly different from the other rock types, in part due to the lack of larger drainage area points. Following the reasoning of Snyder & *alii* (2000) and Kirby & *alii* (2003), the data were regressed again holding the concavity (θ) to a common value of 0.43, based on the average concavity of the three geologic units covering most of the basin (sandstone, carbonate, shale). This yields a normalized channel steepness index (CSI, Kirby & *alii*, 2003) that highlights the effect of rock type on channel gradient assuming no additional affect on concavity.

Deviation from these predicted values (in units of log slope) are plotted and analyzed spatially on profiles and maps. The regressions subset by geology are also used to create theoretical profiles using the regressed AS relationship. These idealized profiles start from the basin outlet, where it is presumed each knickpoint enters the basin from the James and in order to calculate deviation on streams with differing numbers of knickpoints. Elevation is added in the upstream direction using the basin area and geology for each cell. The deviation from this geology-adjusted profile shows the cumulative deviation, or the height above base level at each cell on each profile in the

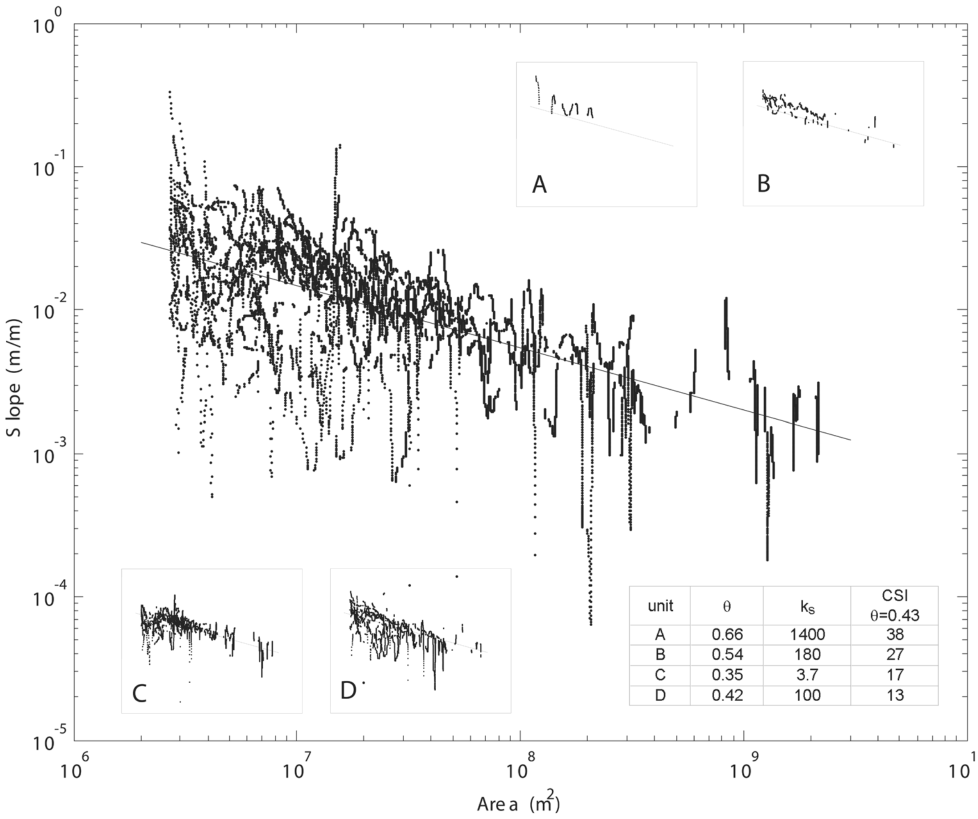


FIG. 3 - Slope-area data for each cell in the drainage basin (main panel) and subset for each major geologic unit (A-basement, B-sandstone, C-carbonate, D-shale). The line in each panel is identical and shows the pooled regression line for the three main rock types (sandstone, shale and carbonates, θ = 0.43, k_s = 15.6). The table gives the coefficients of regressed AS relationship, and the steepness (CSI) holding θ = 0.43 for each unit.

basin, and thus represents, in part, the lag in incision due to knickpoint steps in the profile.

RESULTS

Results of the smoothing and pixelwise area-slope determination show a declining slope for increasing basin area (fig. 3), with a concavity (log-log slope) that is consistent with previously determined values (Stock & Montgomery, 1999). The smooth profile is still subject to low slopes that are up to two orders of magnitude below the mean. Most of these low slopes are a function of the DEM representation of topography and is the object of further study in the field. However, the DEM does preserve a great deal of the longitudinal variability that characterizes these stream profiles in the Appalachian Valley and Ridge. The principal stream has a disequilibrium profile that produces high variability in the reaches with the largest basin area. It is also apparent that the profiles vary by geologic substrate. Blue Ridge basement rocks and ridge-forming sandstones plot clearly higher than the overall average. Carbonate rocks and shale plot closer to the mean and below, although with considerable variability. Clearly there are more influences on profile shape than just geology.

The longest profile in the basin crosses several rock types and shows the relationship of the slope deviation, the DEM profile and the geology-modified theoretical profile (fig. 4). Two obvious knickpoints characterize the Maury River profile: a large step in the folded quartzite rocks of the water gap (location «G» on fig. 1) known as «Goshen Pass» and the knickzone in the lowest 25 km of the profile. The Goshen Pass knickpoint is steeper than predicted even given the change of rock type; the theoretical profile is steeper, but dramatically less so in this anomalous reach (see fig. 3 at A = $7.8x10^8$; see also, Harbor & *alii*, 2003). This knickpoint or knickzone raises the Maury profile more than 50 m above its theoretical graded profile. Knickpoints occur on tributary streams (fig. 4), which could imply the passage of several erosion waves through the basin. The lower knickpoint on the Maury River corresponds to an oversteepened mouth of the confluent stream, Buffalo Cr (B, fig. 1). Farther upstream, the Goshen Pass knickpoint on the Maury River is matched in magnitude by several knickpoints on Hayes Creek, and will be addressed further below.

The disequilibrium nature of the three example profiles shown in fig. 4 is apparent when the area-slope relationship is examined in a downstream fashion. The Maury River profile (fig. 5A) stays close in shape to the predicted profile in much of the upper 75 km, albeit with some gentle reaches that are likely erroneous. The lower portion of the profile however, jumps above the profile over 3 separate knickpoints, all steeper than predicted by any change of lithology. The two major tributaries flow almost completely in carbonate rock. Buffalo Creek (B) has a very steep mouth and then two other distinct zones of high slope, the uppermost of which does not rise above the expected slope. Hayes Creek has 3 increases of slope over three knickpoints, although the highest one is called into question by the increasing gradients found in smaller streams draining sandstone ridges. The highest reaches of Buffalo Creek (B) drain the flank of a sandstone ridge and likely the steepness reflects the influence of the blocks shed from this ridge rather than the equilibrium profile shape in carbonate and shale.

However tempting it is to note the apparent similarity of knickpoints in the principal and its tributary basins, the change in steepness of tributary profiles and of rock type makes correlation tentative at best. However, plotting the difference between the actual profile and the

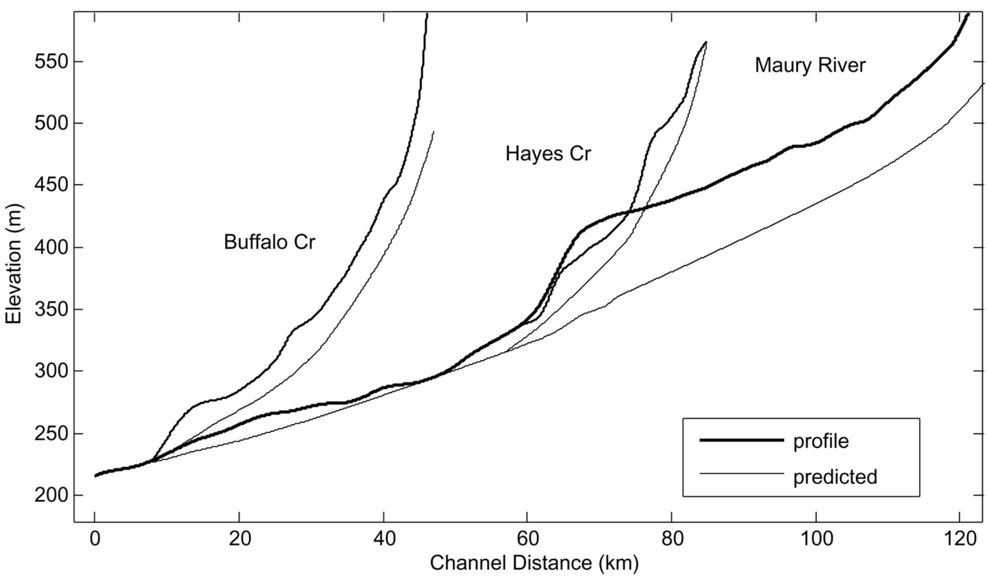


FIG. 4 - Predicted equilibrium profile and smoothed profiles for the Maury River (thicker) and two major tributaries (thinner). See fig. 1 for locations. The predicted profile is created from base level up based on the AS relationship derived using θ = 0.43 and the CSI for each geologic unit.

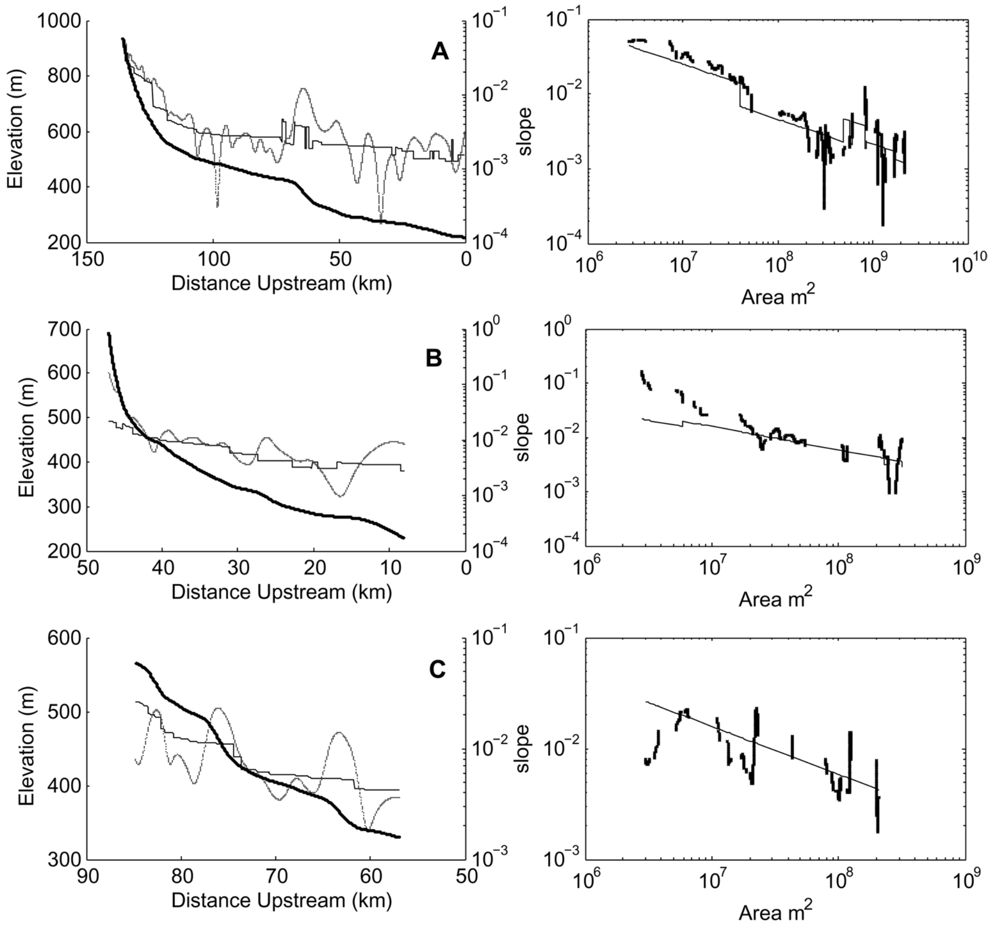


FIG. 5 - Profile and stream power (area-slope) relationships for the Maury River (A) and two tributaries (B-Buffalo Creek, C-Hayes Creek). In the left panels, the thick solid line is the channel profile, the thin solid line is the slope expected for the geology and contributing area, and the points are the pixel-wise channel slopes. In the right panels, the line is the predicted AS relationship based on the different steepness (CSI) values for each lithology and the points are the profile gradient values.

predicted gives the deviation of the profile from its potential base level (figs. 6 and 7). The strong positive steps are knickpoints and represent the lag of erosion in reaching base level attained farther downstream. Negative slope of deviation in the upstream direction results from uncertainty and/or lack of precision in the fitting of concavity and steepness, or possibly to erosional mechanisms that resemble alluvial river slopes (see below). In the lower reaches of the trunk stream (fig. 6), the Maury River and its tributaries flow primarily on carbonate rock and carbonaceous shale through the open Shenandoah Valley floor (fig. 1). With this simplification of controlling variables, the dynamics of knickpoints are more easily observed. The knickpoints labeled A and B (fig. 6) on the tributaries are marked by similar heights above a base level profile, but Maury River gradient is lower than predicted and results in lower deviation elevations. The position of knickpoint B on the Maury River is unclear, but field evidence suggests that the upper of two slightly steeper steep zones is the more significant knickpoint. The migration distance is increasingly less for smaller stream. Morever, it is clear from the shape of the curves that knickpoints are broader («knickzones») on larger streams. Because the smoothing routine incorporates less short wavelength change with increasing stream size, some of this difference may be an artificial product of the smoothing routine. Yet field observations confirm the general shape of these knickpoints. They are clearly identifiable in the field as changes of stream character and valley shape. Buffalo Creek is a cascade of bedrock ledges set into a narrow incised valley in the lowest 5 km. Farther upstream, the valley widens and the stream has a comparatively flat bedrock floor with alternate bars of cobble alluvium. Terraces 50 m above the incised lower portion of Buffalo Creek also indicate the presence of a former alluvial floodplain where none exists today. Tributary to Buffalo Creek just at the Maury River floodplain, Poague Run rises steeply through two distinct steps as a cascading stream with bedrock ledges and small falls up to 3-4 m high. It emerges onto a gentle upland where the stream meanders on bedrock through an alluvial floodplain (fig. 8).

Another set of knickpoints is found in a more geologically and topographically complex region farther upstream in the basin (fig. 7). Just downstream of where the Maury River cuts through the first major sandstone ridge underlain by Silurian rock at Goshen Pass (fig. 1), profiles and base level deviations suggest that rock type, bedrock orien-

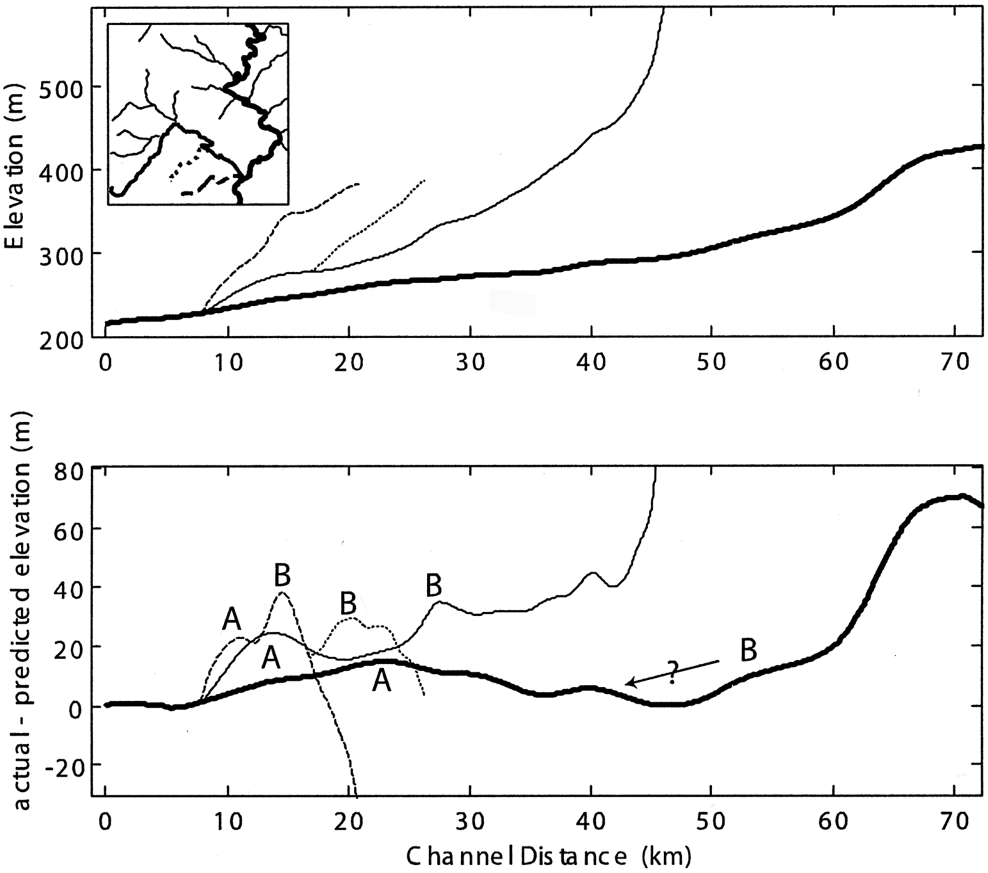


FIG. 6 - Profiles and cumulative profile deviations in a zone of similar geology and physiography for the Maury River (thick), Buffalo Cr (thin), Poague Run (dashed) and unnamed tributary (dotted). The upper panel shows the stream profiles and a map using the same line styles (see fig. 1). The lower panel shows the cumulative height above base level (actual - predicted elevation) for each stream. Letters designate correlative knickpoints and knickzones and are the same on fig. 8.

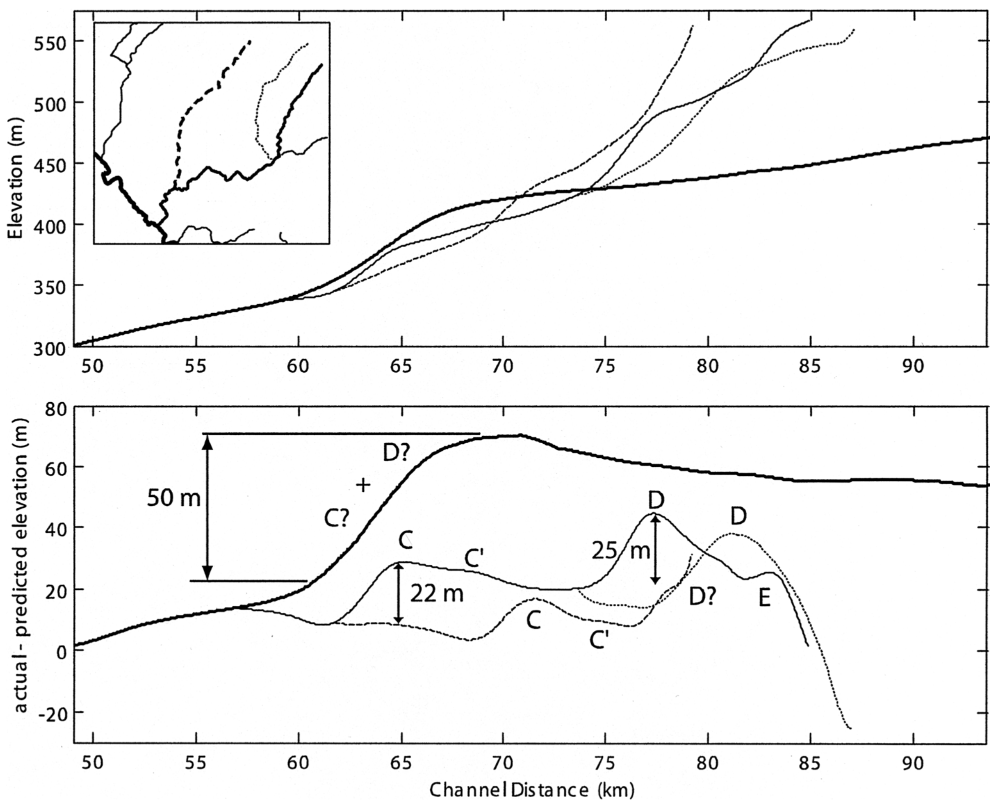


FIG. 7 - Profiles and cumulative profile deviations in geologically complex reaches of the Maury River (thick), Hayes Cr (thin), Walkers Creek (dashed) and unnamed tributary (dotted).

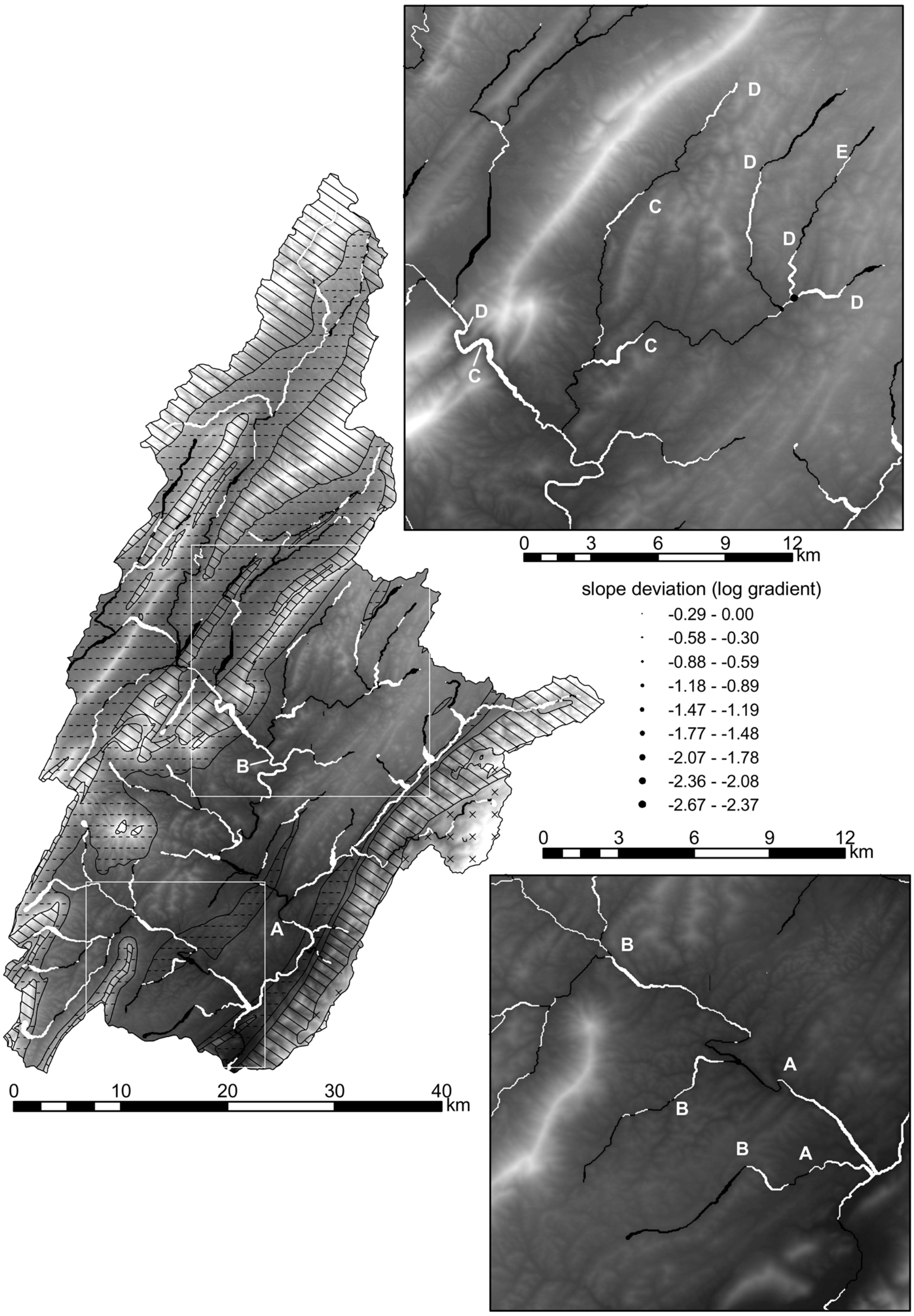


FIG. 8 - Topography, geology and channel slope deviation for streams in the Maury River basin. The size of the line (created by a dot at each 30 m grid cell on the channel) indicates the strength of the slope error and the color of the line indicates higher (white) or lower (black) slope than predicted. The units of the deviation plots are in log slope values away from the slope predicted for the local geology and basin area. They are shown in the legend for the negative error only; positive deviations in white are comparable. Knickpoints shown on figs. 6 and 7 are labeled at their upstream ends using the same letters-note the Maury River knickpoints the map of the entire basin. Information about the DEM and geology are given on fig. 1.

tation, and topographic setting are very important in the dynamics of knickpoint migration. Two, possibly three, knickpoints are found on tributaries to the Maury River, and they occur at distances from the mutual confluence that are not the simple function of stream size of the previous example (fig. 6). The distinct knickpoints are not at all separable on the Maury River DEM profile and the total base level deviation has not progressed as far upstream as it has on the tributaries. These tributaries flow north along strike in the shale and carbonate rocks of the Great Valley (fig. 8). Hayes Creek has an abrupt knickpoint (C) just 5-8 km above the confluence. The smoothing routine greatly subdued the actual topography of this knickzone (see fig. 2B, at the same channel distance), which comprises a set of waterfalls up to 5 m high over approximately one km of channel distance. These falls are topped by travertine dams that grow upward and downstream over several thousand years (Carlson, 1998). These knickpoints do migrate when the dams are breached, but knickpoint migration is episodically stalled by the travertine. Upstream of this large knickpoint, a smaller knickpoint (fig. 7, C') is discernable the field and on the raw DEM profile (fig. 2A), but is negligible on the smooth profiles. Another large step (D) puts the stream up to a high level surface (fig. 8) in the valley center characterized by broad valley floors and alluvial floodplains flanking a bedrock channel. Between C and D, the channel is also broad with an alluvial floor, but is edged by steep valley sidewalls. The knickpoints are considerably less obvious in the field on Walkers Creek, which flows SW parallel to the sandstone ridge (fig. 1) and along the strike of bedrock. Knickpoint C has advanced farther upstream here compared to Hayes Creek even though the drainage area is smaller. The top of knickpoint D on Walkers Creek occurs just several hundreds meters past the end of the stream defined numerically by the drainage area threshold. Thus, the top of the knickpoint is just beyond the end of the profile shown on fig. 7. A fourth knickpoint (E) exists on Hayes Creek and several of its smaller tributaries. Above this final knickpoint, the streams are on a broad upland that is equal in elevation to the drainage divide with the Shenandoah River basin to the north (fig. 8).

The cumulative deviation caused by the knickpoints on Hayes Creek or Walkers Creek is nearly the same as the single step on the Maury River. In the field, and to a lesser degree on the raw DEM profile (fig. 2A), one can distinguish two and possibly, three knickzones on the Maury River that reduce to a single broad step on the smoothed DEM profile. The knickpoints are characterized as steep bedrock reaches that have boulder and bedrock slab accumulations in slightly wider reaches below. The top of knickpoint D is extraordinarily sharp (as accurately recorded in the raw DEM but not the smoothed profile). The knickpoints on the tributaries are for the most part equally sharp having migrated between 5 and 20 km farther upstream (fig. 7). Lastly, the strongly negative deviation above base level for the headwater reaches of streams in carbonate rock suggest that the predicted slope is significantly higher than actual for streams draining the valley center, where there is little relief and scant coarse sediment created by a resistant lithology.

As a first approximation to determining the controls on knickpoint migration, the distance to the top of the knickpoint is plotted against the distance-weighted average basin area. For the lower set of streams flowing mostly in carbonate rocks (fig. 9), the distance of travel for the top of the knickpoint is well-predicted by the drainage area. Because the knickpoint age at the confluence is currently unconstrained, the lines are only meant to show the connection between knickpoint sets, and older sets plot higher on the plot. The difference of slope between sets of knickpoints implies an increasing differential retreat for older knickpoints. Knickpoints on larger streams can penetrate farther into the basin while those on smaller streams advance little.

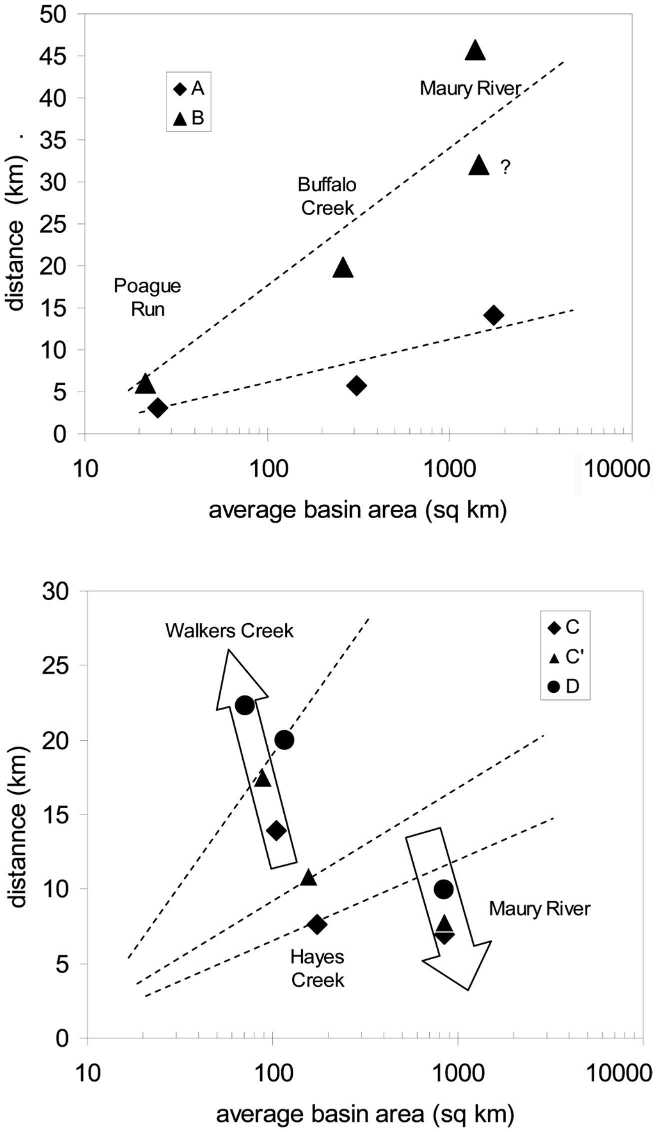


FIG. 9 - Propagation distance for the top of knickpoints in carbonate rocks as shown in fig. 6 (upper panel) and in a mixture of clastic and carbonate rocks as shown in fig. 7 (lower panel). See fig. 8 for the geologic units. The basin area is plotted at the distance-weighted average for the reach starting at lowest confluence through which the knickpoint has traveled, not the basin area of the current location. Letters are the same as for figs. 6-8.

In the upstream set of knickpoints (C-D, fig. 9), topographic and geologic conditions confound this simple relationship between erosional distance and basin area. The expected increase of retreat with basin size, symbolized by the dashed lines passing through the points from the carbonate basin (Hayes Creek), is not matched in any form by actual retreat in the strike-oriented basin at the base of the sandstone ridge (Walkers Creek) or the channel cutting through resistant sandstone (Maury River). The Walkers Creek knickpoints remain comparatively steep, but they have retreated farther upstream (fig. 7). Thus all three knickpoints have propagated farther than expected from the carbonate case (fig. 9). The Maury River knickpoints, even though they are found on the principal stream with a significantly larger drainage basin, have not retreated as far as the tributary knickpoints. Because of the hindered propagation, the knickpoints are much closer together in Goshen Pass and become more widely spread on carbonate basins (fig. 8). From the stream profiles, cumulative deviation, and field observations, it is possible define the waves of incision that connect the tops of knickpoints (fig. 8). Zones of steep valley sidewall slope tend to connect adjacent knickpoints, albeit becoming more diffuse farther away from the channel. Thus our confidence that the knickpoints «correlate» is high.

DISCUSSION

The primary goal of the research was to provide a method to identify and correlate knickpoints in map position throughout a drainage basin. After spatially locating correlative knickpoints, the position and shape of the knickpoints then can be used to constrain the behavior of erosional waves. In this basin, at least one of the knickpoints is likely to have been caused by channel incision following capture and channel realignment around resistant strata near the James-Maury confluence. But because other knickpoints are found downstream on the James River, at least some of the knickpoints are likely to have propagated from the outlet due to a change of base level and climate (e.g., Reusser & *alii*, 2004) or to passive margin flexure or uplift along the coast. However, the cause of the knickpoints cannot be addressed by this method. Knickpoints used in this study (except for Goshen Pass) do not coincide with a lithologic or structural change that would produce a static knickpoint. Moreover, other knickpoints in this basin are clearly migrating based on the coincidence of the knickpoint with the transition of channel beds to exposed straths and adjacent strath terraces.

In this region of tectonic quiescence and highly heterogeneous rock type and geomorphic form, the methodology is quite successful at locating knickpoints. The smoothing routine is sensitive to most of the profile variability that can be observed in the field while removing random and systematic errors in DEM records. The smoothing routine does blunt some of the dramatic knickpoint shapes. In the examples used above, the steepest sections of the travertine dam/plunge pool sections on Hayes Creek have been smoothed, and the sharp crest on the Goshen Pass knickpoint is averaged into the surrounding flat and steep slopes. Other knickpoints that are clearly obvious in the field are lost to the smoothing required to overcome the error of the DEM profile. For example, two migrating knickpoints are located between km 61 and km 64 that are 3 to 5 m high. Without continuous field verification, it would not be possible to accept the level of dramatic slope change observed at these smaller steps without incorporating too many other systematic errors, due for example to stepping on DEMs produced by digitizing contours.

Creating an appropriate slope-area relationship, however, is not without error and the need for finesse in the choosing subsets of profiles to lump into one category. The terminations of the profiles and the base level deviation curves in particular signal the need to account for multiple channel types or geomorphic settings, in addition to simplified geological substrate. For carbonate settings, two types of channels are obvious; the channels that head along sandstone ridges have very steep headwaters that deviate strongly in the positive direction from the average slope-area relationship. These headwater channels are greatly influenced by the coarse clastic sediment load delivered by hillslopes to the fluvial setting and the relief imparted by the resistant ridge. Streams that head on the valley upland, by contrast, are much gentler than predicted based simply on lithology. As a result, the cumulative deviation drops sharply down in the uppermost reaches. These streams are without a clastic load except for minor chert and/or occasional cobble/gravel eroded from older alluvial deposits with a different source area. For example, compare the headwaters of Buffalo Cr (sandstone ridge) (figs. 5 and 6) with the headwaters of Hayes Creek (valley center) (figs. 5 and 7). Likewise, shale streams that are immediately downstream of a water gap tend to have steeper profiles than would be predicted for the rock type. These reaches transport the coarse material delivered to the streams from the resistant lithology holding up the water gap. Streams that are underlain by shale and which run parallel to the fold belt tend to be less steep (see streams above Goshen Pass in fig. 8). Lastly, the fact that the Maury River basin is an incising one, with an extraordinary number of knickpoints causes the average slope area curve to be artificially high on many if not all of middle to larger sized streams. This increases the steepness for the curve and lowers the concavity, which causes the downstream portions of the Maury River in particular to be less steep than predicted (above the lowermost knickpoint at 20-25 km, figs. 4-6). As a result, smaller streams are also steeper than predicted because the concavity is too low. Immediately north of the study area in the less-incised and lower-relief basin of the Shenandoah River, Whipple & Tucker (2002) document a slope-area relationship with a higher concavity (0.56 +/– 0.026), which results in lower slopes for the major rivers. Another possibility is that the low-gradient reaches of the lower Maury River may possess the erosional characteristics of an alluvial stream (transport limited) in the gentle sections between knickpoints. This too would cause a slope less than predicted for the bedrock stream of the same size, but remains unverified by field observation of a persistent alluvial cover.

This poor tracking of «graded» channels limits the utility of the cumulative deviation profiles for learning the height above base level over whole sections of the basin. Ideally, one might expect all knickpoints to rise to the same deviation and then stay flat. In this case, at each height of deviation the landscape including both the streams and hillslopes is still graded to a former base level, remaining insulated from the incision of streams farther downstream. Given the multivariate control of channel gradient, this type of analysis may prove unreachable.

It is clear from the comparison of profiles and knickpoint position that stream power exerts a first-order control on migration, but also that substrate and sediment load change both the shape and the movement of knickpoints. In the purely carbonate case (A and B, fig. 9), drainage area accounts for much of the variation in knickpoint retreat, likely captured by transport-limited stream power equations of erosion (Whipple & Tucker, 2002). Similarly, the prediction that perturbations travel with a constant vertical velocity by Niemann & *alii* (2001) nearly applies in the carbonate case (fig. 6), which implies scaling to stream power. The vertical velocity (or retreat) in the larger streams appears to be less than in the smaller streams, which may in part reflect more pronounced rounding of the knickpoint crest. The sediment cover in the limestone sections is patchy gravel and cobble sandstone derived from resistant ridges and water gaps. In these streams the increase of incision (rather than uplift) and the post-orogenic setting as predicted by Whipple & Tucker (2002) result in detachment limited knickpoints that migrate as kinematic waves. These erosional waves travel by slope replacement rather than the decline as diffusive incision. The degree or rate of migration is significantly modified by erodibility, which appears to be a function of both lithology and sediment load as predicted by other field analyses and experiments (Sklar & Dietrich, 2001, van der Beek & Bishop, 2003).

The differences in retreat of the knickpoints in the topographically and lithologically heterogeneous basins exemplify this importance of both substrate and sediment supply. The lower than expected retreat of the Maury River knickpoints at Goshen Pass (C & D, fig. 9) is consistent with the cutting of folded and fault-repeated section of resistant quartz sandstone through the extraordinarily thick water gap (fig. 8). Knickpoints that are far apart on the tributary streams have collapsed to form what appears to be one large knickpoint with a very sharp crest (fig. 2A). Howard (1998) attributes this step to rock type and the delivery of large boulders to the channel, implying that this knickpoint is stationary. Studies of other sandstone water gaps (Harbor & *alii*, 2003) and the deviation of this gap from the slope of other sandstone channels (fig. 5) suggest that this section of the channel is 6-8 times steeper than other sandstone water gaps. Moreover, no sharp knickpoints are found in any streams flowing through the shale basins upstream of Goshen Pass. However, if knickpoints have passed through Goshen Pass and this knickpoint is stationary, it implies that erosional waves become diffuse as they cut the nonresistant shale in the headwater strike valleys. Further work on the headwaters of the James River will address this question.

The difference in retreat distance between Walker Creek and Hayes Creek is likely related to the clastic debris supply, although the two streams also differ by cutting mostly along-strike or across-strike, respectively (fig. 1), which might influence the style of erosion. Walkers Creek, which runs along strike below the 400 m-high ridge, has abundant coarse load, from sandstone boulders, cobbles and gravel to sand, all of which act as tools for bedrock abrasion. Channels are flanked by significant alluvial floodplains at many locations, and have large gravel bars. The clastic supply to Hayes Creek, in contrast, is the insoluble sand and chert clasts from a few of the carbonate rock units. The Hayes Creek knickpoints are very steep with travertine dams that create a substantial lip. These dams would not survive in a stream system transporting significant coarse sediment, and in fact, in the pools upstream they trap the little sandy sediment that is supplied. These travertine dams seem to hinder knickpoint retreat as much as the tool supply enhances it.

A detachment limited scenario implies that the limestone streams when they are far from the sources of clastic sediment, behave as resistant rock, allowing the knickpoints to wear back instead of decline because the patchy sediment is removed from the knickpoint face. This is particularly true where the travertine dams keep the knickpoint sharp between events of wearing back. The compound sandstone knickpoint in Goshen Pass on the Maury River also has an exceptionally sharp crest (fig. 2A). Sediment delivery to the upper edge of the knickpoint is low, characterized by minor localized gravel/cobble bars and exposed rock. These retreating, sharp crested knickpoints resemble the nonlinear wave behavior case from Tucker & Whipple (2002) where the slope exponent $n > 1$. However, Ries & *alii* (1998) obtained a value for n (0.2) using tributary junction analysis of the Maury River that would predict rounding of the knickpoints instead. The upper beveling of a knickpoint more characterizes the indistinct upper section of the Maury River knickpoint at A (fig. 6), where the sediment delivered from upstream may play a significant role in erosion. The sediment rich setting of Walkers Creek is also associated with a more diffuse knickpoint lacking sharp breaks at the top and bottom. Here, the rapid rate of retreat is also associated with a decline of knickpoints, in strong contrast to the accentuation of knickpoint slope in nearby Goshen Pass.

CONCLUSION

This study has shown that in a region of diverse rock types and structure, knickpoints can be successfully mapped and correlated. The benefit this holds is the eventual ability to study the transient responses of river channel profiles to changes of base level. In addition, the retreat of knickpoints when correlated to dated deposits will allow the determination of relative rock erodibility. Moreover, it gives us a glimpse at the processes responsible for erosional waves, and whether they retreat, recline or diffuse.

Transient effects on river profiles may be a very important component of erosion in some settings. Using the profile of the Maury River near the confluence with the James River we can evaluate the contribution of knickpoints to the overall erosion rate of the basin. Studies of the James River (Howard & *alii*, 1993; Erickson & Harbor, 1998; Ward & *alii*, 2004) and in other basins suggest that terraces 70-80 m above modern river level are not more than 1 million years old, and likely significantly less in the headwaters region west of the Blue Ridge. Assuming they occurred in this period of time, the combined incision by knickpoints just in the lower portion (<50 km upstream) of the Maury River profile is 50 m. Erosion rates for the Appalachians are commonly thought to be near 25 m/M.y. (e.g., Granger & *alii*, 1997) west of the Blue Ridge. Thus, at a minimum, two-thirds of the erosion of the Maury River over the last 75 meters of incision has been accomplished in association with knickpoint retreat. These preliminary calculations carry the implication that transient responses to base level lowering dominate erosion in what is thought to be a declining, tectonically quiescent mountain range. Either this basin is an outlier in the Appalachian topography, or transient responses to disequilibrium are a significant component of basin-wide denudation.

REFERENCES

BANK G., HARBOR D.J. & MORRISS D.W. (1999) - *Erosion history of the St. Marys River*. Banisteria, 13, 161-169.

BEGIN Z.B. (1988) - *Application of a diffusion-erosion model to alluvial channels which degrade due to base-level lowering*. Earth Surface Processes and Landforms, 13, 487-500.

CARLSON M. (1998) - *Knickpoint migration and tufa accretion in five South River tributaries*. Keck research symposium in Geology Proceedings, 11, 226-229.

ERICKSON P.A. & HARBOR D.J. (1998) - *Bringing down Floyd: incision by the James River in the valley and ridge of Virginia*. Geological Society of America, Abstracts with Program, 30-7, 148.

FINLAYSON D. & MONTGOMERY D. (2003) - *Modeling large-scale fluvial erosion in geographic information systems*. Geomorphology 53, 147-164.

GARDNER T.W. (1983) - *Experimental study of knickpoint and longitudinal profile evolution in cohesive, homogeneous material*. Geological Society of America Bulletin, 94, 664-672.

GOLDRICK G. & BISHOP P. (1995) - *Distinguishing the roles of lithology and relative uplift in the steepening of bedrock river long profiles: an example from southeastern Australia*. Journal of Geology, 103, 227-231.

GRANGER D.E., KIRCHNER J.W. & FINKEL R.C. (1997) - *Quaternary downcutting rate of the New River, Virginia, measured from differential decay of cosmogenic* ^{26}*Al and* ^{10}*Be in cave-deposited alluvium*. Geology, 25, 107-110.

HACK J.T. (1957) - *Studies of longitudinal stream profiles in Virginia and Maryland*. US Geological Survey Professional Paper, 294-B, 45-97.

HACK J.T. (1973) - *Stream-profile analysis and stream-gradient indices*. Journal of Research of the US Geological Survey, 1, 421-429.

HARBOR D.J. (1996) - *Nonuniform erosion patterns in the Appalachian Mountains of Virginia*. Geological Society of America, Abstracts with Program, 28, 116.

HARBOR D.J. (1997) - *Landscape evolution at the margin of the Basin and Range*. Geology, 25, 1111-4.

HARBOR D.J. (1998) - *Dynamic equilibrium between an active uplift and the Sevier River, Utah*. Journal of Geology, 106, 181-94.

HARBOR D.J., PANUSKA B.C., TERRY D.O. & KNAPP E.P. (1999) - *River incision and climate history revealed in cave stratigraphy, Maury River basin, Virginia*. EOS, 80-17, S126.

HARBOR D.J., BACASTOW A., HEATH A. & ROGERS J. (2003) - *Drainage basin incision by knickpoint retreat across variable rock types, central Appalachians. Virginia*. Geological Society of America, Abstracts with Program, 35-6, 335.

HOWARD A.D. (1998) - *Long profile development of bedrock channels: Interaction of weathering, mass wasting, bed erosion, and sediment transport*. In: K.J. TINKLER & E.E. WOHL (eds.), «Rivers over rock: Fluvial processes in bedrock channels», American Geophysical Union, 297-319.

HOWARD A.D. & KERBY G. (1983) - *Channel changes in badlands*. Geological Society of America Bulletin, 94, 739-752.

HOWARD J.L., AMOS D.F. & DANIELS W.L. (1993) - *Alluvial soil chronosequence in the inner Coastal Plain, central Virginia*. Quaternary Research, 39, 201-213.

KIRBY E. & WHIPPLE K. (2001) - *Quantifying differential rock-uplift rates via stream profile analysis*. Geology, 29, 415-418.

KIRBY E., WHIPPLE K., TANG W. & CHEN Z. (2003) - *Distribution of active rock uplift along the eastern margin of the Tibetan Plateau: inferences from bedrock channel longitudinal profiles*. Journal of Geophysical Research, 108, DOI:10.1029/2001JB000861.

MONTGOMERY D.R. & FOUFOULA-GEORGIOU E. (1993) - *Channel network representation using digital elevation models*. Water Resources Research, 29, 1178.91.

MONTGOMERY D. & BLANCO J. (2003) - *Post-Oligocene river incision, southern Sierra Madre Occidental, Mexico*. Geomorphology, 55, 235-47.

NIEMANN J.D., GASPARINI N.M., TUCKER G.E. & BRAS R.L. (2001) - *A quantitative evaluation of Playfair's Law and its use in testing long-term stream erosion models*. Earth Surface Processes and Landforms 26, 1317-1332.

PENCK W.O. (1925) - *Die Piedmontflächen des südlichen Schwarzwaldes*. Gesellschaft fur Erdkunde, 81-108.

REUSSER L., BIERMAN P., PAVICH M., ZEN E., LARSEN J. & FINKEL R. (2004) - *Rapid late Pleistocene incision of Atlantic passive-margin river gorges*. Science, 305, I. 5683, 499-502.

RIES J., MERRITTS D., HARBOR D.J., GARDNER T., ERICKSON P. & CARLSON M. (1998) - *Increased rates of fluvial bedrock incision in the Central Appalachian Mountains, Virginia*. Geological Society of America Abstracts with Program, 30-7, 140.

ROE G.H., MONTGOMERY D.R. & HALLET B. (2002) - *Effects of orographic precipitation variations on the concavity of steady-state river profiles*. Geology, 30, 143-46.

SEIDL M.A., DIETRICH W.E. & KIRCHNER J.W. (1994) - *Longitudinal profile development into bedrock: an analysis of Hawaiian channels*. Journal of Geology, 102, 457-474.

SKLAR L. & DIETRICH W. (2001) - *Sediment and rock strength controls on river incision into bedrock*. Geology, 29, 1087-90.

SNYDER N., WHIPPLE K., TUCKER G. & MERRITTS D. (2000) - *Landscape response to tectonic forcing: digital elevation model analysis of stream profiles in the Mendocino triple junction region, northern California*. Geological Society of American Bulletin, 112, 1250-63.

STOCK J.D. & MONTGOMERY D.R. (1999) - *Geologic constraints on bedrock river, incision using the stream power law*. Journal of Geophysical Research, 104, 4983-93.

TUCKER G.E & WHIPPLE K.X. (2002) - *Topographic outcomes predicted by stream erosion models: sensitivity analysis and intermodel comparison*. Journal of Geophysical Research, 107, doi: 10.1029/2001 JB000162.

VAN DER BEEK P. & BISHOP P. (2003) - *Cenozoic river profile development in the upper Lachlan catchment (SE Australia) as a test of quantitative fluvial incision models*. Journal of Geophysical Research, 108, 2309; doi: 10.1029/2002JB002125.

VIRGINIA DIVISION OF MINERAL RESOURCES (VDMR) (2003) - *Digital representation of the 1993 geologic map of Virginia*. Publication 174.

WARD D., SPOTILA J. & HANCOCK G. (2004) - *New constraints on the late Cenozoic incision history of the New River, Virginia*. Geological Society of America Abs. Prog., 36-5, 11.

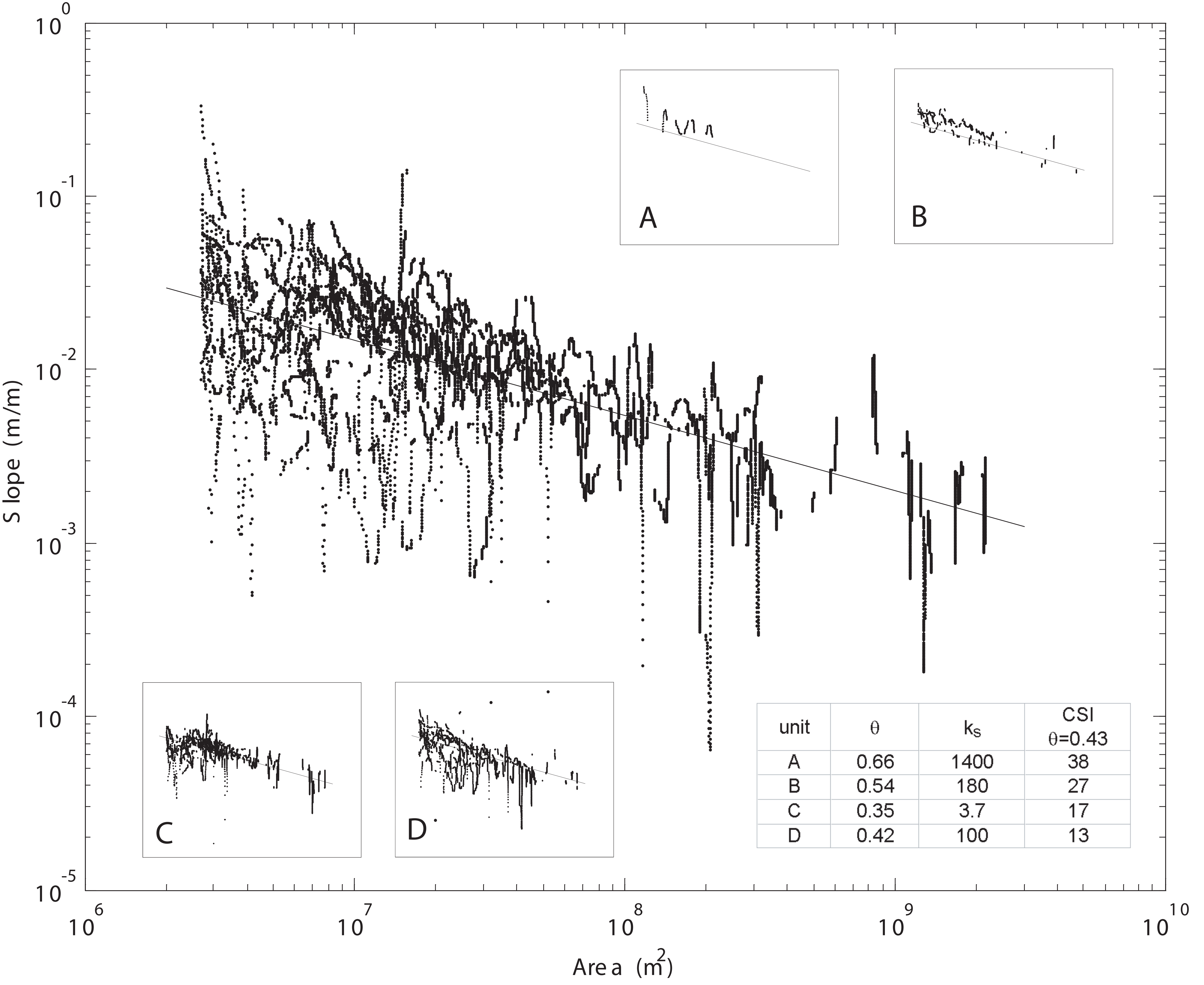
WHIPPLE K.X. (2001) - *Fluvial landscape response time: how plausible is steady state denudation*? American Journal of Science, 301, 313-25.

WHIPPLE K.X. (2004) - *Bedrock rivers and the geomorphology of active orogens*. Annual Review of Earth and Planetary Sciences, 32, 151-85.

WHIPPLE K.X. & TUCKER G.E. (1999) - *Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs*. Journal of Geophysical Research, 104, 17,661-74.

WHIPPLE K.X. & TUCKER G.E (2002) - *Implications of sediment-flux dependent river incision models for landscape evolution*. Journal of Geophysical Research, 107, doi: 10.1029/2000JB000044.

ZAPROWSKI B.J., EVENSON E.B., PAZZAGLIA F.J. & EPSTEIN J.B. (2001) - *Knickzone propagation in the Black Hills and northern High Plains: A different perspective on the late Cenozoic exhumation of the Laramide Rocky Mountains*. Geology, 29, 547-550.



unit	θ	k_s	CSI θ=0.43
A	0.66	1400	38
B	0.54	180	27
C	0.35	3.7	17
D	0.42	100	13