Knickpoint migration and tufa accretion in five South River tributaries, Central Virginia

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INTRODUCTION

The South, Maury, and James Rivers are bedrock rivers which flow through the Great Valley on their way to the Atlantic. For reasons currently under study (Harbor, 1996), the drainage including these three rivers is undergoing incision that is more rapid than surrounding drainage areas. One set of incision rates for the Maury River range from 64 to 140 m/m.y. (Dorale, unpublished data), whereas the reported rates for the Susquehanna River to the north and the New River to the southwest are 10 m/m.y and 40m/m.y., respectively (Pazzaglia and Gardner, 1993; Bartholomew and Mills, 1991). Thus, high incision rates characterize the James River drainage basin as anomalous to basins surrounding it. Anomalies may be apparent in upstream reaches of the James basin, namely the South River. This purpose of this study is to determine which bedrock stream incision mechanisms–abrasion, dissolution, debris flow scour, and knickpoint migration (Seidl and Dietrich, 1992)–govern the high incision rates and to calculate such rates from knickpointed stream analysis. A secondary purpose is to examine the coupling between knickpoint migration and tufa accretion.

STUDY AREA

The five western tributaries comprising the focus of this study traverse four bedrock formations, all Ordovician and Cambrian limestones. The five tributaries are consistent in discharge as well as bedrock base, varying to within one order of magnitude. Thus, the consistency of these five knickpoint-dominated, bedrock streams makes their comparison well-constrained. In order from north to south, the tributaries are Upper Marl Creek, Moores Creek, Marlbrook Creek, Whitesides Run, and Lower Marl Creek (figure 1).

Of the four mechanisms of bedrock incision given by Seidl and Dietrich (1992), I propose that dissolution and the mechanisms of knickpoint migration, plucking and slab quarrying, dominate erosion and incision in the five western tributaries. Because these five western tributaries do not flow over nearby quartzite, and chert beds within limestones are minimal in comparison to carbonate, abrasion is not a major mechanism of erosion. No evidence of debris flow scour is present in these five streams. Hence, dissolution and mechanisms of knickpoint propagation are the major factors in bedrock erosion of these five tributaries.

While knickpoint migration and dissolution promote incision of these five tributaries, tufa accretion slows the incision. Tufa deposits in the five streams under study are of the barrage construction model where phytothermal growth is invoked to account for the presence of tufa dams that develop perpendicular to flow and span the width of the stream (Ford and Pedley, 1996). Because these barrage constructions partially block the flow of water, pools sedimented with lime muds develop upstream from the dam. Tufa systems are self-regulating due to the intricate association between biomediated and physico-chemical-induced precipitation (Ford and Pedley, 1996). However, this self-regulation does not continue indefinitely. At some point, the tufa dam will incise.

METHODS

Erosion mechanisms. Field data includes longitudinal profiles of three streams: Upper Marl, Marlbrook, and Lower Marl Creeks. Profiles were obtained using an automatic altimeter and a 50 meter tape. Each data point represents a point either before or after a major change in slope. The three profiles are partial, yet detailed. Less detailed profiles of all five tributaries were obtained from 7.5 minute USGS topographic maps.

Examination of such topographic maps of the area and use of Atlas GIS software yield drainage areas and stream lengths. Analyzing this data with a method introduced by Howard and Kerby (1983) and further developed by Seidl and Dietrich (1992), quantification of the exponent ratio of drainage area to slope was possible. Modifying the transport law using drainage area as a proxy for discharge, Howard and Kerby (1983) found the following equation:

$$-(dz/dt) = K A^m S^n \tag{1}$$

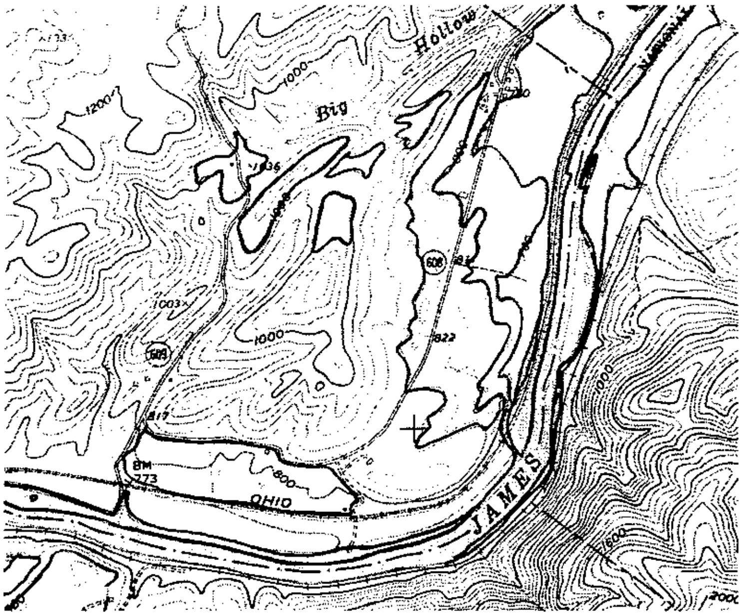

Figure 3 Example terrace mapping by the James River Group on the Arnolds Valley quadrangle

what Dylan discovered. Moreover these two studies contribute valuable observations of the style and mechanisms of incision. Solution, abrasion and scour all take place at distinct places along the channel. What we really need now is some idea of how the knickpoints get started.

Benson Chow and **Dennis Linney** studied the details of rock and mineral weathering in the terrace sediments. Comparing clast weathering to previous work just north of the field area, Benson showed that clay replacement at grain boundaries and grain weathering were responsible for clast weathering in increasingly older deposits. He cautions that the particular mineralogy needs to be accounted for in relative weathering schemes that use clast weathering. Dennis found that changes in the percentages of opaque, heavy minerals might be related to deposit weathering, as was a change of shape for some minerals. Some differences in grain shape may have been due to original deposit grain morphology, perhaps reflecting sources of the grains.

Relying on backs and backhoes, **Carrie Elliott** and **Bala Dodoye-Alali** set out to document the changes of soil characteristics on terraces. Carrie compared two chronosequences, one in limestone and one in shale. She found that in general, soils became more complex, more clay-rich and redder with elevation, and that the two terrace sequences were similar. However, the upper shale terrace sequence was less red than the next lower terrace, even though the clay percentage was greater. Oddly, using color comparisons alone, Carrie showed that the highest terraces in a stream in the Potomac Basin were incising faster (lower rubification) than the James, even though the opposite should be true. Bala found increased reddening with height as well, but determined that great variation of soil texture and redness could be found at similar heights along the river. Some of this may be due to elevation changes caused solution of carbonate bedrock, but she suspects that additional differences are generated by the kind of incision observed by Martha and Justin.

Taken together, these 9 projects have made a huge advance in our knowledge of the timing and dynamics of landscape change in the Central Appalachians. We now have some hypotheses about 1) incision mechanisms, 2) rapid to extremely rapid incision rates from which we can speculate about the amount of time it would have taken to produce the topographic relief we see now, and 3) several stratigraphic and relative weathering time-markers which we can use to correlate deposits around the region. I think we have clearly demonstrated that the upper James River is an actively incising system worthy of more study. As with any good project, we have generated more questions than we set out to answer. We will be able to work on these problems for years to come. Thanks to you all.

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where dz/dt is vertical distance over time, K is the coefficient of erosion, A is drainage area, S is slope, and m and n are constants which vary with bedrock type and erosion mechanism. Taking this approach a step further, Seidl and Dietrich (1992) propose that the ratio of m to n can be determined by plotting the log of the channel gradient ratio against the log of the drainage area ratio, assuming that certain characteristics of the streams and downcutting rates are equivalent. The slope of the resulting line is equal to the m/n ratio (figure 3).

If the incision rate is known, a value for K, the coefficient of erosion, can be obtained. Currently, there is little constraint in the geologic literature on K values for bedrock streams (Stock and Montgomery, in press).

A knickpoint migration rate can be obtained if the following variables are known: incision rate, sum height of knickpoints, and the longitudinal distance from the confluence to the most headward knickpoint. In the equation:

$$dz/dt = Z/T \qquad (2)$$

dz/dt is the incision rate, Z is the sum of all knickpoint heights, and T is time taking a knickpoint of height Z to migrate to its current position. Evaluating the following equation for dx/dt gives a knickpoint migration rate:

$$X = T(dx/dt) \qquad (3)$$

where X is the distance from the confluence to the farthest knickpoint, and T is determined by equation (2) (figure 4).

Tufa accretion. Further study of Marlbrook Creeks includes stratigraphic column analysis of unconsolidated pool sediments that accumulated behind tufa dams (figure 2). Pool sediments from Marlbrook Creek contain woody debris in two layers, one at 0.7 to 1.3 m above base level and the other at 3.4 to 3.7 m. Two wood samples were taken for C-14 radiocarbon dating. A third C-14 radiocarbon sample of gastropod shells was taken from the 7.9 to 8.1 m layer. Because the tufa dam is now incised to within ten centimeters of bedrock, the uppermost carbon sample gives a minimum duration of tufa dam protection.

RESULTS

Erosion mechanisms. Determination of dissolution and knickpoint migration as the two major forms of incision in these streams results from field observations exhibiting a lack of debris flows and abrading siliciclastic sediments. Because precipitation and output data for these streams and the South River are non-existent, the rate of dissolution cannot be determined. Longitudinal profiles from data taken in the field (figure 5) and from topographic maps (figure 6) demonstrate the presence of knickpoints in these streams. I propose that the small, less than 5 m, knickpoints correspond with successive base-level drops; large knickpoints, exhibited in each longitudinal profile, represent the ìstackingî of base-level drop knickpoints. These large knickpoints occur at the point of, or directly upstream from, a formational change or fault (figure 6).

An incision rate was calculated using equation (1). The m/n value obtained in this study is 0.43. Stock and Montgomery (1998, in press) report a range of m values for knickpoint-dominated streams between 0.1 and 0.2 and those of n range from 0 to 0.2. Values for m and n of 0.08 and 0.2 fall approximately within these ranges, and adhere to the ratio 0.43. Stock and Montgomery (in press) report K values on the order of 10^{-2} to 10^{-4} for streams flowing over unresistent bedrock. Evaluating dz/dt where m equals 0.08, n equals 0.2, K equals 10^{-4}, and tributary area and slope are averaged across the five streams, an incision rate of 64 m/m.y. was obtained.

Using equation (2) with an incision rate of 64 m/m.y., falling into the Maury range, and an average sum knickpoint height of 121 m, the duration of knickpoint migration (T) was found to be 1.9 m.y. Evaluating dx/dt from equation (3) using this T and an average X of 4000 m yields a dx/dt value of 2105 m/m.y.

Tufa accretion. The wood sample radiocarbon date from 2.4 to 4.3 feet above base level is 7870 +/- 120 years; that of the sample from 11.2 to 12 feet above base is 8400 +/- 220. Sample impurity, tree age, and cut and fill are three plausible explanations for the inversion. The radiocarbon date obtained from the gastropod shell sample is 5825 +/- 95 years (figure 2). Because the tufa dam has incised to within 10 cm of bedrock, the minimum duration of tufa dam incision is equal to the age of the gastropod sample.

DISCUSSION

Erosion mechanisms. Knickpoint ìstackingî occurs when one knickpoint, produced by base level drop, is upheld by lithological variation, thus allowing the following knickpoint to overtake the first. In the five streams studied, I propose that bedrock variance controls the size distribution of knickpoints to a lesser extent than does base level drop. The large knickpoints in each stream result from bedrock variation. However, the majority knickpoints less than five meters results from base level drop. The correspondence between the large knickpoints and structural and lithological variance shows that the large knickpoints result from the structural and lithological forcing, such as formation change or faulting (figure 6). The smaller knickpoints do not, however, show such a correspondence.

Small knickpoints may be due to the presence of chert beds in the Beekmantown and Elbrook formations. However, small knickpoints also occur in reaches flowing over non-cherted limestones, suggesting that chert beds are not the only producers of knickpoints. These small knickpoints that do not correspond to chert beds could be due to bedding within the limestone. However, intra-formational bedding orientations are similar, with the exception of the Beekmantown. This observation compounded by the known uplift occurring suggests that the majority of knickpoints are indeed produced by base level drop.

In none of the streams studied was there evidence of debris flows. Hence, debris flow scour is unlikely to contribute to erosion or incision of these streams. Likewise, abrasion is minimal. In order to abrade limestone bedrock, siliciclastics or other minerals with a hardness greater than that of calcite are necessary. However, very few siliciclastic sediments are in transport in these streams. The only source of siliciclastic material is in the form of chert beds and is minimal. Therefore, abrasion can be abandoned as a significant mechanism of erosion in these five streams. Dissolution as a major form of erosion is probable. Although dissolution rates cannot be determined here, the water must have a high calcium carbonate content, a consequence of limestone dissolution, in order for tufa to precipitate. Hence, adequate dissolution to supersaturate the water is occurring in these five streams.

Tufa accretion. Concurrent with knickpoint propagation mechanisms in instigating erosion and incision, tufa accretion on the upstream end of knickpoints slows the upstream retreat. This is apparent from the Marlbrook Creek tufa dam incision duration (figure 2). Because the gastropod radiocarbon sample was collected from the highest point to which the tufa dam grew and because the tufa has been eroded almost entirely to its base, the minimum duration of tufa dam incision 5825 +/-95 years. This duration can also be used as a proxy for the minimum duration that the tufa dam protects the knickpoint from migrating.

CONCLUSION

In the five bedrock streams which flow east into the South River, mechanisms of knickpoint migration and dissolution are the major forms of incision. Concurrent with the headward propagation of knickpoints is the formation of tufa dams, or barrage constructions, which impedes this headward migration.

More research in this area will elucidate much of what is currently in question. For example, K values for different types of bedrock are poorly constrained. Although Stock and Montgomery (1998, in press) provide actual K, m, and n values from previously-published data, bedrock types are not covered extensively. Further stream studies finding m, n, and K values will not only elucidate the effect of changing system parameters on the modified transport law, it will also test the validity of the approach.

The knickpoint migration rate presented in this study is poorly constrained due to the inaccuracy of the incision rate used. For increased accuracy, a knickpoint migration rate could be calculated using equation (3) if radiocarbon dates from two subsequent pool sediments formed by the same knickpoint could be gathered. The prevalence of incision tufa dams in these five tributaries suggests that this area would be a prime location for such a study.

The same goal could be attained with a radiocarbon date from one set of pool sediments. If the tufa dam had fully breached, the knickpoint had cut through the pool sediments, and present position of the knickpoint could be determined by following the bedrock strath, a knickpoint migration rate could be obtained by dividing the distance between the tufa dam and the current position of the knickpoint by the change in time. If a knickpoint migration rate were obtained, extrapolation of that migration rate using equation (3) could be performed to obtain an incision rate.

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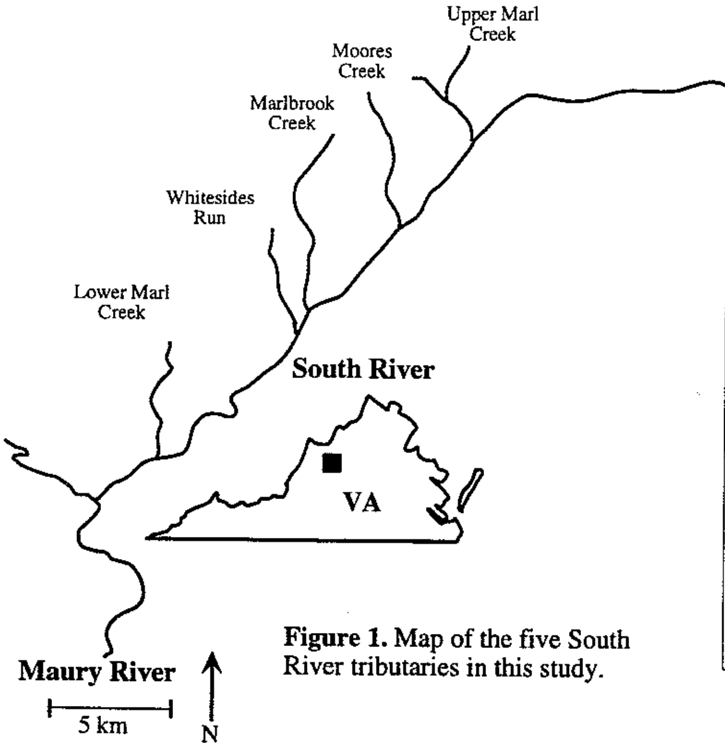

Figure 1. Map of the five South River tributaries in this study.

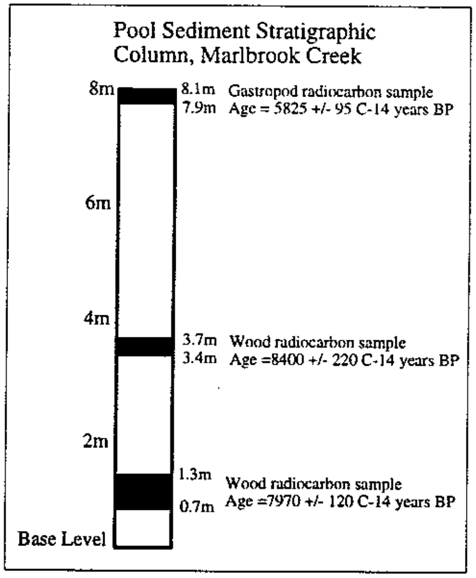

Figure 2. Radiocarbon dates and locations of samples within the stratigraphic column.

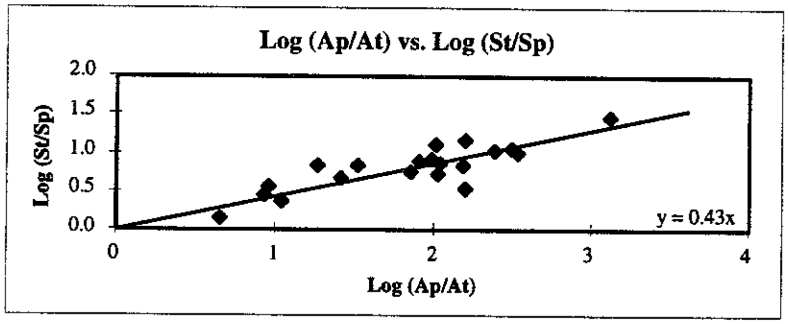

Figure 3. Log-log plot of the principle stream drainage area (Ap) to tributary drainage area (At) ratio against tributary gradient (St) to principle stream gradient (Sp) ratio (after Seidl and Dietrich, 1992).

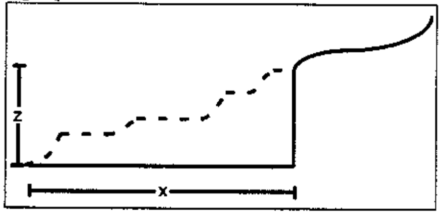

Figure 4. Schematic drawing of a bedrock stream dominated by knickpoints. X represents the overall longitudinal migration distance. Z represents the overall height.

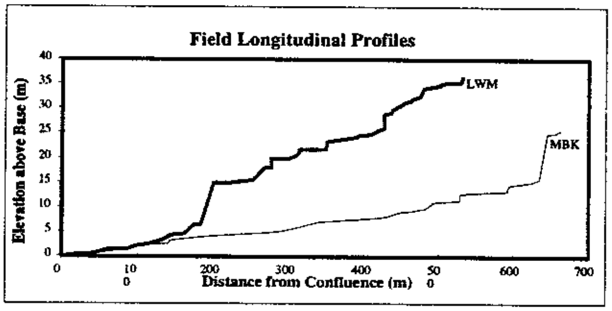

Figure 5. Longitudinal profiles of Lower Marl and Marlbrook Creeks obtained from field surveys.

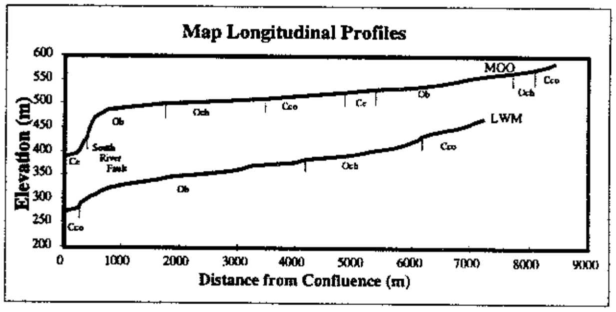

Figure 6. Longitudinal profiles of Moores and Lower Marl Creeks obtained by topographic map analysis. Profiles contain bedrock contacts (Ce = Elbrook, Ob = Beekmantown, Och = Chepultepec, Cco = Conococheague).

Mechanism of Clast Weathering: A Study of Quartzite Cobbles

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ABSTRACT

The object of this study is to understand weathering of quartzite cobbles and to evaluate the potential for correlating river terraces. Two modes of weathering were discovered: grain alteration of feldspar and dissolution of intergranular contacts. Interstitial clay formed along grain contacts appear to play the major role in weathering. Point count data show that qualitative weathering categories are related to increased interstitial clay content.
Key words: terrace cobbles, quartzite clast weathering, correlation techniques.

INTRODUCTION

During the summer of 1997, the Keck Geology Consortium sponsored undergraduate research. Geomorphology projects were supported by 3 advisors in the Ridge and Valley of Virginia. Mapping and correlating terraces along the Maury, James, and South Rivers was a major objective accomplished during the field work. The ultimate goal is to establish age constraints for the terraces in order to calculate river incision rates.

Mapping and correlation of river terraces involved examination of aerial photographs and topographic maps. Terraces identified on maps and aerial photographs were confirmed by field reconnaissance. Elevations above modern river levels were used as a first approximation of correlating river terraces. Unfortunately, some of the terraces were not easily correlated. Uncertain strath contact and uncertain sediment thickness led to imprecise terrace elevations. Other correlation methods being studied involve soil weathering. Preliminary findings have shown an increase in A and B horizon thickness and increased clay accumulation in the B horizon as the soil matures (Dodoye-Alali, 1998; Elliott, 1998). Mature soils yields more clay than immature soils due to leaching of minerals in the upper horizons and depositing the leached materials in the lower horizons of the terrace. Another possibility of correlating terraces is to examine weathered clasts deposited on terraces.

In order to deal with correlation problems of alluvial fan deposits, Whittecar (1992) developed a classification system for weathered quartzite cobbles to assign the relative ages of alluvial fans in the Appalachian Mountains. The classification system is divided into five categories based upon the texture and hardness of the cobble (Table 1). This classification system can be applied to the terraces in this study.

The purpose of this project is to investigate weathering of quartzite cobbles deposited into alluvial terraces and to evaluate an alternative method of correlating terraces. By determining the key mechanism controlling cobble disintegrations, more accurate correlations of terraces might be possible. It is possible that a relationship between cobble weathering and soil development can be established.

CATEGORY	DESCRIPTION
1	**well indurated, very resistant; no oxidation rind visible**
2	**well indurated, very resistant, oxidation rind present (>2 mm thick) or internal oxidation apparent**
3	**breaks into chunks when struck by hammer but chunks not crushable by hand**
4	**removable from outcrop, crushable by hand; disintegrates into individual grains when struck by hammer**
5	**cannot be removed intact form outcrop; sliceable with shovel**

Table 1. F# classification system (from Whittecar, 1992).