CENOZOIC LANDSCAPE EVOLUTION IN THE SOUTHERN SHENANDOAH VALLEY, VIRGINIA

FACULTY
David Harbor, Washington and Lee University
Tom Gardner, Trinity University
Dorothy Merritts, Franklin and Marshall College

STUDENTS
Martha Carlson, Carleton College
Benson Chow, Mississippi State University
Bala Dodoye-Alali, Whitman College
Dylan Easthouse, Whitman College
Carrie Elliott, Carleton College
Peter Erickson, Carleton Collge
Dennis Linney, Elizabeth City State University
Justin Ries, Franklin and Marshall College
Dan Rittenhouse, College of Wooster

PARTICIPATING SCIENTISTS
Rich Whittecar, Old Dominion University
Jeff Dorale, University of Minnesota
Bruce Panuska, Mississippi State University

VISITING SPONSORS
Fred Lobdell, Elizabeth City State University
Bob Carson, Whitman College
Bruce Panuska, Mississippi State University

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David J. Harbor, Project Director
Department of Geology, Washington and Lee University, Lexington VA 24450
with
Thomas W. Gardner & **Dorothy Merrritts**
Trinity University Franklin and Marshall College

THE RESEARCH FRAMEWORK

Over geologic time, mountains exist where the rate of tectonic uplift of rocks exceeds the local ability of erosional processes to tear them down. However, the duration of uplift-producing orgogeny is finite, leaving erosion to plane off not only the uplifted mass, but a greater amount of underlying buoyant crustal mass. This beveling can take hundreds of millions of years, and it leaves in depositional basins thousands of meters of erosional sediment. On our own Atlantic seaboard are great accumulations of sediment where the largest Appalachian Rivers dumped their load on the continental shelf. This sediment stack was not deposited steadily, but in temporal 'pulses' over the last 180 million years. Geologists have traditionally looked to two causes for episodic increases in river sediment delivery; either a change in climate, which provides the erosional mechanism of more rain or collapse of stabilizing vegetation, or a temporary renewal of uplift, which rebuilds the relief.

However, there is another possibility, and it lies in the competition between streams that drain southeast to the Atlantic coast and those that drain northwest toward the Ohio and Mississippi River basins. Due to greater slope, the Atlantic streams capture drainage area from the Gulf streams, pushing the drainage divide into the Appalachian Plateau of WV and PA. This piracy has proceeded from north to south, first allowing the Susquehanna, then the Potomac to cut back across the folded Appalachian Mountains (Thompson, 1939). Once Atlantic streams penetrate this spine of resistant rocks in the Blue Ridge Highlands and eat into the softer sedimentary rocks behind, the great difference in elevation between the Gulf and Atlantic streams is exploited by the latter, generating an extraordinary period of erosion. Here's how Davis viewed it in North Carolina:

> The View from Mt. Mitchell.—The observer on Mt. Mitchell in western North Carolina looks down to the eastward upon one of the most stubborn contests ever wages: the contest between the short Atlantic rivers and the long round-about stream courses that lead through the Mississippi to the Gulf. The Atlantic streams are the victors; they are gradually gaining ground, for they have adopted the strategy of deep entrenchment and they are slowly but surely driving back their opponents. The eastern headwaters are capturing the outermost skirmish lines of the western streams, and occasionally even an important detachment of the western vanguard is flanked, cutoff and lead away captive by a sortie of the attacking party. The western streams are making every effort to hold their upland territory, but in spite of occupying the higher land they are doomed to defeat, for the ground is literally taken from under them by the invaders; and then the rain that has been for so many ages loyally bearing tribute to the Mississippi deserts its long time master, as if eager to return to the parent ocean by the shortest possible route. The rock grains, sleeping in the schists beneath the hills of the upland and looking for no disturbance until in ages yet to come they should be slowly washed away by the then decrepit and wandering western streams, are surprised on being awakened by the eastern daylight and finding themselves hurried down the steep slopes of the conquering Atlantic streams and swept along an unexpected course to the sea.
>
> Wm Morris Davis, 1903, Bulletin of the Geographical Society of Philadelphia, p. 213

The streams and rivers of the upper James Basin (Figure 1) have just accomplished this feat of military might and now continue or are nearly finished with the rapid excavation of the southern end of the Shenandoah Valley. This degree of erosion contrasts sharply with the higher elevation, lower-relief basin of the upper New River (figure 1).

The westward migration of the escarpment must generate irregular patterns of erosion in cutting the trend of the Appalachians and the great variation in rock type and erosional resistance. This is based on two simple conditions of readily observed geomorphic conditions: 1) Given the asymmetry of the topographic profile, the "Blue Ridge Escarpment" (Davis, 1903) in southern Virginia is still migrating, and 2) most of the drainage in the Valley and Ridge province and some in the Blue Ridge province is subsequent and aligned parallel to the strike of the orogen as a whole. Currently, the eastern continental divide cuts abruptly across the Valley and Ridge between the New River (Mississippi basin) and the Roanoke River (Atlantic) basins. I suggest that this configuration results from abrupt diversion of most of the Valley and Ridge drainage in large, basin-scale captures. This is not hard to imagine given how close the New River in southern Virginia is to the Blue Ridge escarpment. Indeed, the New River is the next basin that will be diverted to the SE. Huge areas drained by major streams running very close to the eastern continental divide can be suddenly pirated to the southeast as their base level is dropped up to 500 m.

Accepting this model (figure 2) of episodic erosion means that the rate at which the streams of the upper James River basin, including the Maury and South Rivers, are cutting into the earth should greatly outpace those rivers tributary to the Potomac in the north and to the New in the south (figure 1). The sudden drop in base level following

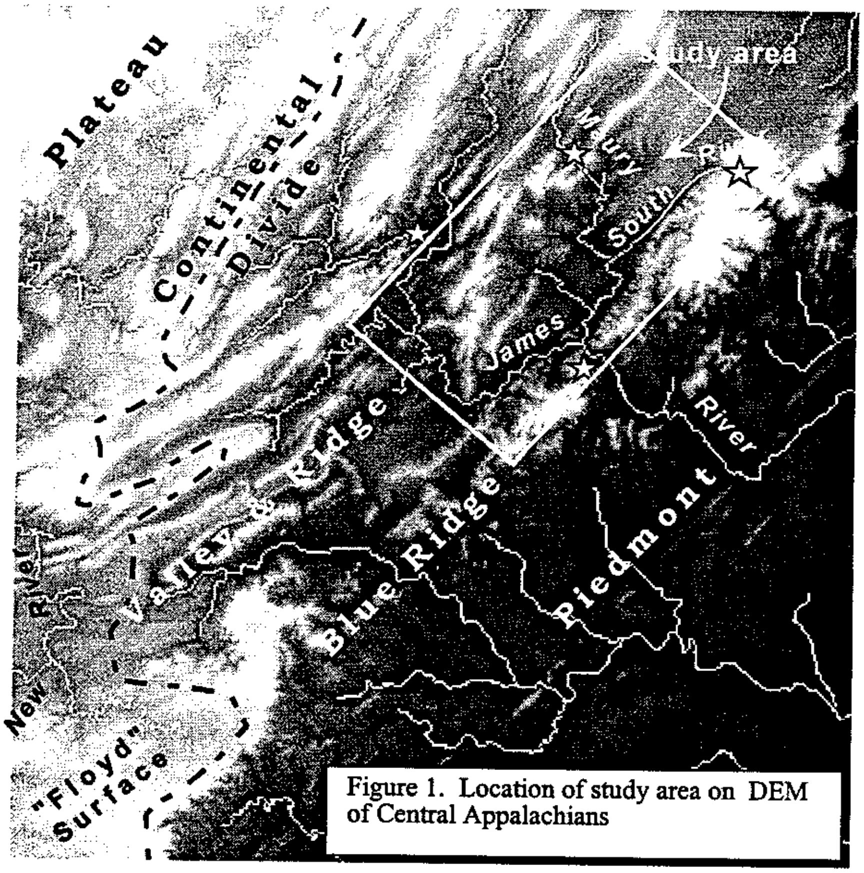

Figure 1. Location of study area on DEM of Central Appalachians

should cause rapid knickpoint retreat into the folded Appalachians, and isostatic and flexural uplift resulting from this erosion will further enhance the erosional potential of the newly energized basins.

The transverse drainage and erosional form of the Appalachian Mountains have been under scrutiny for over 100 years. However, in the last 40 years, considerably less effort has been expended in explaining the history of the landforms as geomorphology turned to the study of geomorphic processes. Now equipped with models of flexure and landscape evolution, as well as new dating techniques, we can return to the long-term geologic history of the Appalachian landscape. This project was brought together to investigate this most rugged of all transverse Appalachian drainages (figure 1). No process studies had been conducted in the southern end of the Shenandoah Valley, and the abundant terraces hadn't been mapped either.

RESEARCH APPROACH

Having only a loosely defined geomorphic model and no surficial mapping, our first goal was to map the terrace deposits in the three main valleys of the upper James River basin. (figure 3). Three mapping teams worked upstream along the three largest water-courses in the upper James Basin, starting at the James River Gap in the Blue Ridge (the mapping areas are marked by stars on figure 1).

The Mapping Teams

The South River: Martha Carlson (Carleton College), Benson Chow (Mississippi State), and Dennis Linney (Elizabeth City State University).

The James River: Peter Erickson (Carleton College), Carrie Elliott (Carleton College) and Dan Rittenhouse (Wooster College)

The Maury River: Bala Dodoye-Alali (Whitman College), Dylan Easthouse (Whitman College), and Justin Ries (Frankin & Marshall College)

This mapping was fast and furious, with people learning to map in a day or less and covering up to 40 km in less than ten days. These maps are in preparation for publication by the State of Virginia; each mapping team is to be congratulated. During the mapping process, conceptual models were developed, problems to be solved were illustrated, and we all learned the terrain. As the mapping drew to a very successful close, projects of three types grew out of the mapping. We were fortunate on this project to have the help of Jeff Dorale and Bruce Panuska who brought expertise in U series dating and paleomagnetic sampling. These allowed some of the students to consider using these techniques to "pin down" erosion rates throughout the study area. In addition, the growing use of cosmogenic isotope dating was available for determining by surface exposure ages of terrace soils, and burial dates of cave and fan alluvium. As exciting as these advances in dating are, one cannot date every terrace or fan in a study area, so one must map deposits and learn to distinguish them based on their weathering characteristics. These can then be used to help validate and extend the result of the numerical dating. Lastly, one needs to have some idea of the process of incision. For example, a good question has always been: Is erosion or incision coeval or synchronous throughout the basin or do knickpoints migrate upstream? The answer to this type of question relies on detailed process-oriented studies that help us to understand the results of both the mapping and the relative dating. The nine students were spread within among three areas; three students (Dan, Peter, and Dylan) undertook the dating of deposits that are characteristic of the higher levels of the "Valley Surface" or deposits in caves abandoned during incision. Four students (Bala, Benson, Carrie, and Dennis) investigated weathering and soil development in terrace deposits of varying elevation above the river. Two students (Martha and Justin) worked on the style of incision in tributary streams connected to the rapidly incising upper James streams.

THE RESULTS

Early during reconnaissance, two important findings were made. First, with the help of Jeff Dorale from the University of Minnesota and Bruce Panuska from Mississippi State, a brief trip into a cave 50 m above a tributary to the Maury River yielded samples for U-Th dating from a speleothem on river gravel and a normal paleomagnetic signal in bedded silts and clays below the speleothem. These samples constrain erosion rates to 65 - 150 m/m.y. This was an exciting finding given that the average Appalachian erosion rate is generally reported as being near 40 m/m.y., and is even lower in the upper New River basin (26 m/m.y., from Granger et al., 1997). The second finding was the significant difference in topography between the James River basin and the New River basin in Floyd County Virginia, which compelled us to name the slowly upland the "Floyd Surface." for the town which resides on it . It is the difference in erosion rate between the study area and this surface that creates and sustains high relief in an orogenic belt deformed 180 m.y. ago.

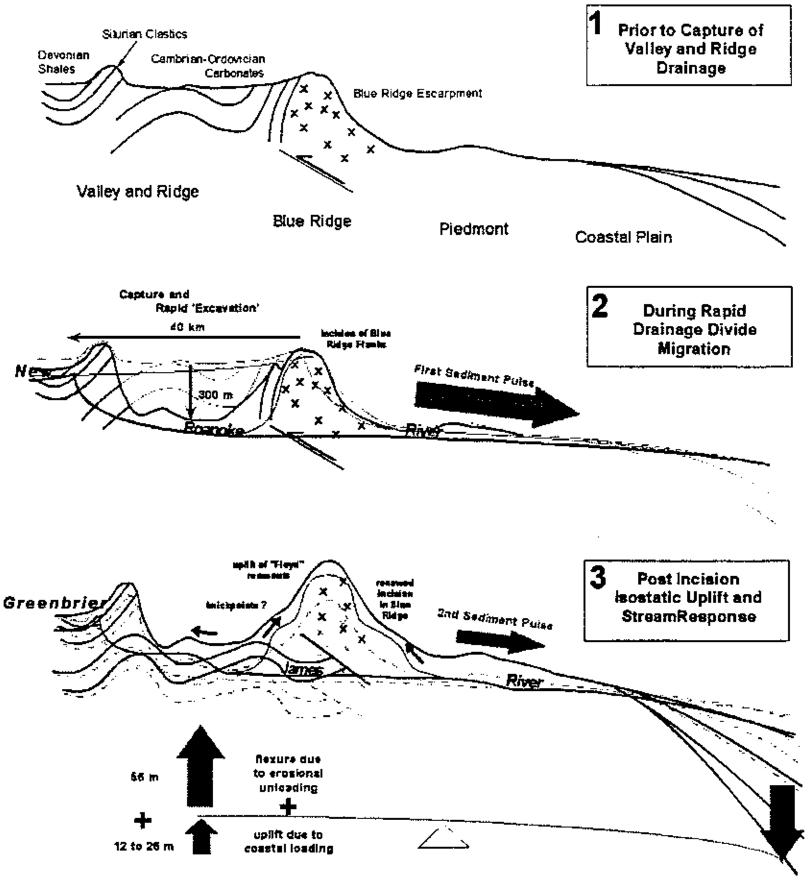

Figure 2 Model of punctuated landform erosion caused by scarp retreat and uplift due to isostatic compensation and flexure (from Harbor, 1996).

Peter Erickson took the largest view of the landscape in his project, seeking to explore the erosion rates from Floyd down to the Valley Surface and that surface to the present. He coupled cosmogenic dating (^{26}Al and ^{10}Be) of samples taken from dispersed remnants of the Valley Surface with a flexure model of erosion and uplift, caused by the erosion of rock between the Gulf drainage system (Floyd) level and the present topography. His modeling and preliminary dating suggest that rapid erosion at nearly 180 m/m.y. has characterized the latest period of incision. That rate of erosion since the mid-Miocene would consume enough rock, including isostatic uplift, and would produce our modern landscape. Peter's erosion rate of 180 m/m.y. was determined from an abandoned James River meander .

Dan Rittenhouse also tried to explore the recent incision using 3 abandoned meanders in the upper James River. Using 5 huge excavations, he documented the stratigraphy of the deposits left in the abandoned courses and tried to date the deposits using radiocarbon on the lowest and paleomagnetic signature on the upper two. He struck out on the carbon date, but found good evidence for a reversal that suggests an incision rate of 75 m/m.y. based on the reversal at 780 ka. This reversal occurred in the same pit from which Peter Erickson took samples that dated to 380 m/m.y. Did Dan catch a short-duration reversal or does Peter's sample suggest surface instability? Although off by a factor of two, the lowest rate is still twice the average Appalachian erosion rate.

Dylan Easthouse searched the caves of the Maury, South and James Rivers for dateable sediment and speleothems. With just a few days and not many good deposits, he was unable to further refine the incision rate. However, using the terrace mapping and cave mapping in the county, he was able to establish that there are indeed distinct terrace levels and that at least the lowest of these correlate well to the number of cave passages at the time when the terrace was the floodplain and the terraces. This is an important discovery that will be used in future correlation.

Working with tributaries to the South River and the Maury River, **Martha Carlson** and **Justin Ries** were able to document the incision processes of streams by knickpoint retreat. The tributaries of the South River migrate by cutting waterfalls often linked to multiple travertine dams. Using data from other regions, Martha estimated that the tributaries are incising at a rate of about 65 m/my and the highest knickpoint had been migrating for nearly 2 Ma since initiation. The erosion rate is close to the range of rates found by other methods. Justin found that terraces merge with the floodplain at knickpoint steps and that the upper reaches of a tributary to the Maury were dominated by debris flow scour. These studies both show that knickpoint retreat is an important process in river incision for this region, as well as imply that the main streams must also have periods (or waves) of incision. This agrees with

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

Martha Carlson
Department of Geology, Carleton College, Northfield, MN 55057
Faculty sponsor: Clint Cowan, Carleton College

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:

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