Bringing down the mountains: Rapid incision, escarpment retreat, and flexural uplift in the Appalachian Valley and Ridge province

Peter A. Erickson
Carleton College
300 N. College St.
Northfield, MN 55057
Faculty Sponsor: Mary Savina, Carleton College

INTRODUCTION

The Appalachian Valley and Ridge Province has been the subject of a long-standing, but recently dormant, controversy over modes of landscape evolution. Up until the middle of this century, debate raged over drainage adjustment, the age and origin of Appalachian peneplains, and continental-scale theories of landscape evolution such as William Morris Davis' Geographic Cycle. Most of these early theories relied on tectonic activity to trigger continental-scale geomorphic change. Although in recent decades interest has waned, new papers have suggested dynamic interactions between crustal and geomorphic processes, and have made the Atlantic passive margin the subject of renewed research.

In this study, I document the presence of two incised erosion surfaces, the Floyd Surface and the Valley Surface, in the James River portion of the Appalachian Valley and Ridge province. I present an average rate of James River incision, based on a cosmogenic isotope date of the Valley Surface. Finally, I suggest that escarpment retreat and isostatic rock uplift may account for all of the observed James River incision, without the need for tectonic forcing.

STUDY AREA

This study focuses on the James River and its tributaries upstream of the watergap through the Blue Ridge. Bedrock in this portion of the Valley and Ridge is folded and faulted Paleozoic clastic and carbonate formations (Spencer, 1994). Local relief is greater than 800 meters between the James River and the highest Blue Ridge summits; typical valley-ridge relief is about 500 meters.

The Valley Surface. The Valley Surface consists of a number of coalescing fluvial terraces and pediment remnants. Remnants of the Valley Surface can be found throughout the James system, and are easily correlated; when standing on one remnant, several others are usually visible at the same elevation. Similarly, 7.5-minute topographic maps show a number of surfaces with nearly flat tops at comparable elevations. The bedrock straths of Valley Surface terraces along the James River consistently lie at 60 meters above the river, and pediments descending from high ridges are graded to a similar elevation. Because the Valley Surface is an erosional feature, deposition ages of alluvium in Valley Surface remnants can be used to approximate its age of abandonment and provide an estimate of the average rate of James River incision.

The Floyd Surface. Less than one hundred kilometers to the southwest in the New River basin, a broad low-relief surface with area greater than 3,000 km^2 slopes gently to the northwest from the Blue Ridge in and around Floyd County, Virginia. Similarly, upper reaches of several James System streams descend gently from the Blue Ridge but then drop rapidly to the James River or its major tributary the South River. These upper reaches are graded to an elevation similar to that of the surface around Floyd County, at an elevation of about 900 meters, 700 meters above the present James River where it cuts the Blue Ridge. Remnants of an elevated Valley and Ridge landscape (Harbor, 1996), these upper reaches suggest that the Floyd Surface may have been continuous along the Valley and Ridge.

METHODS: DATING FLUVIAL TERRACES WITH COSMOGENIC RADIONUCLIDES

Here I use the cosmogenic radionuclide ^{10}Be to date a remnant of the Valley Surface. The basic assumptions of dating with cosmogenic radionuclides are that certain isotopes are produced at the earth's surface by the interaction of cosmic rays with silicates and that production of these isotopes decreases exponentially with depth below the surface. In the case of the ubiquitous mineral quartz (SiO_2), neutrons or muons react with ^{28}Si to produce

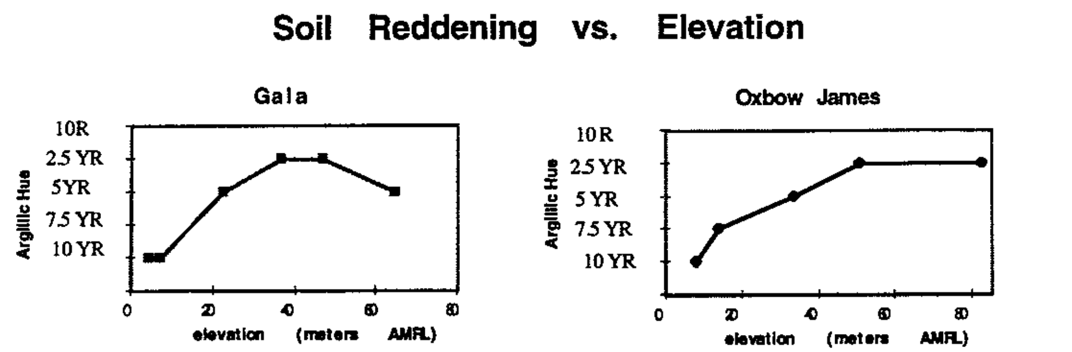

Figure 1: Soil reddening versus elevation for Gala and Oxbow locations. The color was measured in the B or Bt (argillic) horizon.

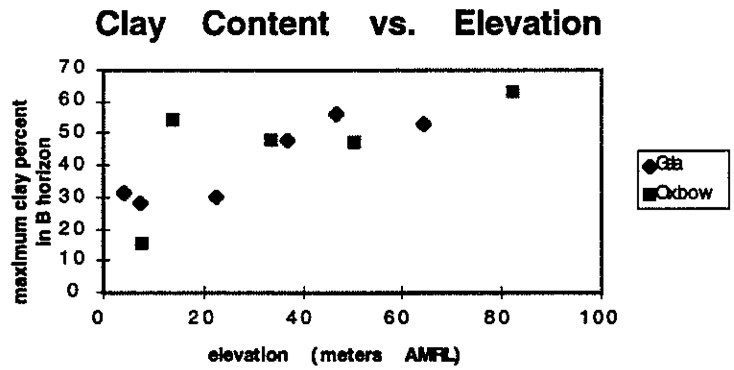

Figure 3: Clay content versus elevation for the two chronosequences. The maximum clay percent of the B or Bt horizon is used for this graph.

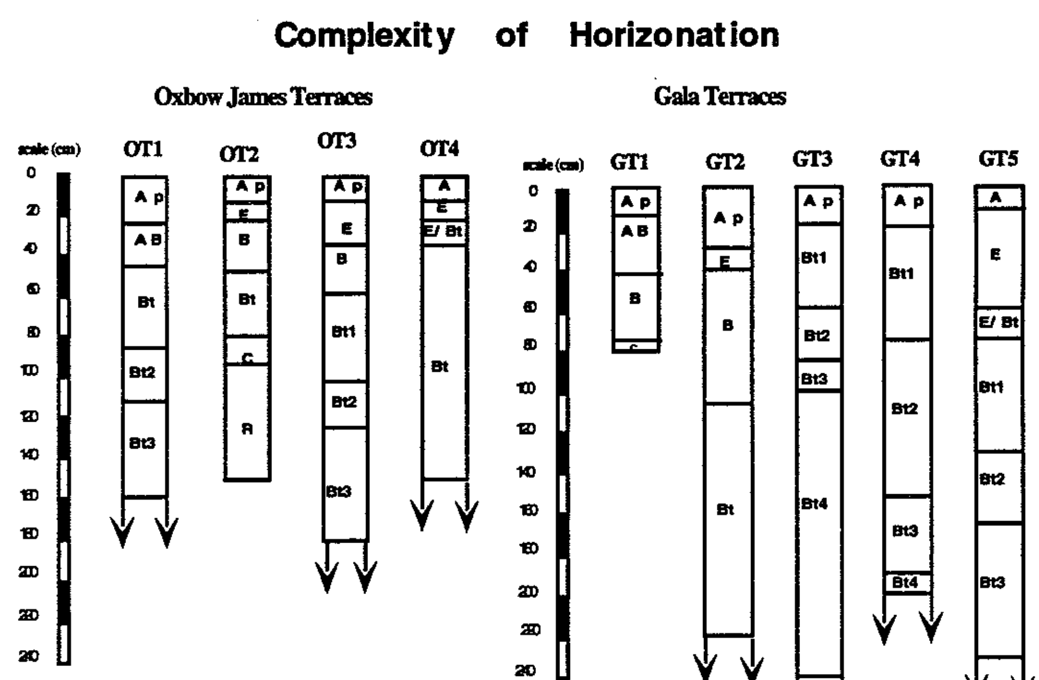

Figure 2: The complexity of horizonation for the two chronosequences. Arrows indicate that the soil pedon extends below the pit depth.

^{26}Al and with ^{16}O to produce ^{10}Be (Bierman, 1994). The concentration of either of these two isotopes is proportional to the sample's exposure time to cosmic rays, but the quantity of interest is the often the residence time, the amount of time a sample has resided in a deposit. Because the amount of time spent in the deposit is usually long relative to the amount of time spent in exhumation and transport, the concentration of cosmogenic isotope in the sample is roughly proportional to residence time. However, Anderson et al. (1996) found that greater than 40% of the total concentration can be inherited from accumulation during exhumation and transport prior to deposition. By measuring the concentration of ^{26}Al or ^{10}Be in two samples, each consisting of an amalgamation of 30 quartzite clasts, at two different depths within a deposit, Anderson et al. (1996) were able to distinguish inheritance from in situ production. The in-situ accumulation can then be used with estimates of production rates to calculate an estimate of residence time. I used the technique of Anderson et al. (1996) to date the Bryant Farm terrace, a remnant of the Valley Surface capped with a thin (< 3 m) veneer of alluvium, near Iron Gate, Virginia.

RESULTS

The concentrations of ^{10}Be in the samples are 1.20 (± 0.04) x 10^6 atoms/gram for an amalgamated sample from depth 0.75 m and 0.51 (± 0.02) x 10^6 atoms/gram for an amalgamated sample from depth 1.65 m. I estimated production rates of 2.96 (± 0.35) atoms/g/y for the sample from depth 0.75 m and 1.03 (± 0.12) atoms/g/y for the sample from depth 1.65 m, using surface production rate estimates of Lal (1991) adjusted for depth as in Anderson (1996). Application of the model of Anderson et al. (1996) to the measured sample ^{10}Be concentrations yields a deposition age of 380 (± 80) ka, implying an average James River incision rate since Valley Surface time of 160 (± 40) m/m.y.

Granger et al. (1997) found the incision rate of the New River, which drains the intact Floyd Surface 100 km to the southwest, to be incising at 27.3 ± 4.5 m/m.y. The James River incision rate of 160 (± 40) m/m.y., though constrained here only by a single sample pair, is about 5 to 6 times greater than in the New River system.

DISCUSSION

Flexural Uplift. The James System displays the steepest topography of all major Valley and Ridge watersheds (Harbor, 1996), preserves a record of 700 meters of incision, marks the departure of the Gulf/Atlantic drainage divide from the Blue Ridge, and has a Quaternary incision rate several times the Appalachian average of 34 m/m.y. (Sevon, 1989) and over 5 times that of the New River. Yet there is no direct evidence for any renewed late-Cenozoic tectonic activity in the middle Appalachians. While some form of uplift has long been recognized and assumed to be tectonic (Poag and Sevon, 1989), few studies have focused on the true uplift mechanisms. However, Pazzaglia and Gardner (1994) have demonstrated with a line-load model that mass removal by denudation in the Valley and Ridge and Piedmont provinces and mass addition by offshore deposition can cause flexural deformation of the crust.

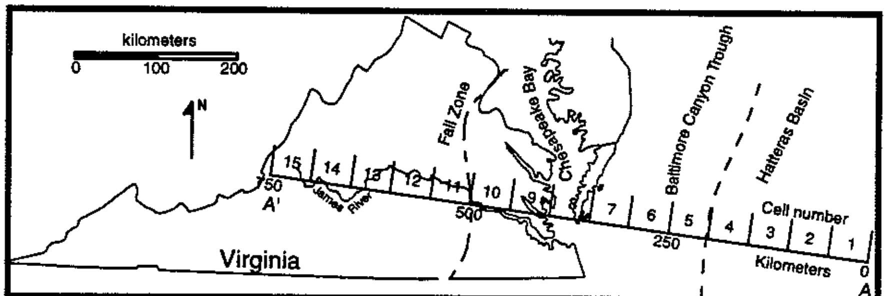

Figure 1. Location of flexural deformation cross-section A-A'. Cells used in the model are numbered 1 through 15. The study area is in western Virginia and coincides with cells 14 and 15.

I applied their model to a 750 km cross-section extending from the study area in western Virginia to the Hatteras Basin, 350 km off the coast (Fig. 1). The model is divided into 15 cells for which the volume of denudation or deposition since the mid-Miocene (estimated time of Floyd Surface capture) is estimated using the position of the Floyd Surface, terrace data in the Coastal Plain (Howard et al., 1993), and Salisbury Embayment, Baltimore Canyon Trough ,and Hatteras Basin sediment thickness maps (Poag and Sevon, 1989). Loads for each cell are then computed using these volumes, the width of the cell (50 km), and the density of the material. Loads are applied to each cell and the flexural deformation is computed as in Pazzaglia and Gardner (1994).

Results of this model show a convex flexing of the Coastal Plain, Piedmont and Valley and Ridge provinces (Fig. 2). Furthermore, results show we can expect 200 meters of rock uplift in the study area (cells 14 and 15) since the mid-Miocene. Of this 200 m of uplift, 150 m is due only to the unloading caused by the incision of the Floyd Surface in cells 14 and 15. The remaining 50 m of uplift is due to erosional unloading in the Piedmont and the minor effects of depositional loading off the coast. Equations derived by Turcotte (1982) show that it would take 150 k.y. to accommodate 200 m of isostatic uplift in response to instantaneous mass removal. Given instead that the Floyd Surface was consumed over *millions of years*, I assume negligible lag time between mass removal and isostatic response.

The total elevation difference between Floyd Surface remnants on the Blue Ridge and the James River in the gap through the Blue Ridge is 700 m. In the Piedmont, model estimates of uplift and observed or extrapolated denudation are very similar (Fig. 2), a result consistent with the assumptions of Pazzaglia and Gardner (1994). Thus in the Piedmont, it appears as if uplift has been matched with equal downcutting. Extrapolating this observation past the Blue Ridge into the Valley and Ridge, we then expect about 200 m of downcutting since the mid-Miocene. Of the 700 m of James River incision, I suggest that 200 m is due to this flexural uplift of the crust in response to some original denudation. However, some amount of incision must have originated this isostatic positive feedback cycle and be responsible for the remaining 500 m of relief.

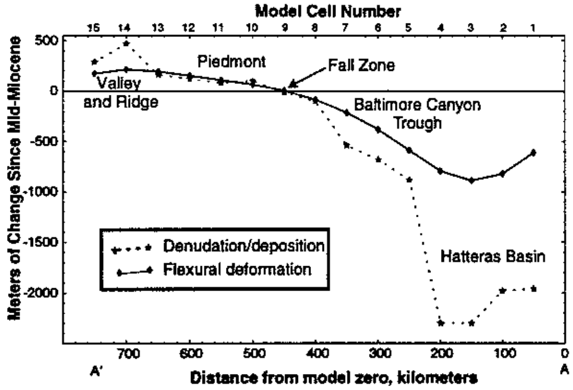

Figure 2. Mid-Miocene to present denudation/deposition and flexural deformation along line A-A' (Fig. 1). Both curves are plotted with the same axes. Positive values of the denudation/deposition curve indicate meters of denudation; negative values indicate meters of deposition. Positive values of the flexural deformation curve indicate meters of uplift; negative values indicate meters of subsidence.

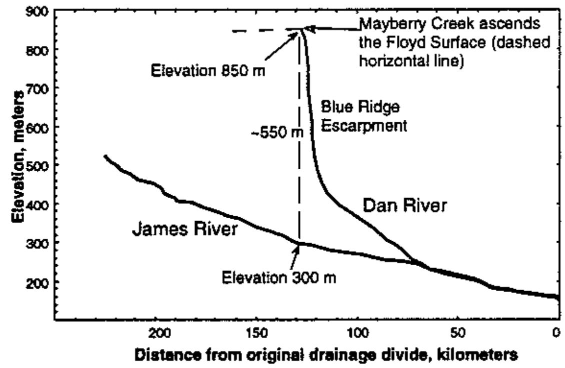

Figure 3. Longitudinal profiles of the James and Dan Rivers, aligned at the approximate location of the former Blue Ridge Gulf-Atlantic drainage divide (Thompson 1939). Note the departure of the profiles as the Dan River climbs the Blue Ridge to the Floyd Surface. When it reaches the Floyd Surface, major tributary Mayberry Creek is about 550 m above the more adjusted profile of the James, implying 550 m of potential erosion.

Escarpment Retreat. Harbor (1996) hypothesizes that escarpment retreat and the breaching of the Blue Ridge by the James River are responsible for a large portion of the Valley and Ridge incision. If the James River cut headward through the crystalline Blue Ridge, it could have captured shallow gradient Gulf drainages, giving them much lower local base levels. The streams could then have rapidly incised through the numerous Paleozoic carbonate formations, initiated isostatic uplift, and created a new escarpment (the Allegheny Escarpment) further to the west.

Pazzaglia and Gardner (in press) concluded that the Blue Ridge escarpment has likely evolved directly from the initial Jurassic rift-flank uplift, and that the escarpment is presently maintained by high flexural uplift (such as that presented here) near the Blue Ridge. I assume that the present expression of the escarpment is due to these factors and not to any more recent structural or tectonic activity.

Comparison to the Dan and New Rivers. The migrating escarpment and capture of shallow-gradient Gulf drainages by steeper-gradient Atlantic drainages is observable where the Dan and New Rivers compete along the Blue Ridge for control of the Floyd Surface. I aligned plots of the longitudinal profiles of the Dan and James Rivers in the Piedmont at the location of the former Gulf/Atlantic divide postulated by Thompson (1939). The difference between the profiles upstream of this alignment should provide *before* (Dan River) and *after* (James River) profiles of Floyd Surface capture and Valley and Ridge incision.

The difference between the present profile of the Dan River just before it descends the Blue Ridge escarpment and the better adjusted James River is 550 m (Fig. 3). This difference suggests that the Valley and Ridge incision due to escarpment retreat is 550 m. However, the Dan River should have experienced 50 m of uplift since the mid-Miocene due to Piedmont denudation and off-shore deposition, as in the James System. Thus the Floyd Surface should have been uplifted 50 m relative to the Dan River, which, unlike the small catchments on Floyd, could counter uplift with incision. I propose, then, that of the 550 m difference between the Floyd Surface and the Dan River, 50 m is due to flexural uplift and that the true amount of incision due to escarpment retreat is not 550 m but rather 500 m. This matches the 500 m of James River incision unaccounted for by flexural uplift, suggesting that a combination of only two mechanisms, escarpment retreat and flexural uplift, may account for all of the observed James River incision.

CONCLUSIONS

The average James River incision rate is 160 (± 40) m/m.y. for the last several hundred thousand years. Although extrapolating this rate back to the elevation of the Floyd Surface suggests an age of Floyd Surface abandonment of 4 (± 1) Ma, this age is probably too young since there is good evidence (the Valley Surface itself, as well as other, higher terraces) that the James River has not been incising continuously since abandoning the Floyd Surface. In calculating loads for the flexure modeling, I assumed a Floyd Surface capture age of mid-Miocene (~10-15 Ma), based on a large pulse of sediment delivered by the James to the coast at this time (Poag and Sevon, 1989). This estimate in itself implies an average James River incision rate of 50-70 m/m.y. since the capture of Floyd, a rate still much greater than the 27 m/m.y. in the New River (Granger et al., 1997). The discrepancy between the 50-70 m/m.y. estimate over millions of years and the 160 (± 40) m/m.y. estimate over hundreds of thousands of years may be explained by further uncertanties in the abandonment ages of the Floyd and Valley Surfaces or more simply by noting that erosional activity is not distributed uniformly over time. In any case, it appears as if the James System has been incising, for several millions of years, at a rate much faster than the Appalachian average of 34 m/m.y. (Sevon, 1989).

Many authors throughout this century have suggested that tectonic uplift may explain the observed Valley and Ridge incision and low-relief erosional surfaces (Davis, 1899; Thompson, 1939; Poag and Sevon, 1989). However, little structural or stratigraphic evidence exists to support late-Cenozoic tectonic activity (Pazzaglia and Gardner, in press). I suggest instead that the mid-Miocene sediment pulse to the coast, the high James River incision rates, and the consumption of the Floyd Surface can be explained, without calling for tectonic uplift, by a combination of only two mechanisms: escarpment retreat and geomorphically-driven flexural uplift.

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The deposition and weathering of heavy minerals relative to South River terrace elevations

Dennis Linney
Department of Geosciences, Elizabeth City State University
1704 Weeksville Road, Elizabeth City, NC 27909
Faculty sponsor: Frederick Lobdell, Elizabeth City State University

ABSTRACT

Heavy minerals with a hardness greater than 5.5 showed little change in overall roundness at the various elevations. Minerals possessing a hardness of 5.5 or less showed considerable weathering. This varied from sub-angular at the highest elevations to well-rounded at the lowest. The downcutting of the South River together with flood episodes over time, appear to be the causative erosive agents. Analysis of these grains may provide information pertinent to the depositional history of the South River.

INTRODUCTION

The primary focus of this investigation was to determine the amount of weathering certain heavy minerals experience and whether or not elevation plays a part in this process. A similar, more in-depth study, has been conducted previously of the New River in southwest Virginia (Mills & Wagner 1984). The scope of this project, however, will be confined mainly to those opaque heavy mineral that can be traced and separated by conventional methods.

The area of interest is located in the west-central section of Virginia amidst the Valley and Ridge province near Lexington (fig.1). Preliminary bank samples of the South River revealed a significant quantity of dark heavy mineral grains. As more samples were collected at various terrace levels, these heavy minerals showed varying degrees of weathering. In addition , the percentage and type of mineral differed as elevation above mean river level (AMRL) increased and decreased. The amount of weathering displayed by specific grains may indicate the length of transport from the source area and quite possibly periods of flood along the South River.

Locale. Thirteen samples were obtained from various terraces along the South River. These were located between Vesuvius at the north end and Cornwall at the south end. This region was chosen primarily because of two major tributaries (Irish Creek and Little Marys Creek) that flow through the major igneous formation. The Pedlar Formation, consisting primarily of hypersthene granodioritic rocks, approaches the South River from the southeast and is separated from the town of Vesuvius by a distance of approximately five miles. In addition, Little Marys Creek skirts the existing terraces before emptying into the South River (fig. 2). The other tributary (Irish Creek) passes through the Pedlar and traverses approximately 25 miles of various terrain and formations before emptying into the South River. Past studies of heavy minerals south of this region revealed that as elevation above mean river level increased, so did the percentage of resistant heavy minerals. Conversely this was accompanied by a smaller percentage of non-resistant minerals (Houser 1981). In addition, research done prior to the aforementioned paper but nearer to the present site, disclosed five heavy minerals that predominated in this locale (Stowe 1939).

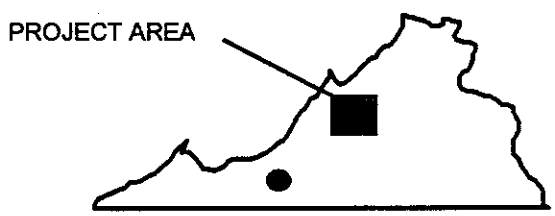

Fig. 1 - Project area reflects current research and that of previous work (Stowe 1939). ● - New River area.

METHODS

The following sampling procedure was applied to the various collection sites to maintain continuity. Bottom and bank samples were first collected at river level to ascertain the type of heavy mineral being transported. This procedure then continued up the mapped terraces with emphasis placed on elevation AMRL. During the collection