Modes and rates of fluvial bedrock incision in the Valley and Ridge Province, Southwestern Virginia

Justin B. Ries
Department of Geology, Franklin and Marshall College, P.O. Box 3003, Lancaster, PA 17604-3003
Faculty Sponsor: Dorothy J. Merritts, Franklin and Marshall College

INTRODUCTION

The purpose of this study is two address the modes and rates of bedrock incision into Cambro-Ordivician limestone by fluvial systems draining the Valley and Ridge province, Rockbridge County, Virginia. The study consists of field and laboratory components. The field component of the study was conducted as part of a Keck Geology Consortium project during June and July of 1997. It consisted of terrace mapping for the James, Maury and South Rivers. The modes of bedrock incision, primarily knick-point erosion and pothole drilling, and the vertical distribution of terraces were observed during a detailed survey of Whistle Creek, a tributary to the Maury River. The goal of the laboratory component of the project is to determine the relative importance of watershed area and stream slope to bedrock incision. This component consists of empirical analysis of watershed area and channel slope data for two fluvial systems: the Whistle Creek and Kerr's Creek watersheds. The importance of area and slope can be quantified with the variables m and n, respectively, in an equation for bedrock incision (Howard and Kerby, 1983):

$$-dz/dt = KA^mS^n$$

where incision ($-dz/dt$) is a function of an erosion factor (K), watershed area (A) and stream channel slope (S). The m and n values are constants that can be determined as a ratio, rather than absolute values. However, the relationship between these two variables will be useful in ultimately calculating a bedrock incision rate for these fluvial systems.

GEOMORPHOLOGICAL BACKGROUND

The evolution of the Appalachian landscape is a highly debated topic among geologists who have studied the region. David Harbor, a geomorphologist at Washington and Lee University, has put forth a model for the erosional history of the Appalachians called the "Floyd model," named after the town of Floyd, VA.

Harbor proposes that at one time a gently westward sloping surface, bounded by a giant escarpment to the east, ran the length of the eastern United States. The high escarpment is the continental divide for the eastern United States. Water which falls to the west of the escarpment drains westward to the Mississippi River, whereas water which falls east drains eastward to the Atlantic Ocean. Due to the steep gradient of the eastern slope of the escarpment, streams began to cut back westward through the escarpment soon after its initial formation. These westward-incising, eastward-draining rivers eventually began to intersect the westward-draining rivers, effectively rerouting or "capturing" their entire upstream section (Lobeck, 1939). This process of stream capture dissects the gently sloping plateau west of the escarpment and results in the westward retreat of the escarpment. The dissected terrane left in the path of the retreating escarpment is the Valley and Ridge Province. My study addresses the rate of vertical fluvial incision into bedrock (via stream power) which occurs in response to this retreating escarpment.

As the more steeply sloping eastward draining stream captures the headwaters of the westward draining stream, the westward draining stream must lower its base level to maintain equilibrium (Playfair, 1802). This lowered base level is translated throughout the tributary systems in the form of propagating knick-points, which reflect instantaneous disequilibrium first at the point of stream capture and subsequently at the confluence of the parent and tributary streams (Seidl and Dietrich, 1992).

MATHEMATICAL BACKGROUND

The sediment transport law states that for alluvial channels, the rate of sediment transport can be defined by the equation:

$$q_s = KQ^mS^n;$$

where Q = discharge; S = slope; K, m and n = constants (Gilbert, 1877). For erosion, area of the watershed (A) can be substituted as a proxy for discharge (Q; Howard and Kerby, 1983). Therefore , a rate of incision ($-dz/dt$) is defined by

$$-dz/dt = KA^mS^n.$$

heavy minerals will not be transported far from their source. This implies that limonite, whose source area appears to be the Rome Formation, should display little weathering. However, in this instance limonite appears as angular to well rounded grains and ilmenite, derived from the igneous rocks of the upper elevations, displays sub rounded grains at best.

The weathering patterns displayed by these two minerals indicates a trend in the mechanism of weathering. The overlap of subrounded grains suggest a period of equal degradation and aggradation which could be interpreted as periods of flood and slackwater of the South River. The frequency, of this event according to figure 4, could have occurred during the formation of terraces along the 60 - 120' level tapering off gradually to 200' AMRL. This interpretation however, requires more definitive proof since little is known about the depositional history of the South River. Most studies of heavy minerals appear to be limited to those non opaque minerals with little reference to the opaque suite of accessory minerals. The most abundant heavy minerals recovered from this area of the Valley and Ridge province are opaque of which few studies have been conducted. Clearly, more research in this area is necessary before these minerals can be used as depositional and erosional indicators.

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Playfair's Law (1802) states that if a tributary is at the same elevation as the primary river at the point of confluence, their rates of incision must be equivalent:

$$-dz/dt_{tributary} = -dz/dt_{primary}.$$

Therefore,

$$K_t A_t^m S_t^n = K_p A_p^m S_p^n.$$

Assuming K represents the bedrock's resistance to erosion and is therefore constant within a primary-tributary fluvial system of similar lithology, then

$$A_t^m S_t^n = A_p^m S_p^n.$$

Further algebraic manipulation yields (Seidl and Dietrich, 1992)

$$\log (S_t/S_p) = (m/n) \log (A_p/A_t).$$

LONGITUDINAL PROFILE OF WHISTLE CREEK

A detailed longitudinal profile was surveyed of Whistle Creek (a tributary to the Maury River) using a hip-tape measure, stadia rod and hand-level scope. The longitudinal profile includes the gradient and distribution of knick-points and terraces along the Whistle Creek tributary (fig. 1). The longitudinal profile was plotted on Excel.

The stream can be divided into two sections with respect to the morphology of the channel floor. The lower section, which makes up about two-thirds of the stream's length, is more gently sloping and characterized by the repetition of knick point systems. The knick-point system has three components: steps, potholes and gravel deposits. The upstream-most section of the system is characterized by bedrock steps which range from several centimeters to several meters in height and are inclined at various angles, usually decreasing in slope upstream. The strath terraces downstream from these steps typically disappear into the modern floodplain upstream of the steps, where the channel floor is at a higher altitude. The next most downstream component of the knick-point system is the grouping of either discrete or coalesced potholes at the base of the steps, which form as high energy sediment flows over the upstream bedrock steps and acts as a "sediment drill" which excavates the downstream bedrock channel floor (Zen and Prestegaard, 1994). The downstream-most component of the knick-point system is a three- to-nine inch thick gravel layer which is deposited on the limestone bedrock channel floor by a decrease in hydraulic energy which occurs after the water exits the pothole zone of the knick-point system. This is the only depositional process acting in the knick-point system, which otherwise consists of lateral incision via the step component or vertical incision via the pothole incision.

The upper section of the stream, which begins at the stream's headwaters and makes up approximately one-third of the stream's total length, is characterized by a substantial steepening of the stream gradient (fig. 1). The channel floor of this section is sedimentary and carbonate bedrock. Multiple debris flow deposits exist along the banks of the stream. The lowest reach of this section of the stream is characterized by a fan structure where the debris flows lost velocity and spread out. The presence of debris flow sequences, the scoured bedrock channel floor, the debris flow fan and the absence of knick-points suggests that debris flow scour is an important incision mechanism in this upper section of the stream (Seidl and Dietrich, 1992).

METHODS

The m/n ratio defines the slope of the logarithmic plot (S_t/S_p) vs. (A_p/A_t). Therefore, the derivation of the m/n ratio, using the relationship between watershed area and stream slope, requires data which evaluates these variables (watershed areas and channel slopes) for primary and tributary streams in the area for which the m/n ratio is desired (Kirkby, 1971; Willgoose, 1989).

Two primary watershed/stream systems were selected for the derivation of an m/n ratio in Rockbridge County, Virginia: Whistle Creek and Kerr's Creek, both of which drain into the Maury River (fig. 2). Within each of these watersheds, the non-seasonal tributaries to the primary steams were identified. The tributaries selected for Whistle Creek were: W2, W1 and Walter's Creek. The tributaries selected for Kerr's Creek were: Waterloo Creek, K5, Linkswiler Brook, K4, K3, K2, K1, Gilmer Creek and Ford Creek.

The watershed areas of the tributary streams were defined by the area of land which drains water into the entire tributary stream. The primary stream watershed areas were defined by the area of land which drains water into the primary stream from its headwaters to its confluence with each respective tributary stream. Watershed areas were hand drawn and then calculated off 7.5' USGS topographic quadrangle maps using an Altek Digitizer.

The profiles of the tributary streams reveal a break in slope which occurs coincidentally with the disappearance of knick-point systems (fig. 2). Since knick-points are the streams' means of maintaining

Playfair's equilibrium law, the slope of the stream can only be used in calculating incision rates (using a derivative of Playfair's equilibrium law) in the section of the stream where knick-point migration is occurring. Therefore, the S_t values were calculated with respect to the lower, more gently sloping reaches of the stream, where knick-point migration is occurring The horizontal component of the slope was determined using an Altek digitizer on 7.5' USGS topographic quadrangle maps.

The calculation of primary stream slope required the construction of longitudinal profiles for each of the primary streams. The primary stream slopes were defined by the slope of the line drawn tangent to the primary channel bed profile at its point of confluence with the respective tributary stream.

RESULTS

The $[A_p/A_t]$ and $[S_t/S_p]$ ratios were calculated for each tributary on Excel (table 1) and then plotted on a logarithmic plot using Kaleidagraph (fig. 3). The curve generated from this plot can be defined by:

$$\log (S_t/S_p) = (m/n) [\log (A_p/A_t)]$$

where (m/n) = slope of the logarithmic curve, defined by:

$$m/n = [\log (S_t/S_p)_2 - \log (S_t/S_p)_1] / [\log (A_p/A_t)_2 - \log (A_p/A_t)_1]$$

The slope of the logarithmic plot of S_t/S_p vs. A_p/A_t yields an m/n value equal to 0.4.

DISCUSSIONS AND CONCLUSION

The steep gradient of the channel floor near the mouth of the stream is possibly the tributary's mode of maintaining equilibrium with the Maury River. According to Playfair's law, a tributary will incise near its confluence at the same rate as the primary river (Playfair, 1802). Therefore, as the Maury incises in pulses (due to episodic base level drops associated with stream capture), Whistle Creek will respond with equivalent pulses of incision. These pulses of incision cause a local steepening of the channel floor of the stream at its confluence with the primary river, resulting in the formation of a "knick-point." As water flows over the knick-point slope, a vortex occurs at the base of each step which effectively undercuts and erodes it. This continual lateral erosion of the knick-points causes their upstream "migration". As knick-points migrate upstream, they erode or incise the channel floor— leaving relic flood plains, now terraces, in their path. Essentially, the terraces are overlapping time lines, each recording the history of knick-point migration simultaneously, but differing in their starting (at the confluence) and stopping times (at the terminal fan of the lowest reaching debris flow) of record.

The m/n value equal to 0.4 is consistent with m/n values determined by Stock and Montgomery (1998) for rivers in Hawaii (m/n between 0.1 and 2) and Australia (m/n between 0.2 and 1). Seidl and Dietrich (1992) determined an m/n value equal to 1 for rivers on the Oregon coast. The consistency of the results for the m/n value in this study with other studies lends credibility to the suggested role of watershed area and channel slope in channel bedrock incision. This m/n value, in conjunction with determined values of K (resistance factor) and absolute values for either m or n, will be useful in calculating absolute rates for bedrock erosion into the Cambro-Ordovician limestone of southwest Virginia, which is occurring in response to the retreating escarpment.

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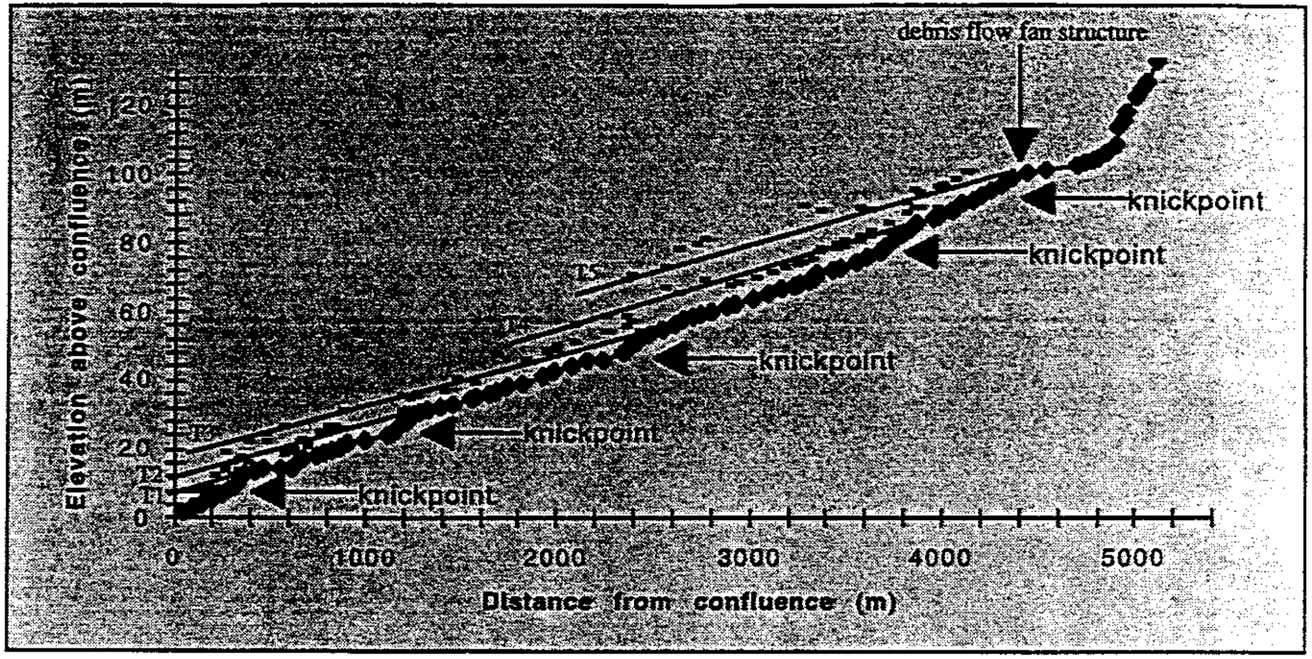

Fig 1. Whistle Creek surveyed profile (diamond symbols) and bedrock terrace elevations (dashed symbols). O meters corresponds to the confluence of Whistle Creek and the Maury River. Terrace levels end abruptly at channel knickpoint locations. Note the debris flow fan structure immediately downstream from the break in slope of the channel floor. The location of this feature suggests a change in the mode of channel bedrock incision at the break in slope of the channel profile.

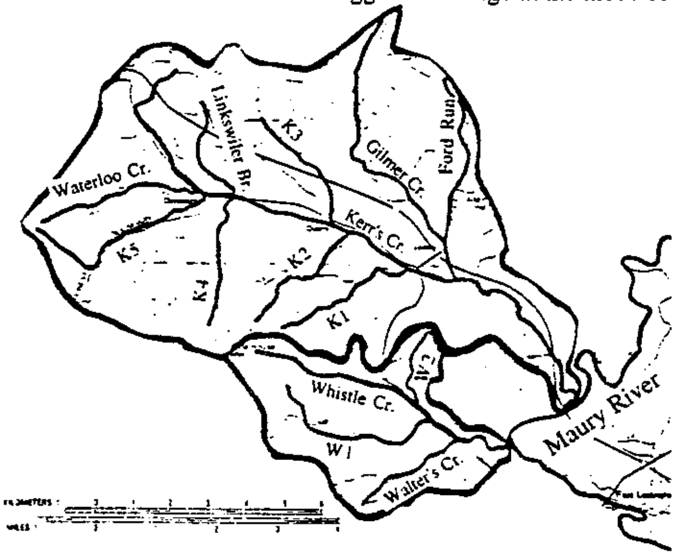

Fig. 2: Map of the Kerr's Creek and Whistle Creek catchments and their confluence with the Maury River. North is oriented vertically upward, and scale is 1:100.000.

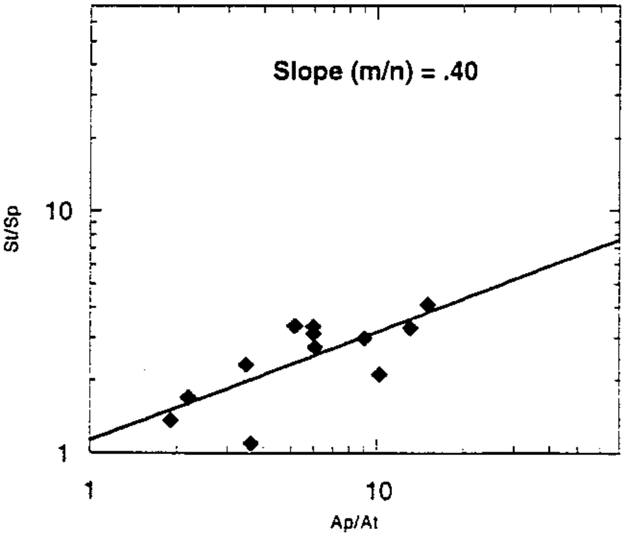

Fig. 3: Plot of Ap/At against St/Sp for Whistle and Kerr's Creek. This data suggest an m/n ratio equal to O.4.

Parent Stream	Tributary	Ap (ft^2)	Sp	At (ft^2)	St	Ap/At	St/Sp
Whistle Cr.	Walter's Cr.	227826000	0.0132	37479000	0.0361	6.08	2.73
Whistle Cr.	W1	184242000	0.0197	96840000	0.0270	1.90	1.37
Whistle Cr.	W2	82124000	0.0229	22748000	0.0252	3.61	1.10
Kerr's Cr.	Ford Run	883962000	0.0072	59137000	0.0294	14.95	4.11
Kerr's Cr.	Gilmer Cr.	883962000	0.0072	171912000	0.0241	5.14	3.37
Kerr's Cr.	K1	595588000	0.0080	58318000	0.0170	10.21	2.12
Kerr's Cr.	K2	521016000	0.0085	57870000	0.0254	9.00	2.99
Kerr's Cr.	K3	451878000	0.0086	75799000	0.0266	5.96	3.11
Kerr's Cr.	K4	333338000	0.0114	55706000	0.0379	5.98	3.33
Kerr's Cr.	Linkswiler Br.	277925000	0.0114	21421000	0.0376	12.97	3.30
Kerr's Cr.	K5	249413000	0.0134	113854000	0.0227	2.19	1.70
Kerr's Cr.	Waterloo Cr.	134449000	0.0145	38884000	0.0336	3.46	2.31

Table 1: Summary of Virginia Valley and Ridge Province data. Ap, Sp, At, St refer to parent stream watershed area, parent stream channel slope, tributary watershed area and tributary channel slope, respectively.

Stratigraphic and Paleomagnetic Evidence for Fluvial Incision Rates of the Upper James River, Virginia

Daniel B. Rittenhouse
Department of Geology, The College of Wooster, 944 College Avenue Wooster, OH 44691-2363
Faculty sponsor: Robert Varga, The College of Wooster

INTRODUCTION

Three landscape features near Iron Gate, Virginia, were determined to be abandoned meanders of the James River through sedimentary analysis of auger holes and backhoe pits dug in all three areas (Fig. 1). The meanders were given the names Bryant Meander, Owens Meander, and Soldiers Retreat Meander. Paleomagnetic dating of abandoned meander sediments exposed in the backhoe pits placed the Bruhnes/Matuyama normal-to-reversed polarity transition at approximately 55 meters above modern James River level (AMJRL). This placement allowed the calculation of a minimum incision rate for the upper James River, Virginia as 75 m/m.y. ±24 m/m.y.

PALEOMAGNETIC DATING OF ABANDONED MEANDERS

Introduction. The abandoned meanders provided a unique opportunity to determine a minimum date of when the James River was at various elevations AMJRL through paleomagnetic dating of their sediments. The abandoned meander segments are unique since the channel deposits are buried and preserved through infilling processes almost immediately after their abandonment. Therefore, each of the abandoned meanders contains a buried terrace, above which was generally deposited a fining upward sequence of fine sands, silts, and clays. A paleomagnetic study of field reversals in the sediments above the channel deposits results in a minimum date of abandonment for that part of the river. This date can then be used to calculate an incision rate.

Collection Process. Samples were taken in oriented plastic collection cylinders by pushing the cylinder into the pit wall. Samples were primarily taken in horizons of silt to silty-clay size sediments, as these sizes best record detrital remanent magnetization (DRM) (Rutter and Catto, 1995). Samples were taken in a vertical line downwards spaced to adequately cover the sediment horizons with silt to clay sized particles. Only one sample core was taken at each vertical height within a pit. A total of 24 paleomagnetic samples were taken from Bryant Pit 2, Owens Pits 3 and 4, and Soldiers Retreat Pit 5 (Fig. 1).

Sample Analysis. Samples were analyzed at the University of Pittsburgh Paleomagnetism Laboratory, in a magnetically shielded room that reduces the Earth's present magnetic field strength to below 2.5×10^{-4} millitesla (mT) (Sasowsky, 1995). The samples were cleaned using alternating field demagnetization (AF), and then measured in a large-bore ScT cryogenic magnetometer. The process was fully automated and corrected for stratigraphic strike and dip. The AF levels were applied by increasing the demagnetization level at 5 mT steps, from 0 to 50 mT, and then increasing the steps to 10 mT from 50 to 70 mT. The resulting paleomagnetic data were then plotted as Zijderveld (1967) vector endpoint diagrams and on steronets. Analysis of these plots allowed the removal of unstable vector components, which often represent overprints of the current magnetic field (Butler, 1992). Vectors at certain demagnetization levels, which ideally showed linear trends to the origin, were then chosen to represent the stable component of remanent magnetization at time of acquisition. This stable component ideally depicts the Earth's magnetic field at the time of sediment deposition .

Magnetic Results. Three general trends were found when the vector endpoint diagrams were analyzed (Fig. 2). Normal-polarity samples generally showed decay towards the origin at high AF levels, while magnetic intensity also fell linearly to well under half of their initial intensity. Sample number 02 was representative of this type of trend (Fig. 2A). Another general trend was for little or no decay towards the origin at high AF levels, while magnetic intensity remained virtually constant. The resulting vector endpoint diagrams showed a clustering of points such as sample 12 (Fig. 2B). This type of plot is most likely attributed to the fact that magnetically "hard" hematite is the primary magnetic mineral in these samples (Butler, 1992). To accurately determine the remanent magnetization of these samples, they would have to be demagnetized at much higher levels, probably through thermal demagnetization, which would be impossible since the samples were taken in plastic containers.

Sample number 24 (Fig. 2C) showed the most convincing reversal. Magnetic intensity only fell to slightly above half of the initial intensity, but the vector endpoint diagram clearly shows that the sample was decaying to a southerly direction. The stereonet plot of this sample also confirmed that the sample was becoming more southerly in orientation. Sample number 18 (Fig. 2D) shows another reversal, albeit more complicated than the last one. This sample does not decay linearly to the origin, and the magnetic intensity only reduced to above half of its initial intensity. However, the sample clearly shows a reversed polarity for its last two AF levels of 60 mT and 70 mT, with both a southerly declination and negative inclination.