Using In Situ 10Be Soil Profiles to Date Fluvial Terraces of the South Fork, Shenandoah River, VA

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Using *In Situ* $^{10}$Be Soil Profiles to Date Fluvial Terraces of the South Fork, Shenandoah River, VA

A thesis submitted in partial fulfillment of the requirement for the degree of Bachelors of Science in Geology from The College of William and Mary

by

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Accepted for (Honors, High Honors, Highest Honors)

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Williamsburg, VA
April 19, 2010
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Abstract:

I determined ages and on fluvial terraces of the South Fork of the Shenandoah River, Virginia, obtained from depth profiles of in situ $^{10}$Be. These dates represent the first numerically constrained ages on fluvial terraces in the Shenandoah system, and allow us to assess the timing of perturbations to the river system and to estimate longterm river incision rates. I sampled three terrace treads near Lynnwood, Virginia, originally identified in mapping completed by King (1950) and Bell (1985). King (1950) suggested a Pleistocene age for the higher terraces, but the terraces are otherwise undated. The lowest terrace level (T2) is an ~7 m above river level (ARL), and has been inundated by historic flooding. The higher terraces are ~11 m ARL (T3) and ~16 m ARL (T4). On each surface, I excavated a ~2.5 m deep by ~10 m long trench to identify soil properties and to collect ~5 kg bulk samples at 0.25 m depth intervals from 0.25 m to 1.75 m depths. The 250-500 µm quartz sand fraction from the soil was extracted to analyze for $^{10}$Be concentration. To estimate terrace age corrected for inherited $^{10}$Be, A MATLAB script iteratively solved for age and inheritance through a least squares fit of modeled $^{10}$Be concentration profiles to measured profiles on each terrace.

T3 showed an exponential profile, which yielded minimum age of 162 kyr and inheritance of 4.62 *10^5 atoms per gram of quartz. The maximum age was taken to be the age and terrace erosion rate that corresponded to ~2 m of denudation. This assumption was made because of field observations of ~2 m of fine overbank deposit sediments in the active T2 deposit that were not in the upper deposits, suggesting that these layers had been eroded on the older terraces. The maximum age and terrace erosion rate was 388 kyr and 4.7 m/Myr. The T4 deposit showed mixing in the top three data points which
corresponded to a paler layer in the profile. To date these terraces a new Inventory method that took into account both radioactive decay of the isotope as well as allow for the input of terrace erosion rates to the model. The age was then checked by iteratively solving for the exponential curve using the inheritance derived from the Inventory calculations. The minimum age assuming no surface erosion was 300 – 340 kyr and the maximum age assuming ~2 m denudation was 640 - 1000 kyr.

These ages give us a range of incision rates between 17 and 65 m/Myr which are statistically higher than the range of bare bedrock summit erosion rates in the Blue Ridge (Whitten, 2009) and suggest a net increase in relief in the Shenandoah Valley over $10^5$ time scales. The incision rates were also comparable to other Appalachian rivers, which suggest disequilibrium across the Central Appalachian landscape. Possible cause of this landscape disequilibrium include (1) the differential response of the landscape to increases in the amplitude and frequency of climate fluctuations at the onset of the Pleistocene, and (2) isostatic flexural uplift caused by loading on the Atlantic Continental shelf and lightening of the Appalachian Plateau from increased erosion of Atlantic draining streams.
Introduction:

The Appalachian orogenic belt is one of the most studied ancient mountain ranges. The tectonic history is well constrained and it is established that the most recent tectonic uplift was the result of three separate island arc collision events during the Paleozoic followed by the rifting of the Atlantic in the late Triassic. (Bailey et al, 2006) The maximum elevation this mountain range achieved from this uplift has been estimated to be 3500 to 4500 meters in height. (Pazzaglia and Brandon, 1996) Models of landscape evolution estimate that mountain ranges should decrease in relief by 10% every 18.5 Myr and completely erode in 107 to 108 year. (Ahnert, 1970) The Appalachian range seems to contradict this model since after hundred of millions of years, its peaks still approach 2000 meters. This is clearly a significant gap in the understanding of post orogenic mountain landscape evolution.

The Appalachians have also been the setting for two of the most influential theories of landscape evolution. W. M. Davis (1899) put forward the first major theory on landscape development. He observed that Appalachian peaks in Pennsylvania and New Jersey were approximately the same height and represented an ancient peneplain that was uplifted and consequently eroded away. He also interpreted flats lower down in the landscape as peneplains that were uplifted and dissected by streams. With this evidence he proposed the theory of cyclical landscape evolution, where uplift of “peneplains” caused incision and an increase in the landscape relief. When uplift ends, the landscape begins to erode back down to base level. Intermediate peneplain surfaces were created when uplift began after partial erosion. This theory was applied to landscapes all over the
Appalachians, including two studies in the Shenandoah Valley by Stose and Miser (1922) and Wright (1934) who interpreted 4, and 2 peneplain surfaces in the Shenandoah Valley.

The Shenandoah Valley, the setting for this study, (Fig. 1, 2) was also the setting where Hack (1965) proposed a counter argument to the concept of cyclic evolution. He studied the landforms and geomorphic processes in the Shenandoah Valley and found evidence for a landscape in a dynamic equilibrium. This theory states that over long enough timescales, all points in a basin are adjusted to have the same long term erosion rate. This meant that relief would stay relatively constant, even in a region experiencing no uplift. This assertion was the main difference from the cyclic theory.

Hack (1965) documented evidence of this equilibrium in the topographic landforms of the Shenandoah Valley. He observed that hill profiles, slopes, and stream profiles were generally adjusted to the underlying materials. This indicates that the topographic patterns are controlled by the underlying geology of the region, where landscapes had to adjust their slopes to erode the underlying geology at the same rates as the rest of the landscape.

Dynamic equilibrium of the landscape has been the basis for many studies on landscape evolution. Whipple (2001) used the stream longitudinal profiles in Taiwan to model fluvial response to climate and tectonic perturbations. The model showed that given enough time a stream can completely adjust itself to equilibrium, but during periods of rapid climate fluctuations, modeled stream profiles rarely achieve equilibrium. Stark and Stark (2001) used artificial Digital Elevation Model (DEM) to study the landscape evolution. When uplift was increased in this model, the landscape would adjust
Figure 1: Shaded relief map of the Shenandoah Valley. The letters stand for towns; W - Waynesboro, M McGaheysville, E - Elkton, L - Luray, And FR - Front Royal, Virginia. Regional map of Virginia and Maryland in the top left Corner. The teal (King, 1950) and red (Bell, 1986) rectangles show the geographic extent of the only two detailed terrace studies on the SFSR.
Figure 2: This is a simplified physiographic map of Page Valley over ESRI 2d imagery layer and ESRI borders and places layer. The SFSR flows through a tight valley in between the Blue Ridge Mountains on the southeastern side and the Massanutten ridge on the northwestern side. The SFSR flows through Paleozoic Carbonates. North of Luray, and the river starts to tightly meander as it flows over the Martinsburg Shale.
its erosion rate from the channels first to achieve new equilibrium. The hill slopes react after the channel had already adjusted.

Hack (1965) acknowledged that there were landforms in the valley that show records of landscape readjustment. He recognized that uplift and climatic influences could temporarily bring a landscape out of equilibrium and the topography would adjust itself to the new erosion rate. One landform that Hack (1965) studied in the valley that recorded phases of disequilibrium was fluvial terraces. He studied terraces on the Middle River; a tributary to the South Fork of the Shenandoah River (SFSR), Hack (1965) mapped 3 continuous terrace units, as well as discontinuous higher terraces, of the Middle River in Augusta and Rockingham Counties (Table 1). Hack (1965) postulated that interglacial periods might have been more humid and the peak discharge would increase. This would cause the river to have more stream power than sediment to move downstream and therefore incise. Since there are no absolute age constraints on these surfaces, the actual cause of disequilibrium recorded by these terraces could not be discerned.

South Fork Terrace Studies

Only two studies have mapped individual units of fluvial terraces on the SFSR (King, 1949, 1950), (Bell, 1986), but no attempt has been made to pair terrace units down valley. The first detailed study on surficial deposits in Page Valley was conducted by King (1950, 1949) around Elkton, Virginia (fig. 1). He mapped three gravel units deposited on bedrock terraces and thick sequences of residuum in the valley. The lowest was 15 to 25 m above river level (ARL), the intermediate between 30 and 60 m ARL, and the highest was 90 m to 200 m ARL and rested above. He also saw older buried
gravel deposits and a large amount of residuum underneath the gravels near the foothills of the Blue Ridge. The mechanism for the gravel unit genesis was that the river aggraded these deposits when the sediment load from upstream increased. He proposed that during glacial epochs the tree line would move further down slope and the bare rock summits would supply more sediment to create these terrace deposits and the incision would happen in the interglacial period. He postulated that the Pleistocene glacial epochs could have caused this mechanism. Hack (1960) agreed with King’s interpretation of three terrace units and thought that Pleistocene climate fluctuations acted on the valley and disrupted the equilibrium.

Bell (1986) mapped surficial deposits around McGaheysville, Virginia (Fig. 1), upstream of Elkton area where she found 5 discrete terrace units. She differentiated these using both topographic position as well as soil attributes. Terrace heights can be found in (Table 1). These terraces were prevalent along the northwestern side of the river, whereas on the southeastern side most fluvial deposits were covered with thick alluvial fan sequences. The SFSR terraces mapped were at different heights than the King (1950) study and were generally closer to the river. Tributary terraces were also found that were comprised of reworked residuum and alluvial fans. Further west of the river were thick sequences of residuum and pediment overlying carbonates. She postulated that these thick sequences of residuum were created during a long period of a graded SFSR. She thought that the SFSR terraces were aggraded when steep tributaries that drain the ridges and dissect alluvial fan complexes delivered coarse sediment that the South Fork could not carry downstream.
Figure 3: This is a shaded relief of the Bell (1986) study area. The mapped units were digitized and georeferenced in ArcGIS. The sampling locations are also marked as red circles. On the southeastern side of the map there is an obvious scarp that denotes the beginning of the alluvial fans. On the Western side of the river, the contact between terrace and residuum is harder to see.
She measured field soil attributes of each terrace unit. The older terraces were more dissected by streams, and the soils were more developed with more clay minerals and iron oxide deposition. The older soils also had discrete horizontal layering with respect to clay enrichment. Giving evidence that the soils had more time to defloculate and redepot clay layers. She then did a thorough soil analyses to measure grain size distributions and soil compositions. Older terrace soils generally had higher percentages of clay. This indicates that the deposit has had more time to weather primary minerals into clay. The older soils also had higher rubification indices, which indicate iron oxidation and hematite formation and is related to the amount of chemical weathering and age of a soil. Bell (1986) also observed that the preservation of terraces was also affected by the underlying lithology. She made models from these observations where the tread on carbonate terraces is generally left intact but solution collapse has caused the mixing of alluvial and residual soils. Groundwater would dissolve the limestone bedrock beneath and cause solution collapse and the soils would be mixed. On shale bedrock, the terrace tread would erode all the way to the strath. The middle member of this model was the degradation of shaly dolomites, which would keep both deposit integrity more intact from both dissolution and surface erosion.

Table 1: Fluvial Terrace Units mapped in the Midatlantic Region

<table>
<thead>
<tr>
<th>River Studied</th>
<th>Author(s)</th>
<th>Terrace Unit, (youngest to oldest)</th>
<th>Height (m ARL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Fork at Elkton</td>
<td>King (1950)</td>
<td>Qg3 – Qg1</td>
<td>Qg3-15 – 25, Qg2 -30 – 60, Qg1--90 – 200 ,</td>
</tr>
<tr>
<td>Lower Susquehanna</td>
<td>Pazzaglia</td>
<td>Lowlands - Qt6-</td>
<td>Tg1 – 140, Tg2 -</td>
</tr>
</tbody>
</table>
Age Constraints of Regional landforms

None of these studies were able to constrain any absolute ages of the terraces so attempts to find mechanisms for terrace creation by the SFSR have been speculative at best. More recently however workers have been able to estimate absolute ages of terraces elsewhere in the region. Pazzaglia and Gardner (1993) studied terraces in the lower Susquehanna valley. They found a total of ten terrace units (Table 1). The ages of these surfaces were estimated by correlating them downstream to upper Coastal Plain formations. This is done with petrographic relationships as well as using the assumption that transgressive sequences in the upper coastal plain stratigraphy translate to aggradation upstream. They interpreted three older units as Tertiary, the oldest (Tg1) being cut during early Miocene. A significant middle unit QTg was interpreted to have formed from significant incision and abandonment at the beginning of the Pleistocene. He attributed the lowland terraces (Qt1-6) to Pleistocene climate fluctuations. The river
cut these terraces when glacial-interglacial fluctuations changed the sediment load and hydrologic conditions of the basin. This interpretation is similar to the one that King (1950) made about the South Fork terraces. These two fluvial systems may act similarly to base level changes since they are both similar distances from base level, though part of the Susquehanna drainage was glaciated so sediment fluxes may have differed during the glacial epochs.

Dunford Jackson (1975) studied fluvial landforms in the Rappahannock River basin. She used topographic analyses to find terrace treads and plot them along the river profile. The analysis yielded 6 surfaces along the Rappahannock River by counting the elevations of the peaks within one kilometer of the river, while also observing the elevations of broad flat features. She then paired these terraces down stream using a linear regression. Since these units followed the valley profile instead of wedging out, which would occur from base level lowering, she attributed their formation to changes in sediment load from upstream. This could happen from an increase in periglacial processes creating sediment supply from the peaks or from a change in an arid to a more humid climate. The terrace ages were correlated with Coastal Plain sediments as Miocene, Pliocene, early and middle Pleistocene from oldest to youngest. She concluded that the Rappahannock system had gone through several stages of disequilibrium.

Numerical ages of the terrace surfaces would allow a better assessment of the origin of the landforms, the timing and causes of basin disequilibrium, as well as constrain incision rates of the rivers. Measuring the in situ cosmogenic radionuclide (CRN) $^{10}$Be can constrain numerical abandonment ages of these surfaces. This technique has been used to date terraces in the region on the New River (Ward et al, 2005), James
River (Hancock and Harbor, 2004), and the Potomac and Susquehanna Rivers (Reusser, 2004).

Ward et al (2005) mapped terraces on the New River near Radford, VA around Big Falls. The study mapped found 6 terrace units (table 1) above the modern floodplain. The highest terrace was a fill terrace and marked a long period of aggradation of the river. There were also several fill cut terraces and two lower strath terraces. He used $^{10}$Be soil profiles to obtain abandonment ages of these terraces as well as an abandoned sandstone rib at Big Falls. The age and mean incision rates from this study can be found in Table 2. The incision into the highest fill terrace marked a change from dominant aggradation to dominant incision ~2 Myr ago. The order of magnitudes of the smaller fluctuations corresponded roughly to the time intervals of Pleistocene climate fluctuations, which could cause a change in sediment load and geomorphically effective discharge in the basin. Another possible explanation Ward et al (2005) addressed was drainage capture by Atlantic draining streams. Drainage capture could change the ratio of discharge to sediment flux into the river and cause incision or aggradation. This could happen by changing the dominant provenance of the sediment being eroded from one that weathers as physical load to one that chemically weathers like a carbonate. One other method of incision that was dismissed was migrating knickpoints from base level fall, because of the distance of the New River from the base level.

The New River was also studied using CRN dating of cave sediments above modern river level. (Granger et al, 1997) This study found incision rates to be $27.3 \pm 4.5$ m/Myr. Cave sediment ages were also found on the Green River in Kentucky which recorded a similar erosion rate of ~30m/Myr. (Granger et al, 2001) Both of these studies
observed a change from aggradation to abandonment of these cave systems by these rivers are around ~ 2 Myr. The $^{26}$Al to $^{10}$Be ratio from the Green River caves gave evidence to a relatively slow ~ 2.7m/Myr upland erosion rate.

Reusser (2004) sampled strath terraces for CRN exposure ages in Mather, and Holtwood gorges on the Potomac and Susquehanna Rivers. The data for these terraces can be found in Tables 1 and 2. The erosion rates from these gorges are an order of magnitude higher than any other incision rates in regional basins. Reusser (2004) suggested that these gorges were created by knickpoint propagation from base level lowering.

Hancock and Harbor (2004) dated two terraces on the James River and constrained incision rates. The ages of the terraces suggest a dominant switch from erosion to incision Tables (1) and (2). They found that the James River started incising at around 1.1 – 1.2 Myr. This implied an incision rate of 35 – 65 m/Myr. They argued that the Piedmont was in disequilibrium as the result of Pleistocene base level changes creating propogating knickzones upstream, rapid climate fluctuations, or flexural isostatic uplift associated with drainage capture of Atlantic draining streams in the Appalachians.

Interpreted age ranges on Appalachian and Piedmont fluvial landforms range from Early Miocene (Pazzaglia & Gardner, 1993) as the oldest to late Pleistocene (Reusser, 2004). Most studies have hypothesized, correlated, or constrained most terrace ages to the Pleistocene (King (1950); Dunford-Jackson (1975); Pazzaglia and Gardner (1993); Ward et Al. (2006); Reusser (2004), Hancock and Harbor, (2004)). The main mechanisms cited for terrace aggradation and abandonment are changes in the sediment flux and peak flows from up stream, or knickpoint propagation from base level
lowering. Sediment fluxes from upstream can increase during glacial maximums, where the tree line in the Blue Ridge moves down slope and more bedrock gets exposed to periglacial mechanical weathering processes. (King, 1950) Decrease in vegetated cover could also arise from an arid environment, but this would also drive down chemical weathering rates. Increase in peak flood discharge could also trigger incision in the system (Hack, 1965). Changes in the sediment flux to discharge ratio also can change through drainage capture. This can cause a change in discharge and sediment load from losing or gaining drainage as well as changing the dominant source rock. If carbonates dominate, there will be little suspended or bed load to add to the sediment flux. (Ward et al, 2006) Knickpoint propagation from base level lowering has been cited for the incision of gorges on the Susquehanna and Potomac Rivers. (Reusser, 2004)

There is also evidence of a region wide shift to incision at the beginning of the Pleistocene (1.5 – 2 Myr) from a tectonic uplift (Granger et al, 1997), glacial repositioning of the Ohio River from glacial events (Granger et al, 2001). This event caused a general shift from aggradation to incision in the New and Green Rivers, and the James and Susquehanna. (Granger et Al, 2001; Hancock et Al, 2004; Pazzaglia and Gardner, 1994) This timing also corresponds roughly to the breaching of the Blue Ridge by the Atlantic draining rivers in the early Miocene (> 5 Myr) (Naeser et al, 2004) as well as global erosion and sediment accumulation patterns (2 -4 Myr). (Molnar, 2004; Zhang et al, 2001)

Table 2: Ages and erosion rates of terraces on similar rivers constrained using CRNs
### Terrace Ages (ka) (from $^{10}$Be) (highest to lowest)

<table>
<thead>
<tr>
<th>River</th>
<th>Potomac</th>
<th>Susquehanna</th>
<th>James</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrace Ages</td>
<td>85.6±9.2</td>
<td>&gt;97.2±10.5, 55.7±5.9, 30.3±6.9, 18.7±0.9, 14.4±1.2</td>
<td>1.1-1.19 Myr, 1.1-1.2 Myr</td>
<td>600±20-955±25, 610±20, 130±15,</td>
</tr>
<tr>
<td>(ka) (from $^{10}$Be)</td>
<td>55.7±5.9</td>
<td>33.3±5.4</td>
<td>12.7±1.5</td>
<td></td>
</tr>
<tr>
<td>Erosion Rates</td>
<td>~500 - 800</td>
<td>~200 - 500</td>
<td>~35 – 60</td>
<td>~25 – 44</td>
</tr>
</tbody>
</table>

No attempts have been made to obtain absolute ages of terraces on the Shenandoah River so far. These ages will allow us to compare the timing of terrace abandonment on the SFSR with the studies mentioned above. The incision rate of the river can also be calculated with terrace ages and heights and can be compared to the incision rates of regional rivers as well as erosion rates in the peaks and basins of the landscape.

Comparing the erosion rates of the peaks and valleys of the Shenandoah landscape will allow for an assessment of the state of equilibrium. Measurements of bedrock peak Erosion rates have been performed in a study by Whitten, (2009), who used *in situ* $^{10}$Be CRNs to calculate erosion rates of Blue Ridge bare bedrock summits. She found the mean erosion rate to be 9.72 m/My, but individual measurements from 2 to 41 m/Myr. The average summit erosion rate was much lower than regional fluvial incision rates so she concluded that the landscape was in disequilibrium because of significantly higher regional fluvial incision rates and that relief was increasing. She also found a week correlation between bedrock type and erosion rate. The highest erosion rates were in the weakest metamorphosed shales. Another study of summit erosion rates of bare rock
highlands in the Appalachian plateau (Hancock and Kirwan, 2007 found mean summit erosion rates of 5.7 m/Myr. These rates were much lower than the Green and New River incision rates and implied landscape disequilibrium. (Ward et al, 2005; Granger et al, 2001)

Duxbury (2008) also calculated Denudation rates in the Blue Ridge mountain basins as well as a South Fork basin erosion rate using $^{10}$Be in fluvial sediments. The mean basin erosion rate was $11.6 \pm 4.8$ m/My with ranges from 3.8 to 24 m/Myr. She measured the SFSR basin erosion rate at 7.3 m/Myr. She found no correlation between erosion rate and lithology, and slope of the basin. She also found no significant difference in erosion rates with long term unroofing rates in the Blue Ridge. (Spotilla et al, 2004) However the results of this study say nothing about the change in relief in the valley therefore there is no conclusive evidence for equilibrium across the whole landscape.

The erosion rates of the peaks and basins of the Blue Ridge are well constrained. But the incision rate of the bottom of this landscape is poorly understood. By studying the terraces on the SFSR we can get a sense of the history of disequilibrium as well as an incision rate of the Shenandoah Valley. By comparing erosion rates of the peaks and mountain basins to the incision rate of the river, we can discern the direction of relief change in the landscape. This information can confirm whether or not there is equilibrium in the landscape at the valley scale. Through comparison with regional stream and landscape erosion rates, we can also assess equilibrium at the regional scale. This leads to the research questions this study addresses:

- How many terrace units are paired downstream on the South Fork?
- What is the age of abandonment of these terraces?
• Do these ages correlate with events in the climate record and with regional river cycles?

• What are the incision rates estimated from the terrace abandonment ages and how do they compare with regional incision rates and erosion rates in other parts of the landscape?

• What is the change in relief in the valley and what does that say about the dynamic equilibrium of the valley.

To answer these questions I used GIS to find terrace landforms that are paired downstream along the SFSR. We constrained the abandonment ages of two SFSR terraces using the $^{10}$Be soil profiles.

**Study Area:**

The South Fork of the Shenandoah River (SFSR) is a tributary of the Potomac River and part of the Chesapeake Bay watershed. It begins at the confluence of the South, Middle, and North Rivers at Port Republic and flows northeast through Page Valley in western Virginia through Rockingham, Page, and Warren Counties until it joins the North Fork at Front Royal. (Figure 1) The SFSR watershed lies in the Blue Ridge, Great Valley, and Valley and Ridge physiographic provinces. (Figure 1)

Much of the landscape is lithologically and structurally controlled. The Beekmantown and Elbrook Limestones, as well as the Martinsburg Shale underlie the valley lowlands. On the southeast side the clastic and metamorphic rocks of the Blue Ridge Anticlinorium border the Valley. These include the Catoactin Greenstone, overlain by the Chilhowee metasedimentary group and the Antietam sandstone. Well-cemented quartz arenites of the Massanutten Synclinorium make up the northwest of the valley.
(Fig. 2) The South Fork flows along strike in between the Anticlinorium and the Synclinoium. As it flows through the softer carbonates and shales the stream profile is adjusted to the least resistant bedrock but then steepens as it forms tight meanders through the Martinsburg Shale. (Hack 1965)

**Methods**

Field mapping and reconnaissance as well as GIS analysis of a 10 m Digital Elevation model was conducted to map terrace units along Page Valley from Port Republic to Front Royal. Reconnaissance mapping of the Bell (1986) study area was conducted to verify the findings. The surface map of Bell (1986) was georeferenced and digitized in ArcGIS to compare the elevations of her terraces to the interpreted surfaces. (Figure 3) We then used a Digital Elevation Model to interpret terraces down valley of the Bell (1986) and King (1950) study areas. Terraces were also sampled for $^{10}$Be using the CRN profile dating method outlined in Hancock et al (1999). Field observations of soil profiles were also taken into consideration.

*GIS analysis*

Analysis was done on a 10 meter DEM from the USGS Seamless Server of the valley floor in order to recognize landforms. The entire analysis was done in NAD83 projection with UTM 17 north Graphical Coordinate System. The basic methodology was similar to the Dunford-Jackson (1975) summit area analysis, where a histogram of peak elevations and large flats was created from topographic maps. The peaks in the histograms were interpreted to be terraces. The method used in this study worked on the same principle that broad flat terraces elevations would have a high occurrence in the
valley and stand out in histograms of the DEM points. This idea of high frequency elevations was used in an attempt to systematically recognize terrace landforms from a DEM, using ArcGIS and MATLAB.

ArcGIS was used to prepare the DEM into a matrix in MATLAB. Rectangle study area shapefiles of the valley were made in order to extract the DEM. This rectangle was buffered by two cell widths (20 m) so that when the DEM was rotated, there would be no errors on the edges of the study area. The buffer increased the area of the study rectangle by two cells in every direction so that the desired DEM values were rotated without creating NoData. The extracted DEM was then rotated using the rotate tool so that the coordinate system was normal to the study rectangle’s dimensions. This rotation was performed so that the matrix brought into MATLAB had down valley columns and cross-valley rows. This rotated DEM was then extracted again from another rectangle in order to get rid of the NoData points on the fringes that are created during the rotation. This final DEM raster was converted to an ASCII file for analysis in MATLAB.

In MATLAB two different analyses were performed on these DEMs, the block analysis and a cross section analysis. The block section analysis took a .3 km long by rectangle width wide block and plotted a cross section of the average elevation along the .3 km transect. This was done so that features that were prominent down valley as well as in cross section could be interpreted. Valley normal cross sections were also plotted every 0.5 km. These sections were normalized to height ARL by subtracting the minimum elevation in the row from the rest of the row. The minimum elevation in that row was assumed to be the height of the river.
**Figure 4:** A & C are shade relief maps of the McGaheysville Cross Section and Block Analysis. B and D are the cross sections take from the highlighted Lines and boxes in A and C. On the cross section and histogram are labeled interpreted terrace flats. Both of these cross sections are good examples of the classic terrace morphology. The terraces are numbered according to the Bell (1986) map units. T3? is a terrace that is topographically distinct from T3 and T4 terraces at ~15 m ARL.
Terrace heights ARL were interpreted from each one of these cross sections and block sections. These heights were recorded and plotted down valley. Significant scarps with flat or slightly back sloping tops were interpreted to be terraces. The slight backslope was interpreted to be sloughs similar to ones seen in the field. The histograms of elevation points of these cross sections were also used to help interpret these, with spikes potentially corresponding to terrace flats. Examples of both cross sections and block sections can be seen in figure 4. These interpreted terraces were plotted down section and a histogram of interpreted terrace heights was created to look for terraces that were paired down valley. Cross Sections and graphs from this analysis, as well as more detailed GIS methods can be seen in appendix I.

Both analyses were performed on 4 reaches of the valley. The reaches were chosen that were locations of previous terrace studies, or where undifferentiated Neogene terraces had been mapped in the Shenandoah National Park Geologic map (Southworth et al, 2009). The width of the rectangle was chosen in order to fit the largest meander into the profile, and the length was chosen to get the longest relatively straight portion of the valley. The four study rectangles can be seen in figure 5.

**Cosmogenic Radionuclide dating**

The terraces were dated using the *in situ* $^{10}$Be profile method of Hancock et al. (1999). Sampling locations were chosen with multiple terrace flights that were extensive both extensive down valley and across valley with obvious scarps. The sampling sites were also looked for that fit into the Bell (1986) units. The profile method assumes no surface erosion, so terrace flights that were flat and had no relict slough or karst collapse
Figure 5. Study Rectangles used in GIS Analysis. The valley between the Elkton and Luray Rectangle was not sampled because of visual evidence of Alluvial fan dominance in that narrow portion of the valley.
and low curvature were preferred. However, most of the terrace flights on the SFSR had sloughs and hints of karst features and imperfections were hard to avoid. The sampling was done at Bogota Farm near Lynnwood, VA (figure 3, figure 6). The location was chosen because it had well preserved T2 – T4 levels from Bell (1986). Terraces, T4 (~16 m ARL), T3 (~11 m ARL), and T2 (~7 m ARL) were trenched and sampled. The trenches were dug in the middle of the terrace at the highest point, which assumed the least amount of erosion. Terraces were trenched to a depth of ~2.5 m and took 7 samples of at least 2 kg at 25 cm intervals from a depth of 25 cm to 175 cm. Several samples from each terrace were also taken to measure the density of the material at different depths using the fence join method. This method uses a fence join open cylinder that is hammered into the deposit to a known distance, therefore taking a known volume of sediment out of the deposit. This sample was weighed in a bag, and to subtract the mass of the bag, 30 empty bags were measured to obtain a mean bag mass. The plots of the densities vs depth can be see in figure 12b.

Laboratory Methods

These soils were sampled for cosmogenically produced $^{10}$Be. This CRN is produced in both olivine and quartz. For this study we used quartz since it is more abundant in the source rocks of these deposits and is also very resistant to weathering so is likely to survive in fluvial transport and in situ weathering. Its chemical stability also makes it relatively easy to separate from other minerals. The targets for this sampling in the soil were the 250 to 500 µm diameter quartz sand grains. These grains are large enough so that quartz does not become completely dissolved during the acid leaches and etching. Sampling sand grains also gives a large sample size. This is needed because the
Figure 6: This is a photo of Bogota Farm facing West on the T2 tread. The SFSR is behind the photographer and down a ~7 m scarp. The Red line indicates the top of the T3 scarp which rises ~5 m above the T2 floodplain. The T4 scarp can been seen behind it and is accented with a blue line. The Barn and Silo are sitting on T4 and give a sense of distance.
assumption is made that the sample size is large enough captures the mean inheritance aquired by sediment during transport to the deposit. This mean inheritance is the asymptote of exponential equation of the CRN profile. (Hancock et al, 1999)

The sand was then sent through procedures for extraction outlined in Kohl and Nishiizumi, (1992) and the W&M Cosmogenic Lab Manual to isolate the quartz and extract the $^{10}\text{Be}$. The soil was mixed with sodium hexa-metaphosphate to deflocculate and suspend any clay particles. The mixture was then wet sieved to extract 250 to 500 µm sand. The sand then went through several acid leaches to isolate the quartz. A 12-hour hydrochloric acid leach was performed to dissolve away any carbonates iron oxides and organics. The sample was then sent through three 12-hour dilute hydrofluoric and nitric acid leaches in ultrasound baths. These leaches dissolved feldspars and clays and also etched off meteoric $^{10}\text{Be}$.

A portion of the quartz was then taken and massed using an analytical balance. This sample was then spiked with a known mass and concentration of $^9\text{Be}$. The sample was then fumed in concentrated hydrofluoric and nitric acid to fume away the quartz and leave Be. The left over material was then sent through a sulfuric acid fuming to fume off residual fluoride. Anion and cation separation columns were used to separate the Be from other cations, such as Fe, B and Ti. These columns are filled with resin that allows only certain ions through the column at a certain pH. Running the sample through these columns at different pHs allows for ion separation. Aliquots have been taken of known solutions run through these columns at different pHs to calibrate the columns. The extracted $^{10}\text{Be}$ was then precipitated as Be(OH), oxidized and packed into Accelerator Mass Spectrometer (AMS) targets.
These targets were sent to the PRIME lab accelerator mass spectrometer to measure the $^{10}\text{Be} / ^{9}\text{Be}$ ratio. These data were then converted into atoms $^{10}\text{Be}$ per gram of quartz, giving us a depth profile of $^{10}\text{Be}$ concentration in the sediment. This was done by first converting the known mass and concentration of $^9\text{Be}$ added to the sample into grams by multiplying the concentration times the mass times the concentration and converted to grams of $^9\text{Be}$. This was then converted into moles by dividing the mass by the molecular weight (9.01218 g/mol). This was converted into atoms by multiplying the moles $^9\text{Be}$ with Avagandros number, $6.022 \times 10^{23}$ mol$^{-1}$. This quantity was divided by the mass of the quartz sample to get the number of atoms $^9\text{Be}$ per gram of quartz, which was multiplied by the ratio of $^{10}\text{Be}/^9\text{Be}$ to obtain the # atoms of $^{10}\text{Be}$ per gram quartz at depth $z$ and age $t$. ($N(z,t)$) These calculations can be seen in table 3.
Table 3: data from AMS converted into CRN concentration

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<th>Sample #</th>
<th>Sample weight g</th>
<th>Mass 9Be carrier added</th>
<th>[9Be] in carrier ppm</th>
<th>Err</th>
<th>10Be/9Be from AMS</th>
<th>Err</th>
<th>Atoms 10Be g sample</th>
<th>Err</th>
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**Table 4: Cronus Model Inputs**

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With these data we can constrain erosion rates in several ways, each has their own assumptions in dealing with the variables for inheritance and the surface erosion rate. For all methods we assumed the $^{10}$Be sea level surface production rate of 5.55 atoms per gram quarts per year. There was no significant topographic shielding at the site so the shielding factor was set at 1. The production rate was scaled to the geographic location using the model of Dunai (2000) located within the MATLAB script (appendix 2). Three methods were used to calculate abandonment ages. We used the Cronus (Balco et al., 2008) model to get exposure ages. This gives us a maximum age assuming no significant inheritance or surface erosion, and that all of the CRNs were accumulated in situ. The inputs to the Cronus model are in table 4.

We also used the exponential profile method outlined in Hancock et Al. (1999). We assume the model for $^{10}$Be production from the Granger and Smith (2000):

$$N(z,t) = N_{inh}e^{-\lambda t} + \left( P_n(z) \frac{\varepsilon}{\lambda + \frac{\varepsilon}{z^*}} \right) \left( 1 - e^{-t(\lambda + \frac{\varepsilon}{z^*})} \right)$$  \hspace{1cm} \text{Equation 1}

Where $N(z,t)$ is the $^{10}$Be concentration (atoms/ g quartz) at depth $z$ and time $t$, $N_{inh}$ is the mean inherited concentration of the sample, $\lambda$ is the decay constant of $^{10}$Be (4.6e-7 / yr), $\varepsilon$ is the terrace surface erosion rate (cm/yr), assumed to be constant, $P_n(z) = P_0 e^{z/z^*}$ is the production from nucleon spallation (atoms/g qtz/ yr) and $z^*$ is the density of the material ($\rho$) over the attenuation length of nucleon spallation (160 g/cm$^2$). Negative and fast muonogenic reactions were not taken into account because the sample depths were shallow enough that these reactions would not contribute significantly. (Granger and Smith, 2000) In this method, age and inheritance are iteratively solved for in equation 1.
by fitting a least squares curve fit to the profile data. The terrace erosion rate can also be adjusted to scale up the terrace age with $\epsilon$.

Soil mixing may occur in the upper profile and would result in a flat upper profile. This mixing could come from bioturbation of burrowing animals or tree throw when the terrace was forested before human settlement. If soil mixing occurred then the CRN inventory method of Perg et Al. (2001) can be used to solve for terrace erosion rate and inheritance. This method works under the principle that the CRN concentration completely homogenizes in the mixing zone of the profile. This method solves for the area under the curve of the deposit by numerical integration. The model for CRN growth in the profile she used was.

$$N(z,t) = N_{inh} + tP(z)$$  \hspace{1cm} \text{Equation 2}

After numerically integrating to a sample depth within the exponential profile the inheritance was substituted out using equation 2 and solved for $t$.

$$t = \frac{S - N_d z_d}{P_0 (1 - e^{-z_d/z^*}) - P_0 z_d e^{-z_d/z^*}}$$  \hspace{1cm} \text{Equation 3}

where $S$ is the numerically calculated integral, $N_d$ is the concentration of a sample within the exponential part of the deposit and $z_d$ is the depth at that deposit. The simplified model from equation 2 for concentration with depth and time assumed no radioactive decay of $^{10}\text{Be}$. While this assumption would be reasonable for young terraces, the terraces in this study are hypothesized to be old enough where this assumption would cause too much error.

In order to improve on this model I used the Granger and Smith (2000) equation (Equation 1) instead for $N(z,t)$, which takes into account both radioactive decay and elevation change. I also try a different way of numerically integrating to find the age than
Perg et al (2001). Instead of numerically integrating to the depth of a point in the exponential profile, we assume that the area under the mixing depth is equal to the line integral with respect to depth. (Figure 7) This may be more accurate because the estimate of the area under the homogenous rectangle is more accurate than discretizing the integral into the exponential profile. After the age and inheritance are found using the equations of proof 1, a curve is fit to the exponential part of the profile using the calculated inheritance to check the age constraint. The mean and standard deviation of the inventory ages and exponential fit ages for these unmixed samples were taken to be the range of terrace age values.

To do this we first make the equation a little less messy by making some new variables.

\[ P(z) = P_0 e^{-\frac{z}{z^*}} \]
\[ \lambda_c = \lambda + \frac{\varepsilon}{z^*} \quad \text{Equation 4} \]
\[ N(z,t) = \frac{P(z)}{\lambda_c} (1 - e^{-\lambda_c t}) + N_{in} e^{-\lambda t} \]

This is the same as Equation one to make fewer variables and easier to work with. The next step is to perform a line integral with respect to z between 0 and the depth of mixing \( z_m \). This integral is equal to the area under the bioturbated zone of the deposit. (figure 7) therefore we can make this relation:

\[ \text{Area} = \overline{N_{mix}} \cdot z_m = \int_0^{\infty} N(z,t) \, dz \]
\[ \overline{N_{mix}} \cdot z_m = \left( 1 - e^{-\lambda_c t} \right) \int_0^{\infty} P(z) \, dz + \int_0^{\infty} N_{in} e^{-\lambda t} \, dz \quad \text{Equation 5} \]

\( \overline{N_{mix}} \) is the average concentration in the mixing zone. Using this instead of the numerical integral can be more accurate if the mixing profile looks relatively flat and the mixing
Figure 7: Above are conceptual graphs for the two different versions of the Perg (2001) Inventory model used in this study. Figures A and B are the different forms of Numerical Integration. A uses trapezoidal integration to depth Zd in the unmixed profile. B assumes a mixed profile to a depth Zm and assumes complete homogenization and calculates the mean concentration in that zone. The area under the rectangle is set equal to the integral to Zm. For both a sample in the unmixed profile Nd substitutes for inheritance in the integral.
depth is well constrained. The part of the integral containing $N_{in}$ is simple, and the left portion of the integral can be solved using u substitution:

$$\int_0^{\infty} P(z) \, dz = \int_0^{\infty} p_0 e^{-z} \, dz,$$

$$u = -\frac{z}{Z}, \quad \frac{du}{dz} = -\frac{1}{z}, \quad dz = -z \, du$$

$$\int_0^{\infty} p_0 e^{-z} \, dz = -z p_0 \int_0^{\infty} e^u \, du$$

$$\int_0^{\infty} p_0 e^{-z} \, dz = -z p_0 \cdot (e^{- \frac{z}{Z}} - e^{\frac{0}{Z}})$$

This analytically solved integral is then inserted into equation 3 above.

$$\overline{N_{mix}} \cdot z_m = \frac{(1-e^{-\lambda t})}{\lambda}, \quad z p_0 \cdot (e^{- \frac{z}{Z}} - 1) + N_m e^{-\lambda t} \cdot z_m \quad \text{Equation 6}$$

We still want to solve for $t$ without needing inheritance. The equation would also be much easier to solve if we only had one exponential function. Therefore in order to do this we use a point in the exponential profile assumed to follow equation one and we can rearrange it to solve for $N_m e^{-\lambda t}$, which yields this equation:

$$N_d = \frac{P(z_d)}{\lambda_c} (1 - e^{-\lambda t}) = N_m e^{-\lambda t} \quad \text{Equation 7}$$

Where $N_d$ is the concentration of a sample deep enough in the deposit to not be affected by mixing and $z_d$ is the depth of that sample. The left side of equation 4 can be substituted into equation 4:

$$\overline{N_{mix}} \cdot z_m = (1-e^{-\lambda t}) \cdot \frac{z p_0}{\lambda_c} \cdot (e^{- \frac{z}{Z}} - 1) + (N_d - \frac{P(z_d)}{\lambda_c} (1 - e^{-\lambda t})) \cdot z_m \quad \text{Equation 8}$$
Now we have a function that contains variables we know or can control like the erosion rate and we can therefore solve for \( t \). In order to do this first we must solve for \( e^{\lambda t} \). First we multiply the parenthesis out and rearrange to factor out \( e^{\lambda t} \).

\[
\bar{N}_{mix} \cdot z_m = (-1 + e^{-\lambda t}) \frac{z^* P_0}{\lambda_e} (e^{\frac{Z}{z_d}} - 1) + N_d \cdot z_m + \frac{P(z_d)}{\lambda_e} (-1 + e^{-\lambda t}) \cdot z_m
\]

\[
\bar{N}_{mix} \cdot z_m - N_d \cdot z = (e^{\lambda t} - 1) \left[ \frac{z^* P_0}{\lambda_e} (e^{\frac{Z}{z_d}} - 1)_m + \frac{P(z_d)}{\lambda_e} \cdot z_m \right]
\]

\[
\frac{z^* P_0}{\lambda_e} (e^{\frac{Z}{z_d}} - 1)_m + \frac{P(z_d)}{\lambda_e} \cdot z_m = e^{\lambda t} - 1
\]

Adding 1 to both sides we isolate \( e^{\lambda t} \) and can take the natural log of the equation and solve for \( t \):

\[
\ln \left( \frac{\bar{N}_{mix} \cdot z_m - N_d \cdot z}{z^* P_0 \cdot (e^{\frac{Z}{z_d}} - 1)_m + \frac{P(z_d)}{\lambda_e} \cdot z_m} + 1 \right) = \ln(e^{\lambda t})
\]

\[
\ln \left( \frac{\bar{N}_{mix} \cdot z_m - N_d \cdot z}{z^* P_0 \cdot (e^{\frac{Z}{z_d}} - 1)_m + \frac{P(z_d)}{\lambda_e} \cdot z_m} + 1 \right) = -\lambda t
\]

\[
\ln \left( \frac{\bar{N}_{mix} \cdot z_m - N_d \cdot z}{z^* P_0 \cdot (e^{\frac{Z}{z_d}} - 1)_m + \frac{P(z_d)}{\lambda_e} \cdot z_m} + 1 \right) = -\frac{\lambda t}{z^* P_0 \cdot (e^{\frac{Z}{z_d}} - 1)_m + \frac{P(z_d)}{\lambda_e} \cdot z_m}
\]

\[
\ln \left( \frac{\bar{N}_{mix} \cdot z_m - N_d \cdot z}{z^* P_0 \cdot (e^{\frac{Z}{z_d}} - 1)_m + \frac{P(z_d)}{\lambda_e} \cdot z_m} + 1 \right) = t
\]

Equation 9

With equation 7 we can solve for age of the deposit by knowing the area under the curve under the mixing zone, the corrected production rate, the density of the deposit as well as the surface erosion rate. All of these we can easily measure except for surface erosion.
rate. We can also use the method outlined by Perg et al. (2001) integrate down to $z_d$. This will yield a similar equation:

$$\ln \left( \frac{S - N_d \cdot z_d}{\frac{P_0}{\lambda + \frac{e}{z}} \cdot (z^* (e^{-\frac{z_d}{z^*}} + z_d e^{-\frac{z_d}{z^*}}) - 1)} \right) + 1 = t$$

Equation 9

Knowing the age ($t$), we can rearrange equation 5 to solve for $N_{in}$:

$$\left( N_d - \frac{P(z_d)}{\lambda e} \right) (1 - e^{-\lambda t}) e^{\lambda t} = N_{in}$$

Equation 10

We then take this inheritance and can create a least squares fit to the exponential part of the profile assuming that inheritance like the method outlined in Hancock et al, (1999). This allows us to check our answer from equation 7. This method was performed using all of the samples in the unmixed profile to get an inventory age as well as an exponential age using each data point below the mixing depth. I performed this method using equation 7 finding the area underneath the rectangle. I also calculated $S$ using the integration by trapezoids and found ages using equation 9.

There is still no easy way to calculate the surface erosion rate directly from the data. In order to constrain the level of sediment removed from the deposit, I compared the soils of the modern floodplain deposit (T2) to the sampled terraces (T3, T4). Soil layers found in T2 and not in the older deposits presumably could have been eroded away. I assumed that the thicknesses of these missing deposits were the maximum amount of sediment denuded from the older deposits. The surface erosion rate input for equation 1 ($\varepsilon$) was increased until the calculated age times the erosion rate equaled this thickness.
Results:

Field Observations

I performed field reconnaissance of the Bell (1986) study area in late August. The sequence of T2 – T4 was easily recognized in the topography on the northwestern side of the river. There were also higher terrace levels and some cobbles were found on these high surfaces as evidence. These terraces may be higher than Bell’s T5 with a distinct scarp above T4. The terrace surfaces were not always flat and had back slopes behind the levies and relict slough landforms as seen in Bell (1986). Only T2 and T3 were present on the southeastern side of the river, though some of the deposits could have been old alluvial fan deposits.

Figure 8a contains a photo of the T2 trench. While pictures of the T3 and T4 soil profiles are in Figure 8b. The soil observations I made matches closely with the soil data from the Bell (1986) study. T2 is the high active floodplain according to the landowner and this is confirmed in Bell(1986). The T2 soil profile was well graded with cobbles at lower than 2 meters, a sandy layer from 2 meters to 1.5 meters grading to silt and clay above. The deposit was massive and little redness according to the Munsell index. These all indicate to a relatively young age and agree with the active floodplain interpretation. T3 had a layer of cobbles in a sandy matrix from ~1–2 m. These are interpreted to be old point bar deposits. The soil above it was layered with a fragipan. A fragipan is a layer of concentrated clays that acts as an aquiclude in the soils. The soil had a much redder color that is reflected in the Munsell index. These observations are consistent with the soil descriptions in Bell (1986) for T3. The cobbles in the layer consisted of vein quartz,
Figure 8a: This is a photo view of the trench in T2 the Sandy layer and silty layers are shown in the trench wall. This photo was taken facing almost due north and at the top of the photograph is the scarp for T3 on the left and an intermediate terrace tread on the right.
Figure 8b: Trench wall photographs of T3 and T4 with highlighted observations. Bracket A refers to the leached E horizon in T4. Bracket B highlights the upper pale horizon of T4 where soil mixing has been observed in the CRN profile. It is also part of the zone of leaching. The dashed red line refers to the contact between the pale layer and the red layer and is assumed to be the depth of mixing in the deposit. C shows the coarse gravel deposits in T3 which most likely are channel deposits. T3 is also much redder than color than T4. The indentions are from the depth sampling of soils for CRNs.
quartz Arenite with *skolithos* from the Antietam and Massanutten Sandstone, as well as meta sandstones that were of the Chilhowee group and chert from limestones.

T4 had a much paler color in the upper profile. There was a leached E horizon just below the A horizon and then a pale brown layer from 25 to ~90 cm depth. This layer was interpreted to be the zone of leaching. Deeper soils have a darker reddish color in the zone of accumulation from clay flocculation and iron oxide development. T4 also had cobbles at > 2m depth. This is consistent with the description in Bell (1986) for T4, in which paling indicies instead of rubification indices were used for this terrace. There was a small intermediate terrace at Bogota Farm between T3 and T2 and the there is a relict slough on the surface of T3.

**GIS Analysis Results:**

The GIS analysis interpreted terraces are plotted in figures 9 and 10. There is significant scatter but terraces that are common down valley can be discerned both visually and with the help of a histogram of interpreted terrace points. Spikes in the histograms of interpreted terraces for each study section were assumed to be continuous terraces. This assumed that the down valley profile of the terraces matched the profile of the river, assuming that these terraces were created from parallel retreat of knickpoints. Interpreted continuous terraces were also plotted along longitudinal profiles in Figure (10, a, b) The only continuous terraces interpreted from the patterns in figure 10 were the 25 m ARL and 13 – 15 m ARL. These linear features were visually interpreted by looking for consistent lines in the data parallel to the longitudinal profile.
Figure 9: Terrace heights ARL plotted down valley for both the Cross section (A) and Block Section (B) analyses. Rectangles show interpreted continuous terraces for that study section from the Histograms (Appendix 1). The Terraces from the Block Section seem to pair downstream better with a 30, 25, and 20 m terrace unit plotting in McGaheysville, Luray, and Luray North. The Cross Section Analysis has fewer paired Terraces downstream, With only 30 m ARL and 5-7 m ARL surfaces appearing in the majority of cross sections.
**Figure 10a:** Interpreted Terraces plotted along the Longitudinal Profile of the SFSR. These show the results of the cross section analysis. Green dashed lines represent interpreted terraces along this profile. The black lines show surfaces that pair all the way down stream. The divide is at the head of the South River on the border of the James and Shenandoah watersheds.
Figure 10b: interpreted block sections plotted along the SFSR Longitudinale Profile. These points are more condensed than the Cross section analysis results. This is because averaging along valley creates artificially low surface heights. The paired terraces that can be discerned from this plot have been drawn as green dotted lines and the ones paired along the valley are solid black lines. Even though paired terraces are harder to find in this data, the 15 and 25 m ARL are paired downstream which is consistent with the Cross Section Analysis.
The most extant terraces are the 25, 30 m ARL surface, and the 10 - 13 m terrace surface, both which occur in three of the four rectangles. The most terraces are preserved in the McGaheysville rectangle, which has six terraces, and the Luray section, which has four terrace surfaces. The rectangle with the fewest paired terraces is the Elkton study area, which had two from the cross section method, and one from the block section method.

The McGaheysville and Elkton results were compared to the terrace heights from Bell (1986) and King (1949, 1950). (Figure 11) The analyses yielded six topographically distinct surfaces in the Bell study area, 3 of which fit into Bell(1986) units. It showed that potentially two terrace surfaces were originally mapped as T4 in height ARL and that there are two extant higher surfaces at ~25 and ~30 m ARL that were originally mapped as residuum by Bell (1986).
**Figure 11:** A.) plot of the Mcgaheysville Cross Section analysis results and the histogram of interpreted terrace heights. The interpreted continuous terraces are shaded rectangles and the terrace units from Bell (1986) are empty rectangles. T2 and T3 from Bell (1986) are interpreted. There seems to be two surfaces in what was mapped as T4 as well as two higher surfaces. B – Cross section analysis plots of the Elkton study rectangle. The Gravel units mapped by King (1950) are the red outlined rectangles. QG1 does not show up in the rectangle. Neither of these units shows up well in the topographic analysis. There are two terraces interpreted from the profile and histogram. The Block Analysis version of both of these study rectangles can be seen in Appendix One.
CRN results:

The CRN depth profiles for T3 and T4 are plotted in figure 12a. The higher T4 has higher concentrations of $^{10}$Be than the lower T3 terrace in the upper profile. T2 was not sampled for $^{10}$Be because it is an active floodplain and there was not enough sand in the upper profile to reasonably sample. The ages calculated using the different models above are shown in table 5.

This maximum erosion rate was estimated using geomorphic field observations.

![Figure 12a](image.png)

**Figure 12a:** Plot of T3 and T4 $^{10}$Be Profiles. There is overlap in the lower profile, which potentially means that there was a higher surface erosion rate in T3.

Since the T2 trench had ~1.75 meters of fine-grained material above the first sandy deposit and this is an active floodplain. This layer of fine over bank silts and clays was
not observed in T3 and T4. The assumption was made that T3 and T4 were deposited in much the same way as the active floodplain T2 and therefore had the same thickness of fine overbank deposit on top of the modern soil profile. With this assumption the maximum terrace erosion rate is one that would denude ~1.75 – 2 meters of surface off of the terrace surface. To do this the ages of the terrace profiles were calculated using the methods above with increasing erosion rate until a combination age and erosion rate brought about that amount of denudation. Measuring the profile characteristics of the modern floodplain can help give a sense of how the older terraces may have changed and can give a reasonable maximum surface erosion rate constraint.

**Figure 12b:** plot of density vs depth measured in the T3 and T4 soil profiles. The lines indicate the mean of the two populations that was used in the CRN analysis.
T3’s profile shows an exponential trend throughout, implying no soil mixing. This is consistent with the layered soil profile observed in the field as well as in Bell (1986). Solving for both the age and inheritance yields an age of 162 kyr, and an inheritance of 4.65 x 10^5 atoms ^{10}\text{Be}/ \text{g} \text{qtz} which is consistent with modern river sediments in the Great Smoky Mountains (2 – 4.6 x 10^5 atoms ^{10}\text{Be}/ \text{g quartz} - Matmon et al, 2003) and Shenandoah National Park (2 – 11 x10^5 atoms ^{10}\text{Be}/ \text{g quartz} Duxbury, 2008). The maximum age assuming no inheritance or erosion from the Cronus model is 248 ± 20 kyr. The maximum erosion rate that will denude 1.75 – 2 m of sediment was assumed to be 4.7 m/Myr and yields an exponential profile fit age of 388 kyr and an inheritance of 5.5 x 10^5 atoms ^{10}\text{Be}/ \text{g} \text{qtz}. The modeled curves can be seen in figure 13a.

T4 shows complete homogenization in the CRN profile (Figure 12) at the top three data points through 75 cm depth. All of these points fall in the upper pale zone that comprises the first 90 cm of T4 (Figure 8b). It was assumed that this leaching zone was the mixing zone. The 100 cm and 125 cm sample are of similar concentration, and may also be bioturbated and not be following Equation 1. Using these two samples as \( N_d \) throw off the age since the concentrations may not be following equation one. Therefore the range of ages for T4 were the two ages calculated using the 150 and 175 cm samples were calculated using both equation 9, as well as equation 10. The age ranges calculated for both methods are in Table 5. The age ranges using all four samples are probably less accurate, since the ages from the 100 and 125 cm samples are not unmixed. Because the exponential age for the unmixed profile is dependent on the inventory age, averaging all of these quantities yields skewed results.
Figure 13a: Modeled ages for T3 from the shifted exponential best fit. The age for max erosion (A) were found assuming that the maximum net denudation would be ~2 meters. This required an erosion rate of 4.7 m/Myr for T3.
Table 5: Inventory and exponential check ages for T4 using the two bottom samples.

The means are the average of the two inventory ages. The values below the means are the standard deviations of the two values. The ages in bold were the best ages interpreted.

<table>
<thead>
<tr>
<th>Nd sample</th>
<th>Inventory age</th>
<th>Inv Inh</th>
<th>Exp Age (yr)</th>
<th>Mean age</th>
<th>Mean Inh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bf_T4_1b</td>
<td>277328</td>
<td>4.77E+05</td>
<td>365000</td>
<td>290681</td>
<td>4.28E+05</td>
</tr>
<tr>
<td>Bf_T4_1a</td>
<td>304034</td>
<td>3.80E+05</td>
<td>435000</td>
<td>19000</td>
<td>68059</td>
</tr>
</tbody>
</table>

Max Erosion = 2.5 m/Myr

<table>
<thead>
<tr>
<th>Nd sample</th>
<th>Inventory age</th>
<th>Inv Inh</th>
<th>Exp Age (yr)</th>
<th>Mean age</th>
<th>Mean Inh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bf_T4_1b</td>
<td>631760</td>
<td>5.61E+05</td>
<td>935000</td>
<td>800000</td>
<td>5.38E+05</td>
</tr>
<tr>
<td>Bf_T4_1a</td>
<td>962370</td>
<td>5.15E+05</td>
<td>680000</td>
<td>234000</td>
<td>0.3E+05</td>
</tr>
</tbody>
</table>

Integrating to Depth Zd

<table>
<thead>
<tr>
<th>Nd sample</th>
<th>Inventory age</th>
<th>Inv Inh</th>
<th>Exp Age (yr)</th>
<th>Mean age</th>
<th>Mean Inh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bf_T4_1b</td>
<td>300000</td>
<td>4.55E+05</td>
<td>380000</td>
<td>321825</td>
<td>4.06E+05</td>
</tr>
<tr>
<td>Bf_T4_1a</td>
<td>340000</td>
<td>3.57E+05</td>
<td>450000</td>
<td>27000</td>
<td>0.69E+05</td>
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</tbody>
</table>

Max erosion = 2.2 m/Myr

<table>
<thead>
<tr>
<th>Nd sample</th>
<th>Inventory age</th>
<th>Inv Inh</th>
<th>Exp Age (yr)</th>
<th>Mean age</th>
<th>Mean Inh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bf_T4_1b</td>
<td>640000</td>
<td>5.32E+05</td>
<td>1000000</td>
<td>845000</td>
<td>5.14E+05</td>
</tr>
<tr>
<td>Bf_T4_1a</td>
<td>100000</td>
<td>4.95E+05</td>
<td>770000</td>
<td>29000</td>
<td>0.27E+05</td>
</tr>
</tbody>
</table>

The ages calculated integrated to depth $z_d$ were used for the analysis. These models can be seen in Figure 13b. This method uses more data points and leaves out the assumption of a mixing depth. However the ages from both methods yield similar ages. This means that the rectangular integral was not far off from the actual area under the curve. The inheritances assuming no erosion from these calculations are reasonable but slightly lower than T3, which would imply a higher basin wide erosion rate.

These ages were used constrain incision rates, both individually by dividing the height ARL by the age (Table 3) and graphically by plotting the height ARL vs age by finding the slope of the linear best fit curve to the origin. The maximum incision rate of the river is ~ 65 m/Myr from the minimum age of T4. The lowest erosion rate is ~ 17 m/Myr is from the T4 age assuming the maximum erosion rate for T4.
Figure 13b: above are the modeled CRN profile curves and data points of T4. The left column uses the modified Perg (2001) method and integrates to Depth Zd in the unmixed deposit. The right column uses the rectangular inventory integrating to Zm. The inventory ages from each Nd sample are adjacent to that sample. The exponential curves were created using the average of the two inventory ages and inheritances from the two samples used. The maximum erosion rate was set to be 2.2 m/Myr for the Zd integration and 2.5 m/Myr for the Zm integration.
Table 5: age and incision rates from models

<table>
<thead>
<tr>
<th>Model</th>
<th>Age of T3 (11m ARL)</th>
<th>Age of T4 (16m ARL)</th>
<th>Erosion rates (m/Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cronus (kyr)</td>
<td>249 ± 20</td>
<td>299 ± 46.1</td>
<td>44 – 54</td>
</tr>
<tr>
<td>no Erosion (kyr)</td>
<td>162</td>
<td>300 – 340</td>
<td>47 - 65</td>
</tr>
<tr>
<td>Inheritance</td>
<td>4.66 x 10^5</td>
<td>4.06 ± 0.69 x 10^5</td>
<td>N/A</td>
</tr>
<tr>
<td>With Erosion (kyr)</td>
<td>388</td>
<td>640 – 1000</td>
<td>17 – 33.5</td>
</tr>
<tr>
<td>Inheritance</td>
<td>5.5 x 10^5</td>
<td>5.14 ± 0.27 x 10^5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Discussion:

GIS Analysis:

SFSR terraces are not easily discernable from topographic data alone. The amount of scatter in the analysis comes both from complications brought about by the geomorphology and geology of Page Valley, as well as issues with the method of analysis. However these results were similar to findings by Bell (1986), but in contrast with King (1950). This method has also potentially found terrace surfaces that are paired downstream in areas previously unmapped.

The Page Valley landscape and geology play a role in the complications found in the GIS analysis. The main geologic contributors to this include the underlying carbonate rocks and meanders forced by Martinsburg Shale bedding. (Hack, 1965) The carbonate
rocks contribute to dissolution collapse and create karst topography on the terraces, making the surfaces less flat and therefore blurring the signal that a perfectly flat terrace would create in a histogram analysis. The affect of solution collapsed was studied by Bell (1986) and she found that it preserved the soil profiles but lowered the elevation of the terrace tread. Some of the meanders in the Luray and Luray North cross section are so significant that a valley normal cross section could cross the river twice and is something that must be looked for when interpreting the cross section. This meandering may put the same terrace at two different levels ARL in the cross section.

Alluvial fans are the main geomorphic influence on the preservation and extent of SFSR terraces. These fans affect the fluvial landforms in multiple ways. Fans can bury terraces; this has been observed in King (1950), Hack(1960), and Bell (1986). And some of these buried terraces become manganese ore deposits. A single debris flow event could supply enough sediment to part of the river and cause local aggradation of an unpaired terrace, This event can also divert the flow of the river and cause the river to erode the terrace on one side. One example can be seen in figure 3 a tongue of an alluvial fan has diverted the SFSR to the northwest and this forced meander has created the most extensive T1 floodplain mapped by Bell(1986). This floodplain is the point bar of this forced meander. This diversion has also caused lateral planation into the older deposits on the northwest side. This shows that by altering the course of the SFSR, alluvial fans can influence where the SFSR both deposits and erodes terraces, as well as covering up old treads and supplying sediment for local aggradation.

There are other issues inherent within the analyses that also affect the ability to interpret terraces. The main problem with the block analysis method is that by averaging
30 cells down valley you will most likely get an averaged height that is somewhat below the actual terrace height. This can be seen in figures 8 and 9 that visually the interpreted terraces are lower in the block analysis than in the cross section analysis. The highest terraces in the block section analysis are 65 m ARL, while in the cross section analysis the interpreted terraces ranged as high as 90 m ARL. These high flats did not extend three hundred meters down valley and therefore the averaging in the block section decreased the height. This is shown in figure 14, where the averaged block section line is ~1/2 as high as the cross section.

The main issue in the cross section analysis is their placement. In order for a quick systematic analysis, the cross sections were automatically created at even intervals down valley within the DEM rectangle. Some of these cross sections may either cross a terrace along the hill slope or go up a tributary flood plain and cause an incorrect terrace interpretation. Taking a histogram of the interpreted terraces in each study rectangle helps rectify the errors under the assumption that a correct extensive terrace height would be interpreted multiple times and the more extensive the terrace, the less significant the block analysis averaging error will become.

In spite of its limitations, the block and cross section analyses has yielded significant results. The analyses found six topographically distinct surfaces in the Bell study area, 3 of which fit into Bell(1986) units. It showed that potentially two terrace surfaces were originally mapped as T4 in height ARL and that there are two extant higher surfaces at ~25 and ~30 m ARL that were originally mapped as residuum by Bell (1986). According to the model of terrace degradation put forth by Bell (1986), these older terrace soils could look like residuum if they have been subject to continued solution
Figure 14: A and B are a block section and a cross section in the same part of the Luray study rectangle. In A the black line represents the maximum height along that column of the valley and the blue line designates the average. The histogram in A shows a spike at 60 m ARL which corresponds with the flat surface in the maximum height line. The averaged block section line shows this surface at 30 m ARL which is evidence that the averaged block section can make surfaces look lower than they actually are.
collapse and mixing with the residuum underneath. The Elkton analysis yielded two extant terraces, neither of which corresponds well with King’s (1950) gravel units. The relative lack of terraces in this area is also consistent with the more recent Shenandoah National Park map (Southworth, et al, 2009), which maps few terraces and mostly alluvial fans in the area. King(1950) never differentiated terraces from fans and the morphology of these gravel deposits favor an alluvial fan interpretation.

The Downstream Luray and Luray north study rectangles also contained continuous surfaces. These occur at ~30 m ARL and around ~50 m ARL. These higher interpretations are partially from the fact that wider rectangles were used because of the severity of meandering. However looking at the plot of the terraces along the SFSR longitudinal profile, some of these surfaces line up parallel to the river in the Luray rectangle and to a lesser extent in the Luray North rectangle. (Fig.10a, b)

This DEM analysis represents one of the first attempts to pair terrace units along the entire length of Page Valley, in Virginia. However the analysis was complicated due to issues from the landscape, including the instability of the bedrock, the entrenched meandering of the river, and the influence of alluvial fan deposits, as well as error from within the analysis. However the results yielded from these analyses show terraces somewhat consistent with Bell (1986) findings as well has higher terraces, but do not support the gravel units mapped in King (1950). Two surface pair downstream in all sections from both analyses, one at ~10 – 13 m ARL and one ~ 30m ARL. This analysis if developed could become an effective tool in mapping terraces and could help check, guide, and expand on fieldwork. It could also be paired up with slopes to get a better
sense of terrace topographic forms as well as soils data to pair surfaces both with soils data and topographic relationships.

**CRN discussion**

For T3, abandonment ages ranged from 162 kyr to 388 kyr. The youngest age, 162 kyr, is similar to the 10 m Kentland terrace from Ward et al (2005). This youngest age implies an erosion rate of ~67 m/Myr. The oldest age assuming ~1.75 m of surface reduction is 388 kyr. This would yield and erosion rate as 33 m/Myr. The range of incision rates from T3 is from 33 – 61 m/Myr is similar to the James River (Hancock and Harbor, 2004), the New River (Ward et al 2005) and the Green River over $10^5 – 10^6$ timescales. (Granger et al, 2001)

The T4 showed a flat profile for the first three data points, which implies soil mixing in the upper profile. This gave the opportunity to use the updated inventory method. This was performed and the exponential checks were generally within the same magnitude. The minimum age assuming no erosion rate was 300 - 340 kyr which would give an incision rate of ~ 47 - 53 m/Myr. Using the same assumption of ~2 meters of fine sediment removed from the deposit, the inventory method yielded a maximum age range of 640 – 1000 kyr. This was from a surface erosion rate of ~2.2 m/Myr which is lower than that of the T3 max erosion rate. This is because the T4 deposit would have more time to erode and reach more resistant layers and erode more slowly thereby driving down the erosion rate over time. This age is probably somewhat too high because T4 had more sediment on top the cobble layer than T3, but it does give us a maximum constraint.
The incision rate from a terrace of this age and 16 + 2 m of height ARL give us a minimum SFSR incision rate of 17 m/Myr. The Cronus ages for the non mixed data points yielded reasonable ages within the bounds of maximum and no erosion but the assumption that there was no inheritance is probably a bad one for both age calculations since Duxbury (2008) found that modern river sediments in the SFSR basin contained significant concentrations of $^{10}$Be.

The ages interpreted from these terraces match the Pleistocene hypotheses made by King (1950) and Hack (1965) as well as terrace ages of similar height ARL on the Susquehanna (Pazzaglia et al, 1994), and the New River on the other side of the Appalachian divide. The age ranges are too broad to speculate whether a glacial or interglacial climate shift caused the abandonment of these terraces, but the interval of $\sim100 - \sim400$ kyr between ages is consistent with intervals on the New River as well as on the James River.

*Incision rates*

With these ages we can put the incision rate of the SFSR in context to regional incision rates as well as other parts of the landscape. The range of 20 – 67 m/Myr it puts the SFSR incision rate in the same ranges as the James River (Hancock and Harbor, 2004), the New River (Ward et al, 2005; Granger, 2001), and the Green River (Granger, 2001b). The accord of these incision rates suggests a regional trend of incision over the $10^5 – 10^6$ region in rivers draining the Appalachians from both sides of the divide. The incision rates of the Holtwood and Mather gorges were an order of magnitude higher than the rates mentioned above (Reusser et al, 2004), but the strath ages used to constrain these were also an order of magnitude younger so incision rate is scaled up because the
Figure 15: A.) This is a cross section of Bogota farm and the sampling sites, with the T3 and T4 surfaces extrapolated over the river level. The erosion rates in black are the ranges assuming no surface erosion rate and using ages from both the Cronus exposure ages and the Exponential profile and Inventory methods. The red surfaces are the surfaces of the original deposits assuming that they lost between 1.75 - 2 m of fine overbank deposits. B.) is a plot of Height ARL of the surface against the calculated age. The slope of the linear regression through each of these points to zero is the average incision rate of the river since incision of the higher terrace. The red line corresponds to the max erosion model and yields a slope of 25 m/Myr. The two black trend lines are for the Cronus and no erosion model and yield slopes of 53 - 55 m/Myr.
time scale contains fewer fluvial cycles. (Mills, 2000) These incision rates are over periods of time where there has been net incision and fewer periods of aggradation so the erosion rate is higher over that period. The ages of terraces were plotted against the height ARL. A trend line of the New, James, and SFSR combined data was created to constrain a regional incision rate of 47 m/Myr. (Figure 15)

The incision rate of the SFSR was also compared with the Blue Ridge basins and the bedrock summits. The range of incision rates of the SFSR is higher than the basin erosion rates from Duxbury (2008) as well as well as Blue Ridge Summit Erosion rates (Whitten, 2009). (Figure 16) This provides evidence that the landscape has been in disequilibrium over the $10^5$-time scale. In an attempt to confirm a statistical difference between the rates, a t test was performed on the range of incision rates and measured summit erosion rates from Whitten (2009). This test calculates the likelihood that the incision rates and summit erosion rates came from the same population of erosion rates. For this sample we will use the range of incision rates from the age models used and calculated using one terrace as well as the best fit slope of both terraces (Figure 14). All of the summit erosion rates from Whitten (2009) were in the summit sample population. (Figure 17) This statistical comparison is acceptable because the summit erosion rates measured are significant over $10^4$ - $10^5$ time scales Whitten (2009) and the ages of the terraces are within the same time scale ($10^5$). The t value found for this assuming the same variance is $6.19 \times 10^{-8}$. This gives 99% confidence that the summit and SFSR erosion rates are not in the same group of erosion rates as the Blue Ridge peaks (Whitten, 2009) and supports the argument for disequilibrium in the Shenandoah Valley.
Figure 16: This is a plot of linear regressions of terrace ages vs height. The slopes of these lines in m/Myr are reported for the individual rivers as black lines. A linear regression of the James River, New River and SFSR combined data is shown in red, and gives an estimate of the region wide fluvial incision rate at 46 ~m/Myr. The Black Dotted line separates the incision rates over different time scales (slope 100m/Myr). Lines plotting to the left of this are incision rates accurate over 10 - 100 kyr time scales, while best fit lines to the right correspond with incision rates over time scales of 100 kyr and ~1 Myr.
The prospect of disequilibrium in the Appalachian landscape was also explored by comparing the incision rates of the rivers mentioned above to regional basin erosion (Duxbury (2008)) as well as the Blue Ridge summit erosion rates (Whitten, 2009) and Appalachian highland summit erosion rates from Dolly Sods, West Virginia (Hancock and Kirwan, 2004). (Figure 18) This shows that the major rivers are incising at a higher rate than the landscape and implies that the region is in disequilibrium.

In order to back this argument a t – test was performed to test the hypothesis that the entire suite of river erosion rates and summit erosion rates are part of the same population of erosion rates. One caveat to this test is that the river incision rates used from the James, New, SFSR, and Green Rivers were on the time scale of $10^5 – 10^6$ and the summit erosion rates from Kirwan and Hancock (2004) and Whitten (2009) are only significant for $10^4$-$10^5$ time scales. To get around this problem the assumption was made that the incision rates of the rivers used were over a longer time scale and therefore would be lower than the incision rates in the time scale comparable to the summit erosion rates. (Mills, 2000) Therefore if the null hypothesis of this t test was validated then it was most likely that the shorter time scale incision rates would also be significantly higher, since more recent erosion rates would be higher. The range of SFSR incision rates from above was used, as well as end member incision rates from the Ward (2005), Hancock and Harbor (2004) and Granger (2001) were used as the river incision rate sampling. The t statistic assuming same variance was $7.02 \times 10^{11}$. This shows that there is 99% confidence that the summit erosion rates and the river incision rates are not from the same population. This is statistical evidence that the entire Appalachian region has had
A. Cross section over the Blue Ridge and Page Valley in between Lynnwood, Va and Loft Mountain. This shows the spatial variation in Erosion rates across the relief of the landscape.

B. Comparison of erosion rates of different parts of the Page Valley and Blue Ridge Landscape

Figure 17: A. Cross section over the Blue Ridge and Page Valley in between Lynnwood, Va and Loft Mountain. This shows the spatial variation in Erosion rates across the relief of the landscape. B. - Box plot of ranges of Incision rates and erosion rates found in the three studies compared. Note that the majority of the SFSR incision rates plot much higher than the Basin and Summit Erosion rates.
net disequilibrium on a $10^5 - 10^6$ timescale and that the relief is increasing on both sides of the divide.

**Figure 18:** Box plots of erosion rate ranges in different parts of the Central Appalachians. The Blue Ridge Summits are from Whitten (2009), Dolly Sods data is from Hancock and Kirwan (2004), Blue Ridge basin data is from Duxbury (2008). Atlantic draining stream data consists of SFSR incision rates and James River incision rates. (Hancock et al, 2004) Gulf draining stream incision rates consist of the New River (Ward et al, 2005; Granger et al, 1997), and the Green River (Granger et al, 2001)
Table 7: Table of data used to perform the t tests for Shenandoah rates and Appalachian rates.

<table>
<thead>
<tr>
<th>Summit rates</th>
<th>erosion</th>
<th>Fluvial Incision Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolly Sods</td>
<td>6.3</td>
<td>SFSR</td>
</tr>
<tr>
<td>Hancock and Kirwan (2004)</td>
<td>5.2</td>
<td>T3 Cronus 53</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>T4 Cronus 44</td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>T4 Max E 17</td>
</tr>
<tr>
<td></td>
<td>6.7</td>
<td>T3 Max E 33</td>
</tr>
<tr>
<td></td>
<td>9.5</td>
<td>T4 no E 47</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>T3 No E 67</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>Cronus LR 50</td>
</tr>
<tr>
<td></td>
<td>4.76</td>
<td>No E LR 63</td>
</tr>
<tr>
<td></td>
<td>2.98</td>
<td>Max E LR 22</td>
</tr>
<tr>
<td></td>
<td>4.34</td>
<td>other Rivers</td>
</tr>
<tr>
<td>Shenandoah t-stat</td>
<td>2.46</td>
<td>Hancock et al 2004</td>
</tr>
<tr>
<td></td>
<td>2.77</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td></td>
<td>James</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>8.07</td>
<td>New Hi 44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ward et al</td>
</tr>
<tr>
<td></td>
<td>6.2E-08</td>
<td>New Low 25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Granger et al 1997</td>
</tr>
<tr>
<td></td>
<td>4.71</td>
<td>New cave 28</td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td>Green 30</td>
</tr>
<tr>
<td></td>
<td>7.02E-11</td>
<td>Granger et Al 2001</td>
</tr>
<tr>
<td>Appalachian t-stat</td>
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<td>23.29</td>
</tr>
<tr>
<td></td>
<td>13.31</td>
<td>5.81</td>
</tr>
</tbody>
</table>

Reasons for disequilibrium in the Appalachians

Evidence for a major change from aggradation to net incision of Appalachian rivers since ~2 – 4 Myr has been seen in several studies. (Ward, 2005; Granger, 2001a, 2001b; Hancock and Harbor, 2004) Though the time scale of the SFSR in this study is too recent to record this dominant trend. This net incision contributes to the state of landscape disequilibrium in the valley as well as the region. This river incision rate across...
the Appalachian divide implies a regional climatic influence on river behavior. Reasons for this net incision could come from the breach of the Blue Ridge by the Atlantic draining streams at ~2 Myr (Pazzaglia and Brandon) or the increase in erosion rates globally due to climate change (Zhang, 2001; Molnar, 2004). Both of these trends could be influencing the change in relief.

There are some issues with the model of Atlantic drainage capture theory. First, there needs to be some outside influence in the eastern streams that gives the rivers the impetus to incise over the Blue Ridge. After a stream breaches the Blue Ridge it begins capturing more and more carbonate lowlands of the Great Valley province. This captured basin would supply less sediment per area of basin because the carbonates would add more dissolved load. This could potentially shift the discharge to sediment supply ratio from upstream higher, which may favor incision over aggradation. This mechanism could cause incision into the Atlantic streams, but on the Mississippi side of the divide the relative amount of carbonate basin would be decreasing which would favor aggradation or stability. There is evidence of the Green river streams having stable periods around 2 Myr, soon after the Atlantic breach, (Granger et al, 2001) but this stability was not long lasting and incision continued on the Green River at 1.5 Myr. One way that Atlantic stream capture could cause incision on both sides of the Appalachian divide is if the loading of sediment deposited on the continental shelf from incising Atlantic streams could cause flexural isostatic uplift of the entire Appalachian region and cause deep valleys to incise and increase the relief on both sides of the divide like in the model proposed by Molnar and England, (1990). They proposed that an increase in erosion
could cause isostatic uplift and an increase in valley incision; causing increase in relief in a tectonically quiet setting.

The beginning of this net incision also corresponds to global climate change. Increase in sedimentation rates in the last 2 – 4 Myr all over the world has been attributed to a global increase in erosion rates from the continents. (Molnar, 2004; Zhang et al, 2001) This trend has been seen on the Atlantic margin (Pazzaglia and Brandon, 1996). Molnar (2004) and Zhang et al (2001) put forward that increase in the amplitude and frequency of climate fluctuations in the Pleistocene has caused an increase in continental erosion rates and shelf sedimentation rates. (Molnar, 2004) Climate fluctuations force landscapes out of equilibrium, and the higher the amplitude the larger this push then the larger the response from these landscapes to adjust back to equilibrium.

Molnar (2004) argues that higher amplitude and frequency responses from the landscapes create higher erosion rates. The increase in frequency of these climate changes also increases the number of adjustments the landscape has to make. These climate changes could drive the landscape by changing the geomorphically effective discharge of a fluvial system, as well as increase or decrease the sediment created upstream from changes in periglacial processes, vegetation changes, and mass wasting recurrence intervals and base level change. All of these potential reactions to climate change have been mentioned in the Appalachians as possible mechanisms for terrace creation and abandonment in this region. (King, 1950; Hack, 1965, Ward et al, 2005)

Though this theory of increased climate change amplitude and intensity explain the increasing erosion rates in the Appalachians, they do not properly address the increase in relief. According to Hacks Theory of Equilibrium, climate change could either act on a
landscape to change the relief in either direction, so climate swings do not necessarily mean a net increase in relief. The net incision from the Pleistocene climate variations could also come from the differences in the abilities of parts of the landscape to adjust to the climate change. The net incision interpreted over this time scale implies that the fluvial parts of the Appalachian landscape are able to respond more quickly to the climate fluctuations than the peaks of the landscape.

This incongruity may have several causes. One cause be due to the fact that changes in hydrologic conditions of the river, mainly the change in geomorphically effective flow and the stream power of the river respond more quickly than increases in the sediment supply from upstream. Therefore the discharge to sediment supply ratio more quickly responds upwards in climate change and causes incision. The difference in reactions could also be due to underlying rock strength, where the rivers can more quickly incise into the soft bedrock of the valleys than the highlands can denude and bring supply the sediment from the harder lithologies. The climate may also fluctuate back before the uplands are truly able to respond to the original increase in erosion. The apparent control of the rivers over the landscape response to these fast climate fluctuations supports the channelization theory of landscape evolution put forth by Stark, and Stark (2001), where geomorphic evolution of the landscape is ultimately driven by changes in channel geometry and behavior, and that the hill slopes only react more slowly to these adjustments. Model results of Whipple (2001) show that fluvial systems struggle to achieve equilibrium during rapid climate change and uplift. One model for Appalachian relief development in the Appalachians is the failure of fluvial systems to adjust to climate fluctuations, which causes constant disequilibrium at the river scale. The
new erosion conditions from these fluctuations do not give the hill slopes enough time to respond and therefore the rivers erode more quickly than the peaks around them.

Though there is a net incision in the river valleys of the Appalachians, there are still Pleistocene age terraces that show periods where erosion mechanisms of the mountain slopes and sediment supply to the river have caught up to the increase in stream power. These sediment supply increases could be driven by climate change ramping up the sediment flux from upstream to cause aggradation. These aggradations could also be internal landscape responses to incision where by incision causes relief to increase past some threshold where increased slope failures and in the more frequent valley debris flows increase the sediment flux. This has been seen in smaller drainages in the North Carolina Blue Ridge, where hill slopes downstream of a knickpoint showed more evidence of slope failure and landslides. (Gallen et al, 2010) This has also been seen in analog models of knickpoint incision, where the increase in relief downstream of the knickpoint causes slope failure and releases more sediment into the fluvial system, therefore causing aggradation and terrace formation as a reaction to the incision. (Schumm, 1976)

Conclusions:

The presence of terraces in the Shenandoah Valley gives record to phases of disequilibrium in the landscape. The extent and pairing of these terraces is complicated by the geology of the region as well as the alluvial fans that dominate the valley floor. These fans cover up terraces, as well as divert river flow to disconnect terrace surfaces and create extensive point bar floodplains in the forced meanders. These debris flows can
also bring localized slugs of sediment that can create local terraces. However there are at least two consistent SFSR terraces that pair all of the way down Page Valley.

The ages of two of these terraces show a pattern of incision and aggradation of SFSR during the Pleistocene that also seen in other rivers in on both sides of the divide. Knowledge of the composition of active floodplain soil profile characteristics allows for a constraint on the total height of sediment eroded from terrace deposits and therefore gives us an absolute minimum age of the deposit. The incision rates inferred from these terrace ages are also similar to regional incision rates. The range of SFSR incision rates presented in this study are statistically higher than summit erosion rates at the peaks of the Blue Ridge, implying that the valley has been increasing in relief in the last $10^5$ yrs. Comparing all of the Regional river incision rates and regional bedrock erosion rates shows a similar trend of increasing relief throughout the Appalachian region.

This disequilibrium most likely stems from an increase in amplitude and frequency of climate fluctuation at the onset of the Pleistocene that caused increased erosion rates worldwide. This increased erosion rate was from the struggle of landscapes to constantly adjust to the new equilibrium conditions. This caused a marked change from net incision to aggradation in many Appalachian rivers at $\sim 2$ Myr. This could also could have driven Atlantic streams over the Blue Ridge and caused flexural rebound with increased Atlantic Margin Sedimentation.

The net increase in relief stems from both isostatic uplift from the lightening of the Appalachians and flexural rebound, as well as the discrepancy between the response of incision mechanisms and the sediment supply mechanisms to climate forcing. This incongruity could either be process related, or related to the strength of the underlying
materials. The apparent dominance of the river response to climate fluctuations suggests a channelization theory of landscape equilibrium. However there are aggradational episodes within this net disequilibrium where sediment supply catches back up to the stream power of the river from climate forcing as well as positive feedbacks inherent within the landscape itself. These episodes create the fluvial terraces seen in the Shenandoah Valley today.

**Future Considerations:**

Future work could include Terrace field mapping along the whole valley to check and improve the GIS analysis, as well as calibrating and improving the GIS analysis in regions where terrace preservation is better and suites of terraces are well mapped. Also many of the conclusions in this study are based on the assumption that bare bedrock summit erosion rates scale back like incision rates or stay relatively constant with respect to time scale. Finding a way of testing this assumption would make the comparison of rates in the landscape made in this study more concrete.

Older terraces exist on the SFSR that could also be dated to get increase the scope of understanding of the river history. The alluvial fans in the valley are another major player that need to be addressed because it is one of the dominant processes that denudes the mountains and supplies sediment to the SFSR system (Eaton, 2004) better understanding on how the amount of sediment from these fans changes with climate as well as the flux of sediment that is actually taken from the fan to the river can help constrain the sediment flux that the river has to take downstream.
Acknowledgements:

I would first like to thank my Advisor, Gregory Hancock, for giving me this opportunity to use cutting edge techniques to study my home landscape and having the patience to train a new researcher. I would also like to thank Jenny Whitten, who was patient enough to help me get acquainted with the W&M Cosmogenic Radionuclide lab while finishing her own honors thesis. I would also like to thank the Surface Processes Research group (Brendan Murphy, Kyle Grimsley, and AJ Saltz) who were good at sharing the lab and keeping things tidy, as well as always being willing to share ideas. I would also like to thank Charles “Dill Pickles” Reilly, who helped both in the sampling as well as the lab work.

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Appendix I: GIS Methods and Graphs

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Appendix I: Introduction

This appendix contains step-by-step instructions, individual maps, and graphs for the GIS methods for this study. Included are instructions on digitizing the Bell (1986) map as well as instructions for DEM preparation in ArcGIS and MATLAB Scripts for the Cross section and Block Section Analyses. For each GIS analysis rectangle, maps of the cross sections and block sections depicted over a shaded relief map are included as well as the down valley profiles of interpreted terraces and the associated histogram of interpreted terrace heights ARL. The Appendix section for each study rectangle also contains cross section and block section graphs and histograms.

Georeferencing

1.) Scanned Bell (1986) plate one and it into the computer in a jpeg format.

2.) loaded jpegs into arc catalog.

3.) Opened an mxd in arcmap of satellite images (from ESRI world imagery layer), a shaded relief img, and a stream polyline shapefile. These are all in the PCS NAD 1983 conformal conical for UTM region 17. GCS is utm 17.

   a. The Dem was made smaller for quicker computation by creating a shapefile of a polygon that covered the Bell Study Area.
The shape file was created in ArcCatalog by right clicking on the file and selecting New> shapefile.

The shape file was then loaded into the map the editor toolbar was selected from view > toolbars, editor > start editing and a new feature was created and the edits were saved.

The tool extract by mask was used on the dem using the shape file as a mask

b. to create a shade relief the hillshade tool was used and placed underneath the partially transparent DEM.

c. To create the stream polyline shape file a flow direction and flow accumulation raster was created from the DEM, using the commands in the Hydrology Toolbox of the Spatial Analyst Toolset.

4.) Went to view > toolbars and opened the georeferencing toolbar.

a. Loaded one part of the map at a time. (it will give you warnings about not being georeferenced but just ignore it)

b. Zoomed into the approximate area of the map photo piece

c. Selected the map piece layer in the georeferencing toolbar

d. Clicked georeferencing > Fit To Display

e. Next step was to make some control points. To do this click on the control points button on the Georeferencing toolbar ( it looks like two plus signs connected by a line)
f. Control points were made by first clicking the point on the picture that you wanted then moved to the corresponding geographic location of that point on the map. Control points were generally added at intersections of streams using the stream polyline file. The file was also checked with satellite imagery because some streams polylines were off.

g. When all of the control points were made Georeferencing > update georeferencing was selected. This made the georeferencing permanent.

h. If a control point needed to be deleted the table button next to the control point button was selected. This brings up a table of control point transformations. One can be selected and deleted by clicking the x box on the upper right hand corner.

5.) All of the map pieces were georeferenced with note to the fact that scanning left out some pieces due to the folds and the pieces had to be warped some. It was also assumed that this map was made in NAD 1983 UTM region 17.

**Digitizing the Map Units:**

These georeferenced map files were now saved as photo raster files. The next step was to digitized the Bell Terrace Map Units into a polygon shapefile.

1.) First a new shapefile had to be created in ArcCatalog, this is done the same as in step 3a of the georeferencing instructions.
2.) This shapefile was brought into Arcmap along with the extracted DEM, as well as the digitized Bell (1986) map photos.

3.) The function “start editing” was selected from the profile. This function requires the user to pick a folder to edit. The folder containing the new shapefile created above was chosen.

4.) In order to create the polygons to represent the map units,
   a. “Create New Feature “was selected in the task bar and the pencil command was created.
   b. Polygons were then drawn in similar shapes of the map units on the georeferenced maps. These were also checked to the DEM to see if these sections aligned with scarps on the DEM.
   c. If two units shared edges as happened often. The “Auto Complete Polygon,” task option was used and a line was drawn from edge to edge to autocomplete the polygon.

5.) When a new polygon was created, the feature table was accessed by right clicking on the shapefile and the “Open Attribute table command was created” New attribute columns were added to give the map unit name and number to the polygon. Three attributes were added,
   a. typeN – is a int attribute that signifies what type of unit it was. Terraces were 1, Tributary floodplains were 3, and Alluvial fans were 4.
   b. Type attribute was a string attribute that was the actual map name of the unit on the Bell (1986) map.
c. Terr_Num was an int attribute that signified the terrace unit number of the SFSR terraces, alluvial fans and tributary units were 99, and the units given two numbers were given the rank of the smaller terrace interpretation.

6.) When these were completed, the edits were saved and the “Stop Editing,” command was used. These shapefiles were used to

**GIS Topographic Analysis methods.**

The following are instructions for extracting the DEM of the desired stretch of river valley with Select drainage basin area –

1. Created new shapfile in ArcCatalog – Polygon

2. Used the advanced editor toolbar to create a rectangle and the rotate scroll to line it up with the valley section. I would put it down valley so that the rectangle is normal to the valley strike. Saved Edits and stopped editing. Saved a Copy of the rectangle before rotating (Step 3).

   a. In order to get the size rectangle desired, double click on a corner which will open up the sketch, Right click on a vertex and go to properties, from I changed the coordinates of the vertices.

   b. Since the rectangle created is oriented north south and the coordinate system is in UTM, create vertex coordinates that are the x and y distances away from each other in the vertex coordinate table. Where x and y are the desired width and length of the rectangle.
c. I rotated the rectangle using the rotate button in the editor toolbar as well as move the rectangle over the desired area using the edit tool in the edit tool.

3. I Buffered the cross-section using the buffer tool for two cells each way (20 meters) this makes sure the rotated DEM doesn’t have NoData cells within the study area.

4. Next I extracted by mask the DEM through the buffered rectangle

5. Rotated the entire data frame in the data frame properties easily to line up the cropped raster and figure out what angle it needs to be rotated

6. I used the rotate tool to rotate the DEM in the coordinate system so that the rectangle was orthogonal to N-S, E-W. The number of degrees to rotate it was found out in step 8.

7. The unbuffered rectangle was copied and pasted in the data frame. This copy was also rotated normal and moved over the rotated DEM using the editor toolbar’s rotate tool. I zoomed in to the corner and scrolled down the sides of the rectangle to make sure it was square with the cells.

8. I extracted the rotated DEM by mask again through the rotated dem. This is because an extraction that is not normal to the coordinate system creates a rectangle of NoData cells surrounding it that are still present after the rotation. These NoData cells that make the ASCII file large enough that MATLAB will not import it.
9. This yielded the final raster layer that contains the length and width of the valley that we desire. Convert this raster data set into an ASCII file to load into MATLAB. To do this I used the “Raster to ASCII” tool in the conversion toolkit.

Matlab Methods

The next steps show how to turn the created ASCII file into a MATLAB matrix.

1. I moved the ASCII file created above into the directory with the MATLAB scripts shown below.
2. First I opened the ASCII file in text editor. The first four lines of the ASCII file are headers about the geographic location of the bottom right corner of the DEM and some other information. I deleted these four lines and did a SAVE AS a different text file (just so I did not lose that information)
3. This new .txt file was imported into MATLAB and converted into a .mat by dragging the file from the folder into the workspace.
4. I renamed this new matrix “Z,” and save it as a .mat file.
5. With this data you can run the xsection_analysis.m and xsection_analysis2.m scripts that perform the cross section and block section analyses respectively.

Analyzing the graphs:

The next step is to analyze the graphs created by the scripts above. The goal is to look for flat surfaces that look like flat stair stepping terraces from the river in the cross
sections. The histogram of the terrace height is plotted below the cross section, and the
elevation histogram of the entire rectangular block section is plotted below the averaged
block cross sections. The interpreted terraces were then recorded in an excel spreadsheet
along with the length down valley from the beginning of the rectangle. These were all
plotted as height ARL over the distance down valley and histograms of the height of
interpreted terraces were used to infer continuous terraces. All of the study rectangles
were combined and the approximate distance between each rectangle was measured using
the measure tool in ArcGIS.

These interpreted terrace heights were then brought back into their elevations by
adding the lowest elevation in each cross section back to the terrace height ARL. First the
min function in MATLAB was used to extract these lowest data points and this was
added back onto the heights ARL of the interpreted terraces to get the elevation ASL in
m. for the block section, the mean of the 30 low points along the block was the elevation
added on the terrace heights ARL.

Each rectangle section was then stretched from down valley distance to ARL to
distance along the longitudinal profile of the river. This was done because the sinuosity
of the river is so high that the distance down river within the rectangle is longer than the
distance down valley. The longitudinal profile for the river was created from the divide
up the South River in between the James River and Shenandoah watersheds, down to the
confluence with the Potomac River. Kyle Grimsley used the stream profile tool from
geomorphhtools.org to make this profile. The highest and lowest river elevation for each
study rectangle was found on the longitudinal profile and the two horizontal distances
were measured. The distance down valley of each interpreted terraces was the stretched
to fit this new horizontal distance using the equation below:

\[ L_t = \frac{D_t}{D_{rect}} \left(L_{down} - L_{up}\right) + L_{up} \]

\( L_t \) is the distance along the river profile from the divide of the interpreted terrace. \( D_t \) is the
distance down valley of the terrace along the rectangle. \( D_{rect} \) is the entire length of the
rectangle. \( L_{down} \) is the distance from the divide of the lowest part of the river in the
study rectangle, while \( L_{up} \) is the distance from the divide of the highest part of the river in
the study rectangle. This is an imperfect stretch because the elevations of the river are
taken from two different river levels. These terrace elevations are plotted against \( L_t \) along
the river profile to show the relationship between the valley profile and the river profile.

**Xsection_analysis:** this the MATLAB script that performs the cross section analysis on
the DEM.

```matlab
%% this script analyzes the loaded data by plotting all of the cross
%% sections in one profile and binning the data to compute a histogram for
%% each cross section and down the profile.
hi = 21;  %%sets the number of steps and is based on the
total rectangle
%length divided by the interval of the cross section
%creates minimums and maximums
r = min(Z');
Norm = zeros(21, 349);
MaxZ = max(Z);
Zmax = max(MaxZ);
MinZ = min(Z);
Zmin = min(MinZ);
tot = Zmax-Zmin;  %this creates the bins
% This plots all of the profiles on one axis normalized to
```

| 10 |
be height ARL

for i = 1:21
    Norm(i,1:349) = Z(i,1:349)-r(i);
    numb = num2str(i);
    graphname = 'Elkton Cross Section Analysis';
    fullgraphname = [graphname ' ' numb];

    figure(3)
    clf
    subplot(2,1,1)
    plot(Norm(i,1:349))
    title(fullgraphname)
    ylabel('Height ARL (m)')
    xlabel('distance along Cross Section (m)')

    subplot(2,1,2)
    hist(Norm(i,1:349),tot)
    title('elevation histogram')
    ylabel('# of cells')
    xlabel('Height ARL (m)')

    name = ['xprof'];

    fullname = [name numb];
    saveas(gcf, fullname, 'tif')
end

%%bins the entire elevation data set

bins=0:tot;
total = zeros(1, tot+1);
Vprof = [];

for j = 1:21
    count(j,1:tot+1) = hist(Norm(j,1:349), bins);

    for k = 1:tot+1
        if count(j,k) > 20 % very important inequality that controls which counts to take for the down valley profile
            %
        end
    end
end
Vprof = [Vprof; j*0.5, bins(k)];
end
end
total = total + count(j, 1:tot+1);
end
figure(2)
clf
bar(total);
figure(3)
clf
plot(Vprof(:,1), Vprof(:, 2), '+');
figure(4)
clf
surf(count);

xsection_analysis2: This is the script modified for the block section analysis

%% this script analyzes the loaded data by plotting all of
%% the cross
%% sections in one profile and binning the data to compute
%% a histogram for
%% each cross section and down the profile.
hi = 35;  %%sets the number of steps and is based on the
total rectangle
%length divided by the interval of the cross section

%%sets up variables and preallocates them
Norm = zeros(30, 300);

Vprof = [];

%%creates minimums and maximums
maxZ = max(Z');
Zmax = max(maxZ);
minZ = min(Z');
Zmin = min(minZ);
tot = ceil(Zmax - Zmin);

total = zeros(50, tot+1);
count = zeros(30,tot+1);

%%This Step bins the entire elevation data set
bins=0:tot;

% This is the major for loop that separates out each grid of elevation in
% 3.5km wide and 0.5 km long valley normal rectangles.
for b = 1:35
    z = Z((b*30 - 29):(b*30), 1:350);
    r = min(z'); % creates the river level
    meanriv(b) = mean(r);
end

%this loop creates the normalized ARL grid
for i = 1:30
    Norm(i,1:350) = z(i,1:350)-r(i);
    count(i, 1:tot+1)= hist(Norm(i,1:350), bins);
    for k = 1:tot+1
        if count(i,k) > 40 % very important inequality that controls which counts to take for the down valley profile
            Vprof = [Vprof; b*0.5, bins(k)];
        end
    end
    total(b, 1:tot+1) = total(b, 1:tot+1) + count(i, 1:tot+1);
end

numb = num2str(hi-b+1);

graphname = 'Elkton Block Analysis Cross Section';
fullgraphname = [graphname ' ' numb];

figure(3)
clf
subplot(2,1,1)
plot(mean(Norm))
title(fullgraphname)
ylabel('Height ARL (m)')
xlabel('distance along Cross Section (m)')

subplot(2,1,2)
bar(total(b,1:tot+1))
title('elevation histogram')
ylabel('# of cells')
xlabel('Height ARL (m)')

name = ['xprof'];

numb = num2str(hi-b+1);
fullname = [name numb];
saveas(gcf, fullname, 'tif')

end

figure(2)
clf
%bar(total);

figure(1)
clf
plot(Vprof(:,1), Vprof(:, 2), '+');

figure(2)
clf
surf(total);
**Buildlongprofile:** This script adds the river elevation back to the interpreted terraces ARL. r1 through r4 are the heights of the lowest points in the cross sections (or averaged block section low points) for each of the rectangles in this study.

```matlab
%%buildlongprofile brings in the terrace heights ARL of the crossections %studied, restores them to their elevations using the minimum data from %each cross section
data = xlsread('xsectionsynthesis.xls', 'xsection'); %reads in the terrace readings

lastrow = 344; %this shows the last row in the excel file and governs the number of functions

for i = 1: lastrow
    if data(i,1)==0
        data(i,5) = data(i,3) + r1(1);
    elseif data(i,1)<= 15000
        data(i,5) = data(i,3) + r1((data(i,1)/500)+1);
        data(i,6) = r1((data(i,1)/500)+1);
    elseif data(i,1) > 15000 && data(i,1) <= 28500
        data(i,5) = data(i,3) + r2(((data(i,1)-18500)/500)+1);
        data(i,6) = r2(((data(i,1)-18500)/500)+1);
    elseif data(i,1) > 28500 && data(i,1) <= 63000
        data(i,5) = data(i,3) + r3(((data(i,1)-43500)/500)+1);
        data(i,6) = r3(((data(i,1)-43500)/500)+1);
    elseif data(i,1) > 63000
        data(i,5) = data(i,3) + r4(((data(i,1)-63700)/500)+1);
        %this adds the proper minimum elevation
```

```matlab
end %this adds the proper minimum elevation
```
\begin{verbatim}
data(i,6) = r4(((data(i,1)-63700)/500)+1);
end
end

figure(1)
plot(data(:,2), data(:,5), 'o')
\end{verbatim}
McGaheysville Analysis:

McGaheysville Cross Section Analysis

McGaheysville Block Analysis

Cross Section Histogram

Histogram of Terrace Heights
Cross Section Analysis Cross Sections:
McGaheysville Block Section Graphs:
Elkton Analysis Results:

Interpreted Terraces From Elkton Cross Section Analysis

Elkton Block Analysis

Elkton Cross Section Histogram
Cross Section Analysis Graphs:

Elkom Cross Section Analysis 1

Elkom Cross Section Analysis 2

Elkom Cross Section Analysis 3

Elkom Cross Section Analysis 4

Elkom Cross Section Analysis 5

Elkom Cross Section Analysis 6
Elkton Block Analysis
Luray Cross Section and Block Analysis Maps

Explanation

Block Sections

<table>
<thead>
<tr>
<th>elevation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1230</td>
</tr>
<tr>
<td></td>
<td>85</td>
</tr>
</tbody>
</table>

Cross Sections

<table>
<thead>
<tr>
<th>elevation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1230</td>
</tr>
<tr>
<td></td>
<td>85</td>
</tr>
</tbody>
</table>

¹
Luray Analysis Results:

**Luray Cross Section Analysis**

**Luray Block Section Analysis**

**Luray Cross Section Analysis Histogram**

**Luray Block Analysis Histogram**
Luray Cross Section Analysis:

- Luray Cross Section Analysis 1
- Luray Cross Section Analysis 2
- Luray Cross Section Analysis 3
- Luray Cross Section Analysis 4
- Luray Cross Section Analysis 5
- Luray Cross Section Analysis 6
Luray Block Analysis

Luray Block Analysis Cross Section 1

Luray Block Analysis Cross Section 2

Luray Block Analysis Cross Section 3

Luray Block Analysis Cross Section 4

Luray Block Analysis Cross Section 5

Luray Block Analysis Cross Section 6
Luray North Cross Section and Block Analysis

Legend
- DEM Blocks

Elevation
- Meters
  - 1230
  - 85

Legend
- Cross Sections

Elevation
- Meters
  - 1230
  - 85

0 2.5 5 7.5 10 15 7

0 1.25 2.5 5

Kilometers

Legend
- DEM Blocks

Elevation
- Meters
  - 1230
  - 85

Legend
- Cross Sections

Elevation
- Meters
  - 1230
  - 85

0 2.5 5 7.5 10 15 7

0 1.25 2.5 5

Kilometers
Luray North Analysis:

Luray North Cross Section Analysis

Luray North Block Analysis

Luray North Cross Section Histogram

Luray North Block Analysis Histogram
Luray North Cross Section Analysis:

Luray Cross Section Analysis 1

Luray Cross Section Analysis 2

Luray Cross Section Analysis 3

Luray Cross Section Analysis 4

Luray Cross Section Analysis 5

Luray Cross Section Analysis 6
Luray North Block Analysis
Appendix II: MATLAB Scripts for CRN Data:

This appendix contains the MATLAB scripts used to exponentially fit the curve and solve the inventory equation. First the concentration in g/cm\(^3\) and the depth of the sample in cm were made into a test_01.mat file. The depths were in column one, the concentrations in column two, and the errors in column three. Other information on the geographic position, elevation, density, surface erosion rate and others were loaded into the script “test_01_fit.” This script would load these variables and use functions that solved for the inventory method as well as the shifted exponential method. These scripts and functions are included in this appendix with short descriptions of their function.

T3 scripts:

**Test_02_fit:** This is the script used to iteratively solve for age and inheritance for the T3 profile. This script loads up or creates all the variables. All units are in g, cm – cm\(^3\) and atoms / gram quartz. This script then calls the CRN_profile_fit_02 which does the actual solving.

```matlab
% starter for T3 profile fitting
clear

% THIS IS FOR T3 data
load test_02

% variables
age_start=20000;   % time since deposition start
age_final=3000000; % final age
dage=2000;         % age change in each step
imax=((age_final-age_start)/dage)+1;
edot=4.8e-4;       % terrace edot
edot_start=1e-4;   % terrace edot
```

II 1
edot_final=10e-4; % final terrace edot_for_search dedot=0.5e-4; % step in edot emax=((edot_final-edot_start)/dedot)+1;

basin_edot=20e-4; % basin wide erosion rate cm/yr basin_edot_start=1e-4; % baseline erosion rate basin_edot_final=100e-4; % final basin edot dbasin_edot=2e-4; % step in basin edot bemax=((basin_edot_final-basin_edot_start)/dbasin_edot)+1;

lambda_Be=4.6e-7; % decay constant for 10Be 1/yr tau_Be=1/lambda_Be; % mean life for 10Be (years) rho=1.805806376; % terrace material density g/cm3 geog_lat_basin=38.3175239; % basin avg latitude h_basin=1000/3.28; % average basin elevation for correction

ggeog_lat=38.3175239; % geographic latitude h=321.07; % site elevation (m) dz=1; % depth increment (cm) z=(0:dz:500); % depth matrix (cm) mix_depth=151; % depth over which to average concentration z_avg=(0:1:mix_depth); % avg depth calculation P_Be=5.55; % surface production rate for spallagenic 10Be source?

CRN_profile_fit_02
CRN_Profile_fit_02: This profile solves using both shifted exponential. The best age, and best inheritance were save and a graph of this modeled profile was also created.

% CRN profile program that allows variation of surface erosion rate, age
% inheritance, density, etc. in a terrace deposit
% incorporates nucleon spallation, fast and slow muonogenic production
% with production systematics from Granger and Smith (2000)
% production rate scaling from Dunai (2000)

% This program is to be used with one of the jr fit files to call
% plotting details are provided from those programs

% VERSION FOR FITTING OF JR-01 PROFILE!!

clf

% regression results matrix setup
reg_results_1=(zeros(imax,bemax));
% regression results assuming expo profile, zero erosion, varying time and basin edot
reg_results_2=(zeros(imax,emax));
% regression results assuming basin edot, varying time and terrace rate
bedot_axis=(basin_edot_start:dbasin_edot:basin_edot_final);
age_axis=(age_start:dage:age_final);
edot_axis=(edot_start:dedot:edot_final);

% call the correction factor calculator
[cf_dunai,cf_lal,atmo_P]=corr_factor(geog_lat,h);
[cf_dunai_basin,cf_lal_basin,atmo_P_basin]=corr_factor(geog_lat_basin,h_basin);

% variables of CRN production - variable names from Granger/Smith (2000)

Y_Al=4.24e-3; % 26Al yield from stopped neg muons (no dim)
L3=4360; % atten " " for
fast muons (g/cm²)
B_A1=0.192; % 26Al yield from
stopped fast muons (no dim)
B_Be=0.026; % 10Be ""
Y_Be=5.6e-4; % 10Be yield from
stopped neg muons (no dim)
A1=170.6; % coefficient in
stopping rate eq (no dim)
A2=36.75; % "" (no dim)
L1=738.6; % atten coefficient
for neg muons (g/cm²)
L2=2688; % ""
atten_length=160 ; % spallation atten
length (g/cm²)
atmo_atten=240; % atmo attenuation
rate for muon (g/cm²)
%atmo_P=988; % avg
atmospheric pressure at sample site (for muon) g/cm²
muon_scale=exp((1013-atmo_P)/atmo_atten); % scaling
factor for muonogenic production (no dim)

% terms in Eq 6 in Granger and Smith (2000)
% FIRST LOOP WITH BASIN EDOT AND AGE VARIABLE - ASSUMPTION
% OF ZERO TERRACE EROSION?

reg_test_1_record=5e20;
reg_test_record=5e20;

for i=1:imax
    age=(age_start-dage)+dage*(i);
    for b=1:bemax
        basin_edot=(basin_edot_start-
dbasin_edot)+dbasin_edot*(b);
% inheritance
        if basin_edot==0
            term1Be_inh_1=0;
        else
            N_inh_1=P_Be*cf_lal*atten_length/(rho*basin_edot); % starting inheritance concentration
            term1Be_inh_1=N_inh_1*exp(-age/tau_Be);
        end
    end
% spallation
term2Be_spall_1 = Spallation(1,P_Be*cf_dunai, rho, atten_length, age, z, edot);

% negative muons
%[term3Be_negmuons_1, term4Be_negmuons_1] = negmuon(muon_scale, rho, age, z, edot);

% fast muons
%term5Be_fastmuons_1=(muon_scale*B_Be*exp(-rho*z/L3)/(1/tau_Be+rho*edot/L3))*(1-exp(-age*(1/tau_Be+rho*edot/L3)));

N_Be_1=term1Be_inh_1+term2Be_spall_1;
%+term3Be_negmuons_1+term4Be_negmuons_1+term5Be_fastmuons_1
;
reg_test_1=((test_01(1:7,2))'-N_Be_1((test_01(1:7,1))).^2)/N_Be_1((test_01(1:7,1)));
%[reg_test_1, xv, P] = CRNregress(test_01(1:7,2),N_Be_1((test_01(1:7,1))),
test_01(1:7,3));

if reg_test_1<reg_test_1_record % allow replacement of
N_Be_1 matrix when fit is better

    reg_test_1_record=reg_test_1;
    N_Be_1_best=N_Be_1;
    best_age_exp = age;
    best_inh_exp = N_inh_1;
end

figure(2)
colormap('default')
% compares measurements to straight exponential profile
results
clf
set(gcf,'Units','centimeters','Position',[1 1 15 15])

plot(test_01(:,2)/1000000,test_01(:,1),'ok', 'MarkerFaceColor','k', 'MarkerSize',8)
set(gca,'ydir','reverse','units','centimeters','Position',[2,2,9,12],
     'Color',[1 1 0.83],'FontSize',14,'FontName','times')
hold on
plot(N_Be_1_best/1000000,z,'k','LineWidth',2)
set(gca,'ylim',[0 500])
set(gca,'xlim',[0 5])
hold on
plot(N_Be_avg_plot,z_avg,'b','LineWidth',2)
hold on
plot(N_Be_inh_plot,z_avg,'r','LineWidth',2)
title('Comparison of JR-01 Grace Farm CRN to predicted profiles')
xlabel('^1^0Be concentration (10^6 atoms/g-qtz)','FontSize',18,'FontName','times')
ylabel('Depth (cm)','FontSize',18,'FontName','times')

**Spallation:** This is the function that created the Spallation growth of the modeled profile.

This was created to make the scripts cleaner.

```matlab
function [Nout] = Spallation(cf, P, rho, a_L, t, z, e)
%% Function Spallation made by Jonathan Garber 02/01/10
%% Spallation inputs parameteres that govern the productions of Be10 by
%% spallation along a vertical soil profil
%% inputs: cf = correction Factor, P = Production rate at surface atoms/g, rho =
%% soil density g/cm^3, a_L = attenuation length kg/m^2, t = age of deposit yr, Z = depth of
%% deposit m, e = surface erosion rate of deposit
%% output: Nout = number of 10 Be created by spallation at depth Z in t
%% years
tau_Be = 1/(4.6e-7);

Nout=((cf*P*exp(-rho*z/a_L))/(1/tau_Be+rho*e/a_L))*(1-exp(-t*(1/tau_Be+rho*e/a_L)));```
T4 Scripts:

**Test_01_fit:** This script iteratively increased the surface erosion rate and solved for T4 using both inventory methods. The total amount of sediment denuded was calculated and plotted against the erosion rate. This was in order to pick out the maximum age of the deposit.

% starter for T4 Garber inventory method
clear

% THIS IS FOR T4
load test_02

% variables
age_start=50000;                % time since deposition start
age_final=2000000;              % final age
dage=5000;                      % age change in each step
imax=((age_final-age_start)/dage)+1;
edotlist=0:1e-5:3e-4;          %creates a range of erosion rates in cm/yr
edot_start=0e-9;                % terrace edot cm/yr
edot_final=0.5e-9;              % final terrace edot for search
dedot=0.5e-9;                   % step in edot
eemax=((edot_final-edot_start)/dedot)+1;
edotsize = size(edotlist);      %this sets the number of iterations by number of terrace erosion rates

%these are the shells to get the model results at different terrace erosion rates
%expshell = zeros(1,edotsize(2));
%inhexpshell = zeros(1,edotsize(2));
%fitinvshell = zeros(1,edotsize(2));
%fit_inv_inh = zeros(1,edotsize(2));

%this is the loop that runs iterations of the different terrace erosion rates
basin_edot=20e-4;
basin_edot_start=1e-4; % basin wide erosion rate cm/yr
basin_edot_final=100e-4; % final "" for search
dbasin_edot=2e-4; % step in basin edot
bemax=((basin_edot_final-basin_edot_start)/dbasin_edot)+1;

lambda_Be=4.6e-7; % decay constant for 10Be 1/yr
tau_Be=1/lambda_Be; % mean life for 10Be (years)
rho=1.874831399; % terrace material density g/cm3
Zstar = 160/rho; % Zstar for the productions
geog_lat_basin=38.3191192; % basin avg latitude
h_basin=1000/3.28; % average basin elevation for correction
atten_length = 160;
geog_lat=38.3191192; % geographic latitude
h=325; % site elevation (m)
dz=1; % depth increment (cm)
z=(0:dz:500); % depth matrix (cm)
mix_depth=90; % depth (cm) over which to average concentration
z_avg=(0:1:mix_depth); % avg depth calculation
mixdat = 3; %number of points down for mixing
datnum = 7; %total number of data points
P_Be=5.55; % surface production rate for spallagenic 10Be source?
[cf_dunai,cf_lal,atmo_P]=corr_factor(geog_lat,h);

for p = 1:edotsize(1,2)
    edot = edotlist(p);
    %CRN_profile_fit_03

    %this uses Jonathan Garbers equation for the Inventory method
    [T(p,1:datnum-mixdat), inh(p,1:datnum-mixdat),s] =
InventoryCRN(test_01, mixdat, mix_depth, datnum, P_Be * cf_dunai, Zstar, edot, lambda_Be);

[T2(p, 1:datnum-mixdat), inh2(p, 1:datnum-mixdat), s2] = InventoryCRN2(test_01, mixdat, mix_depth, datnum, P_Be * cf_dunai, Zstar, edot, lambda_Be);

%this function fits a curve to the exponential part of the profile for a
%given inheritance. It can take in arrays of inheritance and output all of
%them
[b_age(p, 1:datnum-mixdat), best_ch(p, 1:datnum-mixdat)] = ExponentialwInh(test_01, inh(p, 1:datnum-mixdat), P_Be * cf_dunai, rho, atten_length, age_start, age_final, dage, mixdat, datnum, edot, lambda_Be);

[b_age2(p, 1:datnum-mixdat), best_ch2(p, 1:datnum-mixdat)] = ExponentialwInh(test_01, inh2(p, 1:datnum-mixdat), P_Be * cf_dunai, rho, atten_length, age_start, age_final, dage, mixdat, datnum, edot, lambda_Be);

%This section does the exponential check assuming that only samples A and B
%are in the exponential profile so it only solves the profile using the
%bottom two samples
mixdat2 = 5;
[b_age_a(p, 1:datnum-mixdat2), best_ch(p, 1:datnum-mixdat2)] = ExponentialwInh(test_01, inh(p, 3:4), P_Be * cf_dunai, rho, atten_length, age_start, age_final, dage, mixdat2, datnum, edot, lambda_Be);

[b_age2_a(p, 1:datnum-mixdat2), best_ch2(p, 1:datnum-mixdat2)] = ExponentialwInh(test_01, inh2(p, 3:4), P_Be * cf_dunai, rho, atten_length, age_start, age_final, dage, mixdat2, datnum, edot, lambda_Be);

%fitinvshell(p, 1:datnum - mixdat) = T';
%inhexpshell(p, 1:datnum - mixdat) = inh';
%expshell(p, 1:datnum - mixdat) = b_age';
%fit_inv_inh(1,p) = inv_inh_f;

%These average the ages from the bottom two inventory samples in order
%to create the total denuded sediment
\[
\text{ave\_age}(p) = \text{mean}(T2(p, \text{datnum-1-mixdat:datnum-mixdat}))
\]
\[
\text{ave\_age2}(p) = \text{mean}(T(p, \text{datnum-1-mixdat:datnum-mixdat}))
\]
\[
\text{stdevage}(p) = \text{std}(\text{stdT})
\]
\[
\text{mean\_inh}(p) = \text{mean}(\text{inh}(p, :))
\]

% here the total denude sediment is calculated fromt the age and %incision rate
\[
\text{H\_loss}\_a(p) = \text{ave\_age}(p)\times\text{edot};
\]
\[
\text{H\_loss}(p) = \text{mean}(T2(p, \text{datnum-1-mixdat:datnum-}
\text{mixdat}))\times\text{edot};
\]
\[
\text{H\_loss2}(p) = \text{mean}(T(p, \text{datnum-1-mixdat:datnum-
mixdat}))\times\text{edot};
\]

end

% plots the ages from inventory method on the right and the exponential % check on the left
figure(5)
clf
subplot(1,2,1)
plot(edotlist, ave\_age)
hold on
plot(edotlist, ave\_age2)

subplot(1,2,2)
plot(edotlist, H\_loss)
hold on
plot(edotlist, H\_loss2)

% this figure plots the calculated inheritances from the inventory method
figure(6)
plot(edotlist, mean\_inh)
Test_01_fit_A: Once the maximum age and Erosion rate are found with the first script. This script plots the modeled profiles for the two ranges of ages.

% starter for JR-01 Garber inventory method
clear

% THIS IS FOR JR-01
load test_02

% variables
age_start=50000; % time since deposition start
age_final=2000000; % final age
dage=5000; % age change in each step
imax=((age_final-age_start)/dage)+1;
edotlist=0:1e-5:3e-4; % creates a range of erosion rates in cm/yr
edot_start=0e-9; % terrace edot cm/yr
edot_final=0.5e-9; % final terrace edot for search
dedot=0.5e-9; % step in edot
emax=((edot_final-edot_start)/dedot)+1;
edotsize = size(edotlist); % this sets the number of iterations by number of terrace erosion rates

% these are the shells to get the model results at different terrace erosion rates
%expshell = zeros(1,edotsize(2));
%inhexpshell = zeros(1,edotsize(2));
%fitinvshell = zeros(1,edotsize(2));
%fit_inv_inh = zeros(1,edotsize(2));

% this is the loop that runs iterations of the different terrace erosion rates
basin_edot=20e-4;
basin_edot_start=1e-4; % basin wide erosion rate cm/yr
basin_edot_final=100e-4; % final "" for search
dbasin_edot=2e-4; % step in basin edot
bemax=(((basin_edot_final-basin_edot_start)/dbasin_edot)+1;

lambda_Be=4.6e-7; \quad \% \text{decay constant for } ^{10}\text{Be} \text{1/yr}

tau_Be=1/lambda_Be; \quad \% \text{mean life for } ^{10}\text{Be} \text{(years)}

rho=1.874831399; \quad \% \text{terrace material density g/cm3}

Zstar = 160/rho; \quad \% \text{Zstar for the productions}

geog_lat_basin=38.3191192; \quad \% \text{basin avg latitude}

h_basin=1000/3.28; \quad \% \text{average basin elevation for correction}

atten_length = 160;

gcog_lat=38.3191192; \quad \% \text{geographic latitude}

h=325; \quad \% \text{site elevation (m)}

dz=1; \quad \% \text{depth increment (cm)}

z=(0:dz:200); \quad \% \text{depth matrix (cm)}

mix_depth=90; \quad \% \text{depth (cm) over which to average concentration}

z_avg=(0:1:mix_depth); \quad \% \text{avg depth calculation}

mixdat = 3; \quad \% \text{number of points down for mixing}

datnum = 7; \quad \% \text{total number of data points}

P_Be=5.55; \quad \% \text{surface production rate for spallagenic } ^{10}\text{Be} \text{source?}

[cf_dunai,cf_lal,atmo_P]=corr_factor(geog_lat,h);

\%for p = 1:edotsize(1,2)
\quad p = 1;
\quad edot =2.5e-4;
\%CRN_profile_fit_03

%this uses Jonathan Garbers equation for the Inventory method
[T(p,1:datnum-mixdat), inh(p,1:datnum-mixdat),s] = InventoryCRN(test_01, mixdat, mix_depth, datnum, P_Be*cf_dunai, Zstar, edot, lambda_Be);

%this integrates to depth Zd using the Granger (200) formula
[T2(p,1:datnum-mixdat), inh2(p,1:datnum-mixdat),s2] = InventoryCRN2(test_01, mixdat, mix_depth, datnum, P_Be*cf_dunai, Zstar, edot, lambda_Be);
% this function fits a curve to the exponential part of the profile for a given inheritance. It can take in arrays of inheritance and output all of them
[b_age(p, 1:datnum-mixdat), best_chi(p, 1:datnum-mixdat)] = ExponentialwInh(test_01, inh(p,1:datnum-mixdat), P_Be*cf_dunai, rho, atten_length, age_start, age_final, dage, mixdat, datnum, edot, lambda_Be);

[b_age2(p, 1:datnum-mixdat), best_chi2(p, 1:datnum-mixdat)] = ExponentialwInh(test_01, inh2(p,1:datnum-mixdat), P_Be*cf_dunai, rho, atten_length, age_start, age_final, dage, mixdat, datnum, edot, lambda_Be);

% This section does the exponential check assuming that only samples A and B are in the exponential profile so it only solves the profile using the bottom two samples
mixdat2=5;
[b_age_a(p, 1:datnum-mixdat2), best_chi(p, 1:datnum-mixdat2)] = ExponentialwInh(test_01, inh(p,3:4), P_Be*cf_dunai, rho, atten_length, age_start, age_final, dage, mixdat2, datnum, edot, lambda_Be);

[b_age2_a(p, 1:datnum-mixdat2), best_chi2(p, 1:datnum-mixdat2)] = ExponentialwInh(test_01, inh2(p,3:4), P_Be*cf_dunai, rho, atten_length, age_start, age_final, dage, mixdat2, datnum, edot, lambda_Be);

avT = [mean(T(p,1:datnum-mixdat)), mean(b_age(p, 1:datnum-mixdat))];
stdT = [std(T(p,1:datnum-mixdat)), std(b_age(p, 1:datnum-mixdat))];

% these average the ages from the bottom two profile points
ave_age(p) = mean(T2(p, datnum-1-mixdat:datnum-mixdat));
ave_age2(p) = mean(T(p, datnum-1-mixdat:datnum-mixdat));
stdevage(p) = std(stdT);
mean_inh(p) = mean(inh2(p, datnum-1-mixdat:datnum-mixdat));
mixdat));
    mean_inh2(p) = mean(inh2(p, datnum-1-mixdat:datnum-mixdat));
    H_loss(p) = ave_age(p)*edot;

%end
lambda = lambda_Be +edot*rho/atten_length;

N0 = (P_Be*cf_dunai/lambda)*(exp(-z*rho/atten_length))*(1-exp(-lambda*ave_age(p)))+mean_inh(p)*exp(-lambda_Be*ave_age(p));

s_plot = ones(1,mix_depth)*s/mix_depth;
inh_plot = ones(1,201)*mean_inh(p)/100000;

%plots the ages from inventory method on the right and the
%exponential
%check on the left
figure(1)
clf
plot(N0, z, 'LineWidth', 3)
set(gca,'ydir','reverse','units','centimeters','Position',[2,2,9,12],...
'Color',[1 1 0.83],'FontSize',14,'FontName','times')
hold on
plot(test_01(:,2), test_01(:,1), 'o')
hold on
plot(inh_plot*100000, z,'r', 'LineWidth', 3)
hold on
plot(s_plot, 1:mix_depth, 'g', 'LineWidth', 3)
hold on

InventoryCRN: This function solves for the age using the inventory method and integrating to depth Zm while using a deeper point Nd to substitute for inheritance. This can take in an array of Nd values and output an array of age and inh values.

function [T, Inh,S] = InventoryCRN(prof, mixdat, mixdepth, datnum, P, Zs, e, lam)

%%%Function InventoryCRN calculates the CRN age and inheritance of a Profile
%%%using the Method of Perg et al (2001)
%% this is a different method from gregs to calculate an
inventory method

**Inputs:** prof - the profile matrix with row one as depth
and row two as
concentration, mixdat is the the number of points the
mixing profile, mixdepth is the depth to which soil mixing
evidence was observed, Datnum is the number of data points
in the profile,
%, and P is the production rate of CRNs corrected to
latitude and, e is
the terrace erosion rate, lam is the decay constant for
the CRN

**Outputs:** T = age from each point below mixing depth, Inh
- inheritance
from each point below mixing depth
CRNs in atoms/ gram
for a profile using each undisturbed point in the
profile assumes no
surface erosion
written by Jonathan Garber 03/26/10

S = 0;
s = 0;
lambda = lam+ e/Zs;
T = zeros(1,datnum - (mixdat));
Inh = zeros(1,datnum - (mixdat));

S = mean(prof(1:mixdat,2)*mixdepth);  %this averages the
concentrations in the mixing zone and multiplies them by
the mix depth

Zd = prof(mixdat+1:datnum,1)';
Nd = prof(mixdat+1:datnum,2)';

%this part solves for time and inheritance for each
%point in the profile

T = log((S-Nd.*mixdepth)./(P/lambda*(Zs*(exp(-
mixdepth/Zs)-1)+mixdepth*exp(-Zd./Zs))+1)/-lambda;

Inh = (Nd - P/lambda*(1-exp(-lambda.*T)).*exp(-
Zd./Zs)).*exp(lam.*T);
InventoryCRN2: This function is similar to the one above but instead of integrating to depth Zm it integrates all the way to the point in the mixing profile. It numerically integrates using the trapz function in MATLAB.

```matlab
function [T, Inh,S] = InventoryCRN(prof, mixdat, mixdepth, datnum, P, Zs, e, lam)

%%Function InventoryCRN calculates the CRN age and inheritance of a Profile
%%using the Method of Perg et al (2001)
%% this is a different method from gregs to calculate an inventory method
%% this uses the trapz function to numerically calculate integral and then
%% uses the equation in Garber 2010
%%Inputs: prof - the profile matrix with row one as depth and row two as concentration, mixdat is the the number of points the mixing profile, mixdepth is the depth to which soil mixing evidence was observed, Datnum is the number of data points in the profile,
%%, and P is the production rate of CRNs corrected to latitude and, e is
%%the terrace erosion rate, lam is the decay constant for the CRN
%%elevation
%%outputs: T = age from each point below mixing depth, Inh - inheritance
%%from each point below mixing depth
%%CRNs in atoms/ gram
%% for a profile using each undisturbed point in the profile assumes no
%% surface erosion
%% written by Jonathan Garber 03/26/10

S = 0;
s = 0;
lambda = lam+ e/Zs;
T = zeros(1,datnum - (mixdat));
Inh = zeros(1,datnum - (mixdat));
```
l = 1;       %easy way to count up the S array
for j = mixdat+1:datnum    %this finds the inventory by
    %integrating the mixed points over trapezoids
S(l) = 25*(trapz(prof(1:j,2))+prof(1,2));      %This
    %integrates the function to Nd using trapezoids
l = l+1;
end

%S = mean(prof(1:mixdat,2)*mixdepth);       %this averages
    %the concentrations in the mixing zone and multiplies them
    %by the mix depth
Zd = prof(mixdat+1:datnum,1)';
Nd = prof(mixdat+1:datnum,2)';

%this part solves for time and inheritance for each
    %point in the profile
%for i = mixdat+1:datnum

    T = log((S-Nd.*Zd)./(P/lambda*(Zs.*(exp(-Zd./Zs)-1)+Zd.*exp(-Zd./Zs))))+1)/-lambda;
    Inh = (Nd - P/lambda*(1-exp(-lambda.*T))).*exp(-Zd./Zs)).*exp(lam.*T);

%end

ExponentialwInh: This function solves iteratively for age
    with a given inheritance. This can take in an array of
    inheritances and solve for multiple ages.

function [b_age, Highest_X] = ExponentialwInh(prof, Inh, P_Be, rho, atten_length, minage, maxage, dage, mixdat, datnum, edot, lambda)
% function exponential with curve solves an exponential
    % curve for the
    % unmixed zone of a mixed method, using the Inheritance
    % found from the
    % Inventory Method
% inputs; prof- depths and CRN concentrations column 1 is
depths 2 is
% concentrations, Inh - inheritance found from Inventory
Method, P_Be -
% production rate, rho - soil density, atten_length is the
attenuation of
spallation production, minage is the minimum age, max age is the
maximum age both in years, d age is the age increments.

num = size(Inh); % this sets the number of iterations
to run for the different inheritances
pmax = num(2);

imax = (maxage-minage)/dage;
z = 1:prof(datnum,1);

zmax = size(z);
zm = zmax(1,2);

for p = 1:pmax
  reg_test_1_record=5e20;
  reg_test_record=5e20;
  
  best_age_exp = 0;
  % this is the loop that solves iteratively for the curve
  for i = 1:imax
    age=(minage-dage)+dage*(i);
    decay = -lambda*age;
    
    term1Be_inh_1 = Inh(1,p)*exp(decay);
    % spallation
    term2Be_spall_1 = Spallation(1,P_Be, rho, atten_length,
age, z, edot);
    
    % negative muons
    %[term3Be_negmuons_1, term4Be_negmuons_1] =
    negmuon(muon_scale, rho, age, z, edot);
    
    % fast muons
    %term5Be_fastmuons_1=(muon_scale*B_Be*exp(-
rho*z/L3)/(1/tau_Be+rho*edot/L3))*(1-exp(-
age*(1/tau_Be+rho*edot/L3)));
    
    N_Be_1=term1Be_inh_1+term2Be_spall_1;
    %+term3Be_negmuons_1+term4Be_negmuons_1+term5Be_fastmuons_1
  
  end

end
reg_test_1=(((prof(mixdat+1:datnum,2))' - N_Be_1((prof(mixdat+1:datnum,1)))).^2)/N_Be_1((prof(mixdat+1:datnum,1))));

if reg_test_1<reg_test_1_record  % allow replacement of N_Be_1 matrix when fit is better
    reg_test_1_record=reg_test_1;
    N_Be_1_best=N_Be_1;
    best_age_exp = age;
end
end
b_age(p) = best_age_exp;
Highest_X(p) = reg_test_1_record;
%bestprof(p,1:zm);
end