New constraints on the late Cenozoic incision history of the New River, Virginia

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Abstract

The New River crosses the core of the ancient, tectonically quiescent Appalachian orogen as it follows its course through North Carolina, Virginia, and West Virginia. It is ideally situated to record the changes in geomorphic process rates that occur in the Appalachians as a response to late Cenozoic climate variations. Active erosion features on resistant bedrock that floors the river at prominent knickpoints demonstrate that the river is currently incising toward base level. However, large packages of alluvial fill and fluvial terraces cut into this fill record an incision history for the river that includes several periods of stalled downcutting and aggradation. Cosmogenic ^{10}Be exposure dating, aided by mapping and sedimentological examination of terrace deposits, is used to constrain the timing of events in this history. Fill-cut and strath terraces at elevations 10, 20, and 50 m above the modern river yield cosmogenic exposure ages of approximately 130, 610, and 955 ka, respectively, but uncertainties on these ages are not well-constrained. This translates to a long-term average incision rate of 43 m/my, which is comparable to rates measured elsewhere in the Appalachians. During specific intervals over the last 1 Ma, however, the New River's incision rate reached 97 m/my. Fluctuations between aggradation and rapid incision appear to be related to late Cenozoic climate variations, though uncertainties in modeled ages preclude direct correlation of these fluctuations to specific climate change events. Erosion rates on higher alluvial deposits adjacent to the river are estimated from ^{10}Be concentrations; these rates are very low, about 2 m/my or less. This demonstrates a disequilibrium in the modern landscape, with river incision greatly outpacing erosion from nearby landforms.

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Chapter 1: Introduction and Background

1.1 Introduction

The roles of tectonics and climate in long-term landscape evolution have recently been the focus of much debate (e.g. Raymo et al., 1988; Molnar and England, 1990). Climate is certainly an important factor in landscape evolution and shares feedbacks with tectonic processes (e.g. Beaumont et al., 1992; Willett, 1999), but the relative importance of climate and tectonics in dictating geomorphic evolution and topographic character are not well understood. For example, a landscape's response to climate change is difficult to predict (Whipple et al., 1999). Ancient, "dead" mountain belts such as the Appalachians are ideal for studying the role of climate change in landscape evolution, because in most cases climate change is the only modification to erosional and depositional systems.

In the absence of tectonic activity, processes of erosion dictate the rate and form of the evolution of the landscape. Since major rivers are the sole outlet for sediment removed from the tectonically quiescent landscape, the erosional efficacy of these rivers applies a dominant control over the evolution of the landscape in ancient orogens (Anhert, 1970). The capacity for erosion and sediment transport of a major river is affected by a large number of external influences, such as climate, bedrock lithology and structure, tectonic activity, sediment supply as determined by rates of hillslope erosion, global base level change, and regional drainage reorganization. Complex feedbacks exist between many of these factors, causing difficulties in predicting how any one factor affects the fluvial system (e.g. Blum and Törnqvist, 2000).

To determine how climate change affects a river in a given setting, it is necessary to construct a chronology of the erosional and depositional events and associated rates in the river's incision history. A river's incision history reflects local, regional, and often global changes in climate because such changes affect the river's stream power, base level, and sediment supply (e.g. Bull, 1979; Blum and Törnqvist, 2000). This history can be compared to independent climate records to assess the correlation between events in the river's history and, for example, glacial-interglacial cyclicity. A detailed study of an Appalachian fluvial system and its deposits thus helps to quantify the roles of climate change in the landscape evolution of an ancient orogen.

Construction of an accurate incision history for a fluvial system requires assigning ages to deposits left by the river that record the change in the river's position through time. Many workers have attempted to assign ages to Appalachian river deposits based on relative age indicators such as degrees of soil development and fluvial terrace morphology (e.g. Colman, 1982; Mills and Wagner, 1985). However, until the past decade there was no absolute age data by which to calibrate these relative indicators, as most deposits are well beyond the age range of radiocarbon dating techniques. Recent advances in cosmogenic isotope dating, especially ^{10}Be and ^{26}Al exposure dating, allow ages to be assigned to formerly undatable river deposits such as ancient alluvial terraces (e.g. Hancock et al., 1999; Perg et al., 2001). These ages can be used to calibrate relative age indicators in associated deposits, allowing reconstruction of a river's incision history even where absolute ages cannot be obtained.

1.2 The New River: Background and general geologic setting

The New River is the only major river that drains to the Gulf of Mexico while cutting through the Blue Ridge, Valley and Ridge, and Cumberland (Allegheny) Plateau physiogeologic provinces of the Appalachians. Its headwaters lie in the crystalline rocks of the North Carolina Blue Ridge, and it drains approximately 19,500 square kilometers and drops 1360 meters in elevation as it passes from North Carolina through Virginia and West Virginia before joining the Ohio River (Fig. 1-1). In the Valley and Ridge province, the river meanders across Cambrian and Ordovician carbonate rocks flooring wide valleys before entering more tightly folded and uptilted Cambrian through Mississippian sandstones, shales, and carbonate rocks of the central Valley and Ridge. Near the Virginia-West Virginia border, the New River enters the Cumberland Plateau province, incising through flat-lying packages of Mississippian and Pennsylvanian sandstones and shales. The New River Gorge is carved into these rocks, a 300 m deep canyon that stands as a testament to the incisive power of the New River. Just below the gorge, the New River joins the Gauley River and its name changes to the Kanawha River for the rest of its length to the Ohio.

The New River's longitudinal profile (Fig. 1-2) reflects the drastic changes in lithology that the river crosses. Prominent knickpoints exist where the river emerges from the crystalline Blue Ridge rocks into the Valley and Ridge carbonates and where it

crosses the most resistant Valley and Ridge units such as the Tuscarora Sandstone. The river becomes drastically steeper upon entering the New River Gorge, then assumes a very shallow gradient for its last 100 km before entering the Ohio.

1.3 Study area and scientific problem

In the Virginia Valley and Ridge, the New River has deposited impressive flights of unpaired, fill-cut and strath terraces between the city of Radford and the town of Pearisburg (Fig. 1-3). These alluvial terraces are extensively preserved at elevations ranging from a few meters to over 100 meters above modern river level (AMRL), with remnants of terrace deposits preserved even higher and many kilometers from the river's present course. The better-preserved terraces are excellent candidates for recording the late Cenozoic incision history of the New River. The few dated New River deposits are along this reach of the river and indicate a complex history of aggradation and incision (Granger et al., 1997). However, more than a tentative correlation between terrace suites along the New River has not been possible without numerous absolute ages (Mills and Wagner, 1985; Granger, et al., 1997).

Because the New River terraces are unpaired and laterally discontinuous, and many have been obscured in form due to dissolution of the carbonate bedrock on which they rest, it is impossible to correlate individual terraces downstream (Mills and Wagner, 1985). It is therefore unknown whether disjointed terraces at similar elevations formed contemporaneously. If so, then specific elevations with extensive terraces indicate a few major fill events between periods of relatively continuous downcutting. If not, the river's history may be characterized by multiple small aggradational events interspersed with discontinuous incision events. It is unknown whether the incision and aggradation events that formed the terrace deposits are related to glacial or to interglacial times, or to other, non-glacial climate fluctuations. If periods of stability or aggradation are coincident with glacial periods, a sediment supply control over the river's regime is suggested. If glacial times are coincident with incision, however, a base level control over the river's regime is implied. This problem has implications for the dominant controls over denudation in ancient orogens such as the Appalachians.

This area also affords an opportunity to examine differences in erosion rate and form as the New River crosses different lithologies. Downstream of Radford, the river

crosses from erodible carbonate rocks through a narrow belt of folded, resistant sedimentary rocks including the ridge-forming Tuscarora Sandstone. Where the river crosses the Tuscarora there exists a knickpoint and band of riffles known as Big Falls, a partially bedrock-floored reach where large ribs of bedrock emerge from the river and active bedrock incision features are abundant. A few kilometers farther downstream, the river passes back onto carbonate rocks. Terrace deposits are common both above and below the knickpoint, so a comparison of incision history between the two areas should be possible based on the record of that history in the terraces.

1.4 Previous studies

Harris et al. (1980) described soil development and mineral weathering in a sequence of four progressively higher terrace soils ranging from 1 to 80 meters above the New River. Generally, resistant minerals such as micas and feldspars decreased while clays such as kaolinite and hydroxy interlayered vermiculite increased with increasing elevation. This demonstrated that soil weathering characteristics could be used as relative age indicators in New River terrace deposits. Mills (1981) logged soils in 20 backhoe trenches on terraces between Radford and Pearisburg, increasing the catalog of soils data available for these terraces.

Based on the distribution of high-level gravel deposits in the Valley and Ridge, Houser (1980) inferred that three major tributaries of the New River were captured by the James and Roanoke rivers during the Neogene. Bartholomew and Mills (1991) studied similar gravels and proposed that the New River's course upstream of Big Falls formerly lay several kilometers further to the east. The river migrated to its present course as a response to structurally-controlled erosional exposure of more and less resistant lithologies. Their mapping suggested that the river established its present course by the time it was about 125 meters above its current level. They found no evidence that the New River's course below Big Falls changed significantly since a time when the river was 275 meters above its current elevation.

Mills and Wagner (1985) mapped New River terrace deposits in the Valley and Ridge and noted that certain elevations had a much greater area of terraces than others (Fig. 1-4). They inferred that these modal elevations represent times of aggradation or floodplain widening, while elevations with few preserved terraces represent periods of

incision in the river's history. This was corroborated by further soil mineral data, which implied that terraces of similar elevation were of similar age. Further mapping by Mills (1986) showed that the modal terrace elevations upstream and downstream of Big Falls were offset (Fig. 1-4). He proposed that this offset may represent uplift, and consequently higher incision, in the downstream area related to tectonic tilt associated with the Giles County Seismic Zone.

The first absolute dating of New River deposits was performed by Granger et al. (1997). This study used a cosmogenic burial technique (differential decay of ^{10}Be and ^{26}Al) to date river sediments emplaced in limestone caves along the river between Big Falls and Pearisburg. The results from four caves 25-35 m above the river and one cave 12 m above the river imply a mean downcutting rate of 27.3 ± 4.5 m/my over the past 1.5 Ma. The limited range of elevations above the river of dated cave deposits and broad age scatter from different caves of similar elevations precludes a more detailed reconstruction of the river's incision history from these results. Moreover, burial of sediment in a cave is not indicative of a change in the river's behavior, so these ages cannot be correlated to other dated deposits or to climate records. This study also dated cobbles buried in terrace alluvium downstream of Big Falls at 1.5 ± 0.27 and 2.0 ± 0.29 Ma for the shallower and deeper samples, respectively. However, these are apparent burial ages that have been reduced by an unknown period of exposure near the surface of this terrace. The oldest, deepest of these can be considered as a minimum bound on the time since deposition of this alluvium.

Figure 1-1: The New River, important tributaries, dams and date constructed, and regional physiogeography. Maximum glacial advance lies subparallel to Ohio R., just beyond the northwest corner of this map.

Figure 1-2: Longitudinal profile of the New River from the confluence of the North and South forks in NC to Bluestone Dam, WV. Note steepenings of profile at the transition between the Blue Ridge and Valley and Ridge and irregularities in the Valley and Ridge related to specific lithologies. Vertical exaggeration is ~280x.

Figure 1-3: General distribution of terrace deposits in the study area. Modern floodplain and terraces lower than 25 m AMRL are not shown, but are ubiquitous along the river throughout this area. Based on data presented by Mills (1986).

Figure 1-4: Plot of terrace area vs. elevation AMRL.
 Note offset modes above (Radford) and below Big Falls (Pearisburg).
 Based on data presented by Mills (1986).

Chapter 2: Characterizing the New River and its Deposits

2.1 Introduction

In order to correctly interpret ages obtained by dating river deposits, it is necessary to understand the relationships between these deposits and the river system. The stratigraphy and arrangement of fill terraces on bedrock straths, coupled with relative age indicators such as soil development, can be used to construct a sequence of deposition and erosion events. This serves as a framework by which sample sites for cosmogenic dating can be chosen and by which the resulting dates can be interpreted. In this study, New River terraces were mapped both from airphotos and in the field. Soils on different terraces were examined for indicators of relative age, degree of surface erosion, and changes in erosional provenance, as these might affect the apparent exposure age of the terrace. To better understand the stratigraphy and depositional history of New River alluvial deposits, core from a thick sequence of terrace fill was logged in detail. Further, micromorphology of quartz sand from terrace soils was examined as a potential relative age indicator for terrace deposits. The New River was surveyed for depth changes and the locations of riffles and knickpoints, and bedrock incision features were examined for the purpose of further understanding the mechanisms by which the river incises through the landscape.

2.2 Examination of New River terraces

Topographic maps were used in conjunction with maps of surficial deposits by Mills (1986) to locate terraces for detailed examination. Upstream of the knickpoint at Big Falls, Virginia Tech's Kentland Farm Agricultural Research Station at Whitethorne, VA, provided easy access to a well-preserved flight of terraces at elevations ranging from 128 m down to the modern floodplain about 1 m above the modern river (Fig. 2-1). Downstream of the knickpoint, fewer terraces are well-preserved and land access is more difficult to obtain, so examination was reconnaissance in nature. However, a core through 40 m of terrace fill collected for a previous study from a downstream terrace near Pembroke, VA (Law and Robinson, 1999) was logged in detail.

2.2.1 Mapping of Kentland Farm terraces

A detailed map of the terraces at the Kentland Farm site was generated from stereo airphotos and topographic maps of the area in conjunction with field exploration (Fig. 2-2). Sub-horizontal surfaces exhibiting very low relief in the stereo airphotos and on the USGS 1:24,000 topographic quadrangle were delineated as terrace treads. High (>70 m AMRL) terrace remnants required field checking to be identified as such. Most high hills in the area are composed of cobble-rich alluvial soils. Delineation of these extends to areas that are thought to represent the remnants of the terrace tread, allowing for a few meters of vertical deformation. Elevations of terraces were measured with a pressure-calibrated handheld GPS receiver and were checked against topographic maps. These elevations are representative of the elevation of each terrace, as all terraces exhibited up to 3 meters of relief. Field mapping of the locations of bedrock exposures in drainages and on steep sideslopes constrained the elevations of the bedrock straths beneath the terrace fill (Fig. 2-3).

This flight of terraces appears to consist of a thick fill sequence stacked on bedrock straths (Fig. 2-4). Bedrock was not found more than 60 m above modern river level (AMRL) in the Kentland Farm area, yet the highest terrace is 128 m AMRL. This implies that 70 m or more of fill was deposited here and subsequently cut into to form the upper terraces.

The upper fill-cut terraces show a more dissected morphology than the low straths. The highest levels are preserved as remnant hills, with little flat tread area remaining. The most extensively preserved terrace level is at or near 50 m AMRL, but its morphology varies widely from gently sloping treads cut into large hills to small remnant hills to broad karstified areas. The 50 m level appears to consist dominantly of fill-cut terrace but is locally shallowly underlain by a strath; this strath is in most parts of the area the highest occurrence of bedrock above the river. This, and the extent of the 50 m terrace, imply that the river may have spent an extended time creating a floodplain at this elevation.

2.2.2 Profiling of terrace soils

Several workers have described the chronosequence formed in soils on New River terraces (e.g. Harris et al, 1980). It was important in the context of this study to be able to correlate specific soil characteristics with terrace ages determined by cosmogenic exposure dating. Soil profiles were thus logged at each cosmogenic sampling site (Figs. 2-1, 2-2) to a depth of over 2 meters. Profiling was performed in collaboration with Dr. John Galbraith of Virginia Tech's Department of Crop and Soil Environmental Sciences; standard soil survey procedures and terminology were used to describe the soils at each site. The detailed profile descriptions are included as Appendix A.

At the four Kentland Farm cosmogenic exposure dating excavations on terraces 128 m, 50 m, 20 m, and 10 m AMRL, a clear chronosequence is described by the soil profiles (Figs. 2-5 to 2-8). Soil taxonomy ranges from Hapludults and Hapludalfs on lower terraces to kaolinitic Paleudults and Kandiodults on high, old terraces. B horizon clay content and redness increase consistently with elevation; B horizon textures ranged from loam and gravelly loam on lower terraces to clay and sandy clay on higher terraces, and colors ranged from 10YR 4/6 (dark yellowish brown) on lower terraces to 10R 3/6 (dark red) on the highest terraces. B horizon color, depth of development, and clay percentage thus appear to be functions of the age of each terrace.

All of the profiles became generally coarser and more cobble-rich with depth, implying that the upper layers of each deposit consist of overbank fines deposited as the terrace was abandoned. This suggests that little erosion has taken place from these surfaces since abandonment, as deep erosion would tend to leave the channel gravels at the surface. Some remnant hills in the area are capped by dense gravel with no upper layer of fines; these hills are interpreted to represent localities of deeper erosion. The 50 and 10 m soils are dominantly fine-textured to 250 cm depth, and the 20 m deposit is distinctly layered, fine soil overlying dense gravel sitting directly on shale saprolite. Mica flakes, locally found in modern overbank deposits, are abundant in the 10 m soil, common in the 20 m soil, and are present in soils up to 80 m AMRL at proportions less than 1% of the sand fraction. It is to be expected that mica will weather to clays with time, and its presence in older soils suggests a high initial concentration of mica, again supporting the idea that overbank fines are preserved at the CRN sampling sites.

The Pearisburg cosmogenic sampling site's soil was similar to that of the highest

Kentland Farm terrace, a Rhodic Kandiudult with 10R 3/6 (dark red) color and sandy clay texture in the B horizons (Fig. 2-9). This is curious as the site is about 50 m lower in elevation above the river than the high Kentland Farm site. This suggests either that soil development reaches a plateau at an age younger than that of the Pearisburg terrace or that the terraces are similar in age and have changed elevation relative to each other since deposition. Cosmogenic ages from these two deposits will resolve this issue, hopefully allowing a correlation between terrace age and soil development that can be applied to many other similar deposits in the area to further constrain the New River's incision history.

2.2.3 Provenance of terrace deposits

Changes in the provenance of the material making up terrace deposits can reflect changes in the upstream organization of the drainage network. To determine the provenance of the material making up the New River terraces at Kentland Farm, cobbles were collected at random from the waste piles of four cosmogenic exposure dating excavations made in the 128 m, 50 m, 20 m, and 10 m AMRL terraces at Kentland Farm. Between 39 and 59 cobbles were collected from each sampled terrace, broken with a hammer, and logged by lithology. They were then compared with hand samples of lithologic units from the Valley and Ridge and Blue Ridge physiogeologic provinces.

The results of the clast counts are summarized in Fig. 2-10. There does not appear to be a significant change in cobble provenance between the four terraces. The three higher terraces all had more than 85% cobbles with a Blue Ridge provenance. Though the 10 m terrace has a slightly lower percentage (70%) of Blue Ridge cobbles than the higher terraces, mica flakes are abundant in the soil of this terrace. The only major upstream sources of mica are the metamorphic rocks of the Blue Ridge. The Kentland Farm terrace deposits all reflect a dominant Blue Ridge provenance, which is to be expected as the portion of the Valley and Ridge upstream of this location contains only limestones, shales, and other nonresistant lithologies.

Provenance of terrace deposits downstream of Big Falls was not evaluated quantitatively. However, field observations from a cosmogenic sampling site and a drill core through downstream terrace material suggest that these terraces are dominated (~75%) by Valley and Ridge sandstones and quartzites with a smaller component

(~25%) of Blue Ridge quartzites. A number of tributaries that drain Valley and Ridge uplands, such as Little Stony Creek, enter the New River between Big Falls and the Pembroke and Pearisburg sites and likely contribute much of the Valley and Ridge material found in these terraces. This implies that terrace material is dominated by the resistant rocks in abundance in the drainage network in close upstream proximity to the terrace deposit.

2.2.4 Log of core through terrace fill

Two boreholes were drilled and cores extracted in 1997 from a set of deformed New River terrace deposits near Pembroke, VA (Fig. 2-1). The deformation is suspected to be the result of deep karst collapse, forming a complex graben structure at the core of a broad, shallow anticline in the terrace deposits (Law and Robinson, 1998). One borehole was drilled on each limb of the anticline. Only the first of these was logged.

The core was logged at the centimeter scale, with attention to small changes in material, color, and texture that might represent changes in depositional conditions. Munsell colors were recorded for each interval, but were often measured in the dry condition because the core had been stored for six years prior to logging. Grain size distribution was estimated by eye and feel. The complete text of the log is found in Appendix B. A summary of this log is presented in Fig. 2-11.

Three main depositional periods are interpreted to have occurred during the formation of this sequence. The lower, bouldery sequence is thought to represent a time during which the riverbed was the location of deposition. This is followed by a thick package of fine sands and silty clays, interpreted to represent deposition away from the river in the floodplain. Above this is another mixed cobbly and bouldery sequence, once again representing riverbed deposition.

Three horizons of pale clays are interpreted to be remnants of paleosols, all found within the floodplain depositional sequence. Absent, however, is evidence of deep soil development, such as that described from the Kentland Farm terraces, at any point within this sequence. Any incision events that may have occurred during the floodplain sequence's formation were likely very minor with little time passed before deposition resumed.

This is corroborated by two Be/Al burial dates from pebble beds within this

terrace sequence. The sampled pebbles were taken from trenches near the boreholes, one sample from near the top of the first bed deposition sequence and the other near the base of the second bed deposition sequence, separated by about 20 m of terrace stratigraphy. The lower sample yielded a burial age of 2.0 ± 0.29 Ma, while the upper was dated at 1.5 ± 0.27 Ma (Granger et al., 1997; Law and Robinson, 1998). The ~500 ka time difference between deposition of these units implies a mean deposition rate of 40 m/my and precludes any extended hiatus in deposition during which a deep soil could develop.

2.3 River surveys

To better understand the modern erosional system, specifically where and how the New River incises the landscape, several surveys were conducted using a variety of tools. Airphotos were taken to locate riffles and other unusual reaches of the river. Bedrock features were examined at Big Falls to ascertain how resistant bedrock is removed from the river's channel. A preliminary depth survey was conducted by canoe to understand the relationship between the river's course, profile, and depth.

2.3.1 Airphoto survey

A light aircraft was flown along the New River for the purpose of taking oblique aerial photographs of river terraces and the river itself in the study area. During this flight, many unmapped riffles were located and photographed (Fig. 2-12). These riffles represent locations where the river expends the most energy as it passes through the landscape. Most riffles are caused by ribs of resistant bedrock protruding from the riverbed; these riffles are locations where the river is incising through the lithologies that support the local topography. The largest of these are at Big Falls and Narrows where the river crosses the Tuscarora sandstone, and are correlated with knickpoints.

Some riffles appear to be caused by debris that entered the river in the form of landslides or alluvial fans from tributaries. This debris causes the river to expend energy that could otherwise be used to incise through bedrock, implying that the rate of incision is somewhat self-regulating: increased incision steepens slopes and promotes introduction of material into the river by colluvial and alluvial processes, which

requires extra energy from the river for removal and slows incision.

2.3.2 Bedrock incision features

The resistant Tuscarora sandstone is crossed by the New River at Big Falls. Here, the river is actively incising into bedrock by a number of mechanisms. Ribs of sandstone emerging from the riverbed exhibit classic abrasion features such as potholing and fluting (Fig. 2-13). Because the bedrock has a steep upstream dip and a strike nearly perpendicular to the river, small channels form along the exposed ends of bedrock horizons. These channels contain flutes oriented orthogonally to the river's overall flow, indicating flow along the strike of the bedrock (Fig. 2-13 b). While potholes vary widely in size, with diameters from 2 to 50 cm, flutes are more uniform, generally ranging from 7 to 30 cm in length and 4 to 18 cm in width.

In addition to abrasion features, quarrying features are also observed at Big Falls. Many rectilinear voids exist where the river has plucked out large blocks of sandstone (Fig. 2-13 c). Though quarrying is generally regarded as more efficient than abrasion (e.g. Whipple et al., 2000), it is likely that the two processes interact strongly at Big Falls. Abrasion along and between bedding planes reduces the size of joint blocks until they are small enough to be quarried during a high flow event (Fig. 2-14).

The reach of the river around Big Falls contains hundreds of smaller riffles (Fig 2-15), all formed where resistant horizons cross the river, but most of these are continually submerged and are beveled off a few centimeters above the riverbed. It is thus the largest, meter-thick ribs of Tuscarora sandstone that appear to place the strongest limits on the rate at which the New River can incise. Some of these most prominent ribs are only covered by water during high flow events, and hence are only actively eroded a few times a year. During events such as these, boulders can be heard tumbling along the riverbed, supporting the idea that bedload abrasion and impact quarrying are important in the erosion of the resistant bedrock. Most of the New River's erosional work on these strong units is done in a few high flow events each year, when bedload is most active and the bedrock ribs are submerged. Measured 35 km upstream at Radford, VA, the flood needed to submerge all of the bedrock at Big Falls is about 30,000 cubic feet per second; the annual-series recurrence of this flood is 1.4 years (Fig. 2-16). Assuming a linear relation between drainage area and discharge, discharge at Big

Falls is expected to be ~10% higher than that at the gage site. It is possible that these largest ribs are not removed by top-down erosion but by undercutting. Deep holes have been scoured in many locations immediately downstream of, in some cases underneath, the upstream-dipping ribs (Fig. 2-14).

Preliminary results using a total station to create a contour map and 3D model of the bedrock outcrops and riverbed of Big Falls indicate a complex set of rock protrusions and scour holes in the falls themselves, even though the riverbed immediately upstream of the falls is very uniform. This indicates that erosion at the falls requires very turbulent water and represents a large expenditure of energy on the part of the river.

2.3.3 Depth and surface profiling

To examine depth changes in the New River for correlation with bedrock, river slope, and river geometry, a canoe and weighted line were used to survey a 10 km reach of river between Whitethorne and Big Falls. River depths were surprisingly uniform throughout the entire reach, approximately 2 meters except very near the shore. The depth only changed when entering the riffle-rich 1.5 km reach above Big Falls; here, the depth was extremely shallow (0-50 cm) over resistant bedrock ribs in the riverbed, deepening to approximately 1 m between ribs. The river's width increases in the reach immediately above the falls to accommodate the shallower depths. The riverbed is dominantly mud or fine gravel alluvium upstream of the 1.5 km of riffles. Within this reach it is bedrock or coarse gravel. The uniformity of river depth and accumulation of mud between major riffles suggest that much of the New River's energy is expended at these major riffles. This in turn implies that bedrock exposed at major riffles limits the rate at which the river incises.

2.4 Micromorphology of quartz sand from terrace soils

Quartz sand residing in the subsoil becomes etched by acids in the soil, eventually developing a rough surface texture dominated by pits and grooves. This texture is sometimes apparent upon visual inspection and is very clearly seen by scanning electron microscopy (SEM). Using SEM, Howard et al. (1995) described a sequence of

alluvial deposits across Virginia in which a progression in the degree of etching was observed to correlate with age of the deposit. The youngest deposits had sand with minimal etching, while sand grains in the oldest deposits were very strongly etched. This study was entirely qualitative, using relative ages and degrees of etching.

Since the suite of New River terraces in the Kentland Farm area show a clear age progression based on elevation and soil development, SEM examination of quartz grain micromorphology from these deposits might reveal a useful relative age indicator that can be calibrated against cosmogenic exposure dates. Quartz micromorphology might then be used to approximate the ages of similar New River terraces in other reaches of the river.

2.4.1 Procedure

Nine soil samples were collected from terrace surfaces at Kentland Farm ranging in elevation from 20 to 128 m above modern river level. Samples were taken from existing soil pits and, on terraces where no pit existed, from small shovel pits. Existing exposures were cut back to expose fresh material, and new pits were dug to a depth of approximately 70 cm, so samples could be taken from the B horizon of the soil on each terrace. Samples were wet sieved for the very fine and medium sand fractions. The sand was cleaned in a solution of sodium hexametaphosphate to remove clay films from the grains. Each sample of sand was dried and randomized by shaking and several hundred grains from each were mounted on carbon tape. The sand was then carbon coated by vaporization to an approximate thickness of 250 Å and examined by SEM. Within each sample, several dozen randomly selected grains were photographed at 570x magnification to examine surface texture in detail and at lower magnification so overall grain shape could be observed. Each grain was verified to be quartz by electron dispersive spectrometry.

To determine if the etching on sand grains in the soil was relict on grains in decomposing sandstone cobbles, an effect of the weathering of these cobbles, or due to chelation in the soil, three samples of sand were taken from a decomposing, friable sandstone cobble embedded in the wall of a soils pit on the highest terrace. The 8 cm. diameter cobble was sliced in half vertically by a shovel during excavation, then scraped to expose fresh material before sampling. The cobble exhibited a clear

progression of weathering from the outside in, with a mm-thick dark red weathering rind then a ~2-cm thick gradational rind from pink to pale yellow at the center. Several grams of sand were collected from each of three positions: the outer 1 cm of the cobble in the weathering rind, approximately 2.5 cm from the outer edge, and in the very center of the cobble. Samples were prepared and inspected by SEM using the same procedures as the soil sand samples.

2.4.2 Results

Inspection of grains from five different terrace levels did not reveal a clear correlation between age of the terrace and degree of quartz etching. Some higher, presumably older deposits contained abundant fresh-looking grains, while sand from younger deposits was commonly strongly etched (Fig. 2-17). The degree of etching across several samples of sand grains from each terrace was so variable that no strong time progression across multiple terraces can be described.

The samples taken from the weathered cobble also showed no clear trend. The inner, middle, and outer samples all contained grains with a mixture of fresh-looking surfaces and deeply pitted, etched surfaces (Fig. 2-18).

2.4.3 Conclusions

It is likely that local variations in weathering process and rate within the study area destroyed any clear time progression of quartz etching. For example, younger deposits that showed strong etching had soils that were more aquic than those of older deposits, so chelation of quartz grains may have been enhanced by frequently high water tables. Older deposits contained sandstone cobbles so weathered that they crumble to sand with only light handling; these may be a source of fresher sand grains in these deposits. A systematic examination of samples from a statistically significant number of these cobbles would be needed to determine whether the etching of grains progresses inward into the cobbles with weathering or if the surface features on grains within cobbles are relict and related to the diagenesis of the cobble's source lithology. Many terraces in the Kentland Farm area are strongly dissected and in close proximity to each other, so some mixing of materials by erosion is also possible.

Because no clear correlation was made between quartz micromorphology and terrace age, no attempt was made to quantify the degree of etching of the examined quartz grains. This technique was not useful as a relative age indicator in the context of this study. It may be useful on a broader scale, however, such as that described by Howard et al. (1995).

Figure 2-1: Topography, important features, and location of sampling sites in the primary study area. Based on USGS 1/3-second National Elevation Dataset and 1992 National Land Cover Dataset.

Figure 2-2:
Kentland Farm area
terraces, types, and
elevation above
modern river level

Figure 2-3: Topographic map of Kentland Farm area. Triangles represent locations where bedrock outcrops from the alluvial soil that covers most surfaces in the area. Based on 7.5" USGS DRG, Radford North quadrangle. Contour interval is 20 ft.

Figure 2-4: Schematic profile of terraces and elevations AMRL at Kentland Farm. Exact elevation of bedrock under thick upper fill package is unknown.

Figure 2-5: Kentland Farm 10 m terrace soil. Depths in photomosaic correspond roughly to those in profile; scale and angle vary slightly across mosaic. USDA soil series name and series general description are listed above profile.

Figure 2-6: Kentland Farm 20 m terrace soil. Depths in photomosaic correspond roughly to those in profile; scale and angle vary slightly across mosaic. USDA soil series name and series general description are listed

Figure 2-7: Kentland Farm 50 m terrace soil. Depths in photomosaic correspond roughly to those in profile; scale and angle vary slightly across mosaic. USDA soil series name and series general description are listed above profile.

Figure 2-8: Kentland Farm 128 m terrace soil. Depths in photomosaic correspond roughly to those in profile; scale and angle vary slightly across mosaic. USDA soil series name and series general description are listed above profile.

Figure 2-9: Pearisburg 80 m terrace soil. Depths in photo correspond roughly to those in profile. USDA soil series name and series general description are listed above profile.

Figure 2-10: Provenance of cobbles in Kentland Farm terrace alluvium

Figure 2-11: Summary log of core through Pembroke terrace alluvium. Colors represent approximate dominant material color. Top of core is at ~55 m AMRL. Thicknesses are vertical, not stratigraphic; dip of bedding at drill site is ~10°.

Figure 2-12: Locations and oblique airphotos of riffles and other New River features in the study area.

Figure 2-13: Bedrock incision features at Big Falls. Ruler is 30 cm. A - Large pothole. B - Fluting on large rib. Note flutes oriented parallel to bedding strike and perpendicular to flow. C - Plucking scars. Note polishing and rounding of scar by abrasion since quarrying occurred.

Figure 2-14: Summary of erosion forms and mechanisms at Big Falls

Figure 2-15: Part of the 1.5 km reach upstream of Big Falls containing hundreds of small riffles where resistant sandstone horizons underlie the New River

Figure 2-16: Flood stages at Big Falls (A) and flood recurrence by discharge (B). Discharge reported as measured at Radford, 35 km upstream; discharge at Big Falls is estimated to be ~10% higher than at the gage site. Bedrock ribs are fully submerged at ~30,000 cfs. The annual-series recurrence of this flood is 1.4 years.

A

30 May, 2003
2,000 cfs

8 June, 2003
14,000 cfs

3 July, 2003
28,000 cfs

Figure 2-17: SEM photomicrographs of etched quartz grains. From 128m terrace (A & B) and 20m terrace (C & D).

Figure 2-18: SEM photomicrographs of sand samples from positions A, B, and C on fresh cut face of friable cobble. Note variety of surface textures at all sampled positions. Magnification of micrographs is ~150x.

Chapter 3: Cosmogenic Exposure Dating

3.1 Introduction

Assigning absolute ages to surficial deposits such as river terraces has always proven troublesome, particularly when dealing with deposits older than the useful range of radiocarbon techniques. Geomorphologists have long relied on relative age indicators such as soil development calibrated by stratigraphic relationships to fossil assemblages, volcanic ash beds, or other traditionally datable material (Nishiizumi et al., 1993). However, most surficial deposits are not situated where stratigraphic age control can be applied, and relative age indicators are seldom useful outside of a particular climatic, geographic or geologic context. Recently, cosmogenic radionuclides (CRNs) have been widely employed to determine absolute ages and erosion rates in a variety of geomorphic settings.

The basis of cosmogenic radionuclide dating is the production of specific isotopes in host material by exposure to cosmic radiation. For example, ^{10}Be and ^{26}Al are produced in quartz exposed at the surface of the earth by interaction with cosmic neutrons and muons. Over the past two decades technological advances in mass spectrometry and nuclear physics have made it possible to measure the concentrations of these CRNs in soil and rock material collected from geomorphic surfaces (e.g. Bierman, 1994). Several methods exist to take advantage of CRNs, including burial dating by differential decay of cosmogenic isotopes and long-term erosion rate determination by CRN concentrations in sediment (Bierman, 1994). The method relevant to this study is cosmogenic exposure dating, which allows determination of the amount of time a particular deposit such as a river terrace has been exposed at the Earth's surface. With a known rate of CRN production and measured concentration of the isotope in a surface deposit, an age can be derived for the deposit.

By measuring ^{10}Be in quartz, deposits exposed for tens of thousands to several million years can be dated; this makes the technique extremely useful for Quaternary geologists. The maximum usable age of a particular CRN is approximately 3-4 times the radioactive half-life of the isotope in use; after this time, the rates of production and decay approach equilibrium, and CRN concentration ceases to increase measurably with time (Gillespie and Bierman, 1995). Rates of CRN production are calibrated based

on measurements from surfaces of known age (e.g. Lal, 1991; Clark et al., 1995). Production rates are dependent on local characteristics of the geomagnetic field, and so must be scaled for use at a particular altitude and geographic latitude (Lal, 1991; Dunai, 2000).

Sampling a range of depths from each site in a deposit such as a river terrace allows construction of a depth vs. CRN concentration profile. The ideal profile, produced in a constantly exposed, undisturbed deposit with no surface erosion, is exponential in shape, with the maximum concentration at the surface (Fig. 3-1). Because CRN production becomes exponentially slower with depth, the minimum concentration, deep in the deposit, represents the initial concentration of the cosmogenic isotope in the deposited materials. This helps constrain the concentration of CRNs inherited from erosion and transport (Hancock et al., 1999). Bioturbation and soil forming processes can mix part or all of a profile over the time of exposure; this mixing must be accounted for when calculating the age of a deposit (Perg et al., 2001). Since some New River terraces have formed deep, well-mixed soils over their long exposure history, a method modified from that of Perg et al. (2001) is employed, which uses the measured profile to calculate a total inventory of CRNs across the mixed part of the profile. The amount of time needed to produce this inventory is the exposure age of the terrace.

3.2 Location of Sampling Sites

Terrace sampling sites were chosen at elevations with a significant amount of terrace area so that the resulting ages would represent the most significant periods of floodplain and terrace development. Sites were located on mostly flat terrace treads away from eroding sideslopes and obvious sources of deposition, as erosion lowers the apparent cosmogenic age of the surface and deposition can raise or lower the apparent age depending on the source of the deposited sediments. Sites were preferentially located where the upper horizons of the soil were fine-textured, not cobbly, as gravel-capped surfaces suggest that all overbank fines deposited as the terrace was abandoned had been eroded since deposition. In turn, this suggests a site with a significant amount of surface erosion.

Terraces that had been deformed by karst processes were also avoided. Many

terraces resting on carbonate rock in the Valley and Ridge are pitted by sinkholes and exhibit an irregular surface due to differential lowering by carbonate dissolution. Terraces situated over non-carbonate rock were preferred; over carbonate rock, only terraces with broad, uniform treads were considered.

On each terrace chosen, a shovel or a soil auger was used to sample the soil at several potential sites, allowing a site to be chosen with soil characteristics (e.g. color, texture, clay content) that were representative of the terrace as a whole. This helped to screen for sites that had been modified after deposition in a way that was not apparent upon examination of the surface.

At the Kentland Farm site, four sites were chosen at 10, 20, 50, and 128 meters above the river (Fig. 2-2). These elevations included the highest and lowest preserved terraces in the area. Downstream, in the town of Pearisburg, one site was chosen at 80 meters above the river. The soil characteristics at each site are described in section 2.2.2. Other characteristics of each site are outlined in Figs. 3-2 through 3-6.

In addition to the terrace soil sampling sites, three samples were collected along a Tuscarora sandstone bedrock rib protruding from the river at Big Falls (Fig. 3-7). Sites were chosen to be horizontal so as to avoid an inclination correction of CRN production rates. The upper surface of the rib exhibited two meter-square areas where plucking had not recently occurred. These areas were separated by a small scour depression, but were away from active abrasion features such as flutes and potholes, and so had been exposed longer than more quickly eroding parts of the rib. Moreover, they were at opposite ends of the rib (~3 m apart) and at the same elevation above the river, so should provide some measure of the variability of the CRN concentration along the bedrock ribs. The third bedrock sample consisted of a cobble-sized joint block that had been exposed by plucking long ago (as evidenced by its abraded corners) and was only weakly held in its place. Presumably, this block was ripe for plucking by the river, so its exposure age should provide a reasonable estimate of the recurrence interval of plucking at this site.

3.3 Sampling Methods

3.3.1 Terrace excavation and trench preparation

To sample a depth profile in terrace material, a backhoe was used to excavate a trench at each sampling site. Trenches were approximately 3 m deep, 1.5 meters wide, and 7 m long, with three sub-vertical sides and one end sloped gently down to allow easy access to the bottom. A measuring tape was hung from a shovel handle or pole laid across the top of the trench, and nails were placed at 25 cm intervals in a vertical row. The pole was then moved along the trench about a meter and another row of nails placed, until several meters had been marked out horizontally at each depth interval. For the Pearisburg trench, one vertical row was placed in this manner, then a laser level was used to locate points at each depth to mark horizontal rows. Both methods provided satisfactory results; the laser level method is preferred because it is slightly more efficient and is insensitive to local perturbations in the ground surface at the rim of the trench.

3.3.2 Soil sampling

Once the horizontal lines had been established, a flat scraper was used to clean the trench wall by removing the outer millimeters of soil between the nails along each line, cleaning to at least 15 cm above and below the line. A trowel was then used to etch a horizontal line into the soil between the nails to serve as a guide. Using a trowel, soil was dug from along each horizontal line and placed in a gallon-sized plastic zipper bag (Fig. 3-8). Usually two people performed the sampling, one to dig and the other to hold the bag. Material was removed from an interval no more than 5 cm above or below the line; care was used so no material from higher up the wall fell into the bag. Each line was dug no more than about 5 cm into the wall to avoid inadvertently digging down or up from the sampling depth. The goal of sampling was to obtain at least 100-200 g of quartz sand in the 250-500 μ fraction; to be sure of collecting enough, two gallon bags were filled with soil from each sampled interval. Sampling was started at the lowest interval and proceeded upwards so as to avoid contaminating lower intervals with material from higher ones. Digging implements were cleaned between sampling

intervals.

Excepting only the 128 m Kentland Farm trench, samples were collected at every 25 cm depth interval. The 128 m terrace was sampled at 50 cm intervals because it was unknown at the time if the samples would be too old and saturated with ^{10}Be to be of use, and because sampling proceeded very slowly due to the hardness of the kaolinitic clayey soil. A complete list of all trenches and depths sampled is shown in Table 3-1.

3.3.3 Sand cone density test

Because the rate of cosmogenic nuclide production at depth is dependent on the density of the overlying material, a standard sand cone density test was performed on the soil at 50 cm depth intervals at each site. At each interval to be tested, a flat bench large enough to fit the sand cone baseplate was cut into the exit ramp of each trench. Sand weight differences were determined to the nearest ounce using a small postal scale in the field, calibrated by an electronic balance in the laboratory. Excavated soil was removed in plastic bags to the laboratory and weighed on the electronic balance. Soil density data for each site is included as Appendix C.

3.3.4 Big Falls bedrock sampling

To sample the quartzite rib at Big Falls, a rock hammer and a small sledge were used to flake off the very hard rock. Usually, an existing weakness in the rock, such as a small crack, was exploited to maximize the efficiency of the sampling process. For the first two sites, sample material was collected from an area on the rib surface of no more than 25 cm², and not more than 1 cm deep into the rock (Fig. 3-9a). Again, two people were involved in sampling; one hammered at the rock while the other held the sample bag, collected flakes as they were removed, and blocked rock flakes from flying off into the river. The elevation of each sample site from the riverbed was measured and recorded. The third bedrock sample, a cobble-sized joint block, was easily pried loose with a hammer (Fig. 3-9b).

3.3.5 Topographic blockage survey

The rate of cosmogenic nuclide production at a site is dependent on exposure to the sky at that site. At sites surrounded by significant topography, production is reduced by an amount proportional to the percentage of sky obstructed. Influx of cosmic radiation decreases rapidly with angular distance from the zenith, so low topography has only a minor shielding effect, while production at sites with a large amount of nearby relief can be reduced by more than 10%.

At all sites, a Brunton compass was used to record the azimuth and elevation of surrounding topographic features that partially obstruct the sky. This data was input to a spreadsheet that calculates a correction factor for scaling of local CRN production rates based on integrated ray flux from obstructed quadrants of the sky (G. Hancock, pers. comm.).

3.4 Target Preparation

The goal of the preparation procedure used in this study was to isolate the cosmogenic isotopes ^{10}Be and ^{26}Al from the raw soil or rock material collected in the sample. Target preparation was performed at the Department of Geology at the College of William and Mary in Williamsburg, Virginia, in collaboration with Gregory Hancock. The procedure followed was designed for the William and Mary CRN Lab. The procedure to obtain purified quartz from soil or rock sample is modified after that of Kohl and Nishiizumi (1992). The chemical isolation of the cosmogenic isotopes is based on the procedures of Nishiizumi et al. (1984).

Due to limitations in the number of analyses we could perform, targets were not prepared from all samples that were collected; generally, every other sample in a depth profile was prepared. A detailed list of samples prepared from each site is shown in Table 3-1.

3.4.1 Physical preparation

The majority of samples collected in this study consisted of soil and regolith containing quartz sand, so no crushing was necessary to obtain the ideal starting grain

size of 250-500 μ . The three quartzite samples collected at Big Falls, however, had to be crushed to the appropriate size.

Cobble-sized fragments were first broken with a rock hammer on a clean surface to fragments of 5-10 cm length. Fragments were placed in an electric jaw crusher and crushed to a size of 0.5-2 cm. This process was repeated until approximately 500 g of crushed rock had been obtained from each sample or until all rock from each sample was consumed. Before crushing and between samples all surfaces of the jaw crusher were cleaned with brushes and wiped down with acetone to remove any potential contaminants.

An electric disc mill was used to grind the crushed rock to its final size of 250-500 μ . This required several passes through the mill for each sample, incrementally reducing the mill exit opening size from a few mm to $\sim$ 0.5 mm. The crushed material was passed through a 500 μ and a 250 μ sieve after each pass to avoid further crushing of grains of the correct size; the >500 μ fraction was then fed back into the mill. Once all of the >500 μ fraction was gone or about 200 g of 250-500 μ sample had been collected, the sample was placed in a clean plastic zipper bag. As with the jaw crusher, all surfaces of the disc mill were cleaned with brushes and wiped with acetone to remove contaminants before grinding each sample.

Soil samples collected from terrace material were dominated by clays, which had to be removed from the sample. Up to $\sim$ 1500 g of soil sample was placed in a clean 5 gallon bucket, and large pebbles, roots, and other debris were removed by hand. Approximately 1.5 L of 2.5% sodium hexametaphosphate solution and 7.5 L of deionized or tapwater were added to the bucket and the mixture was stirred with a PVC stirring rod for several minutes to thoroughly suspend the sample. The stirring rod was also used to tamp the sample against the bottom of the bucket to break up any clumps of clay. The bucket of sample was allowed to sit for several hours to allow the clays to thoroughly deflocculate.

Each bucket of sample was subsequently poured through a stack of sieves: 4 mm, 500 μ , and 250 μ . Water and finger pressure were used to break any remaining clay clumps so they would pass each sieve. The >4 mm fraction consisted mostly of gravel and was discarded. The 500 μ to 4 mm fraction was retained in case the yield of 250-500 μ sand was insufficient; the larger fraction can be crushed to this size if necessary. This did not prove necessary for any of the samples used in this study. The deflocculation

and sieving steps were repeated until at least 100 g of 250-500 μ sand had been obtained from each sample.

Sieves were cleaned between samples by sonication in a small ultrasonic tank for several minutes to remove the majority of stuck grains, then by drying and tapping to remove any remaining grains. Buckets and stirring rods were rinsed with deionized water and wiped thoroughly with large Kimwipes between samples.

Heavy liquids separation can be used at this point to separate quartz from other minerals in the 250-500 μ fraction. This is only necessary if quartz does not dominate the sample. Most samples used in this study yielded sand that consisted of more than 90% quartz, so a heavy liquids separation was not necessary.

3.4.2 Chemical preparation

About 100 g of each sample was measured out for use in the rest of the procedure. At each weighing step, the mass of each sample was recorded on a sample preparation sheet. Extra sample was stored in clean plastic zipper bags. The remaining steps were performed on batches of eight samples.

Samples that retained a significant amount of organic matter after sieving were leached overnight in 1 mL 30% hydrogen peroxide and 2 mL deionized water per gram of sample. Leaching was performed under a fume hood. This step is important as organics will react with H_2O_2 and HCl to form abundant bubbles that will not burst, creating a foamy mess in the HCl leach step. After leaching, each sample was rinsed with deionized water several times, oven dried, and reweighed.

To remove any remaining clay films and clumps, as well as iron oxides and carbonate minerals, each sample was transferred to a 1000 mL beaker with 4.5 mL water and 4.5 mL 12.1N HCl per gram of sample. 1 mL H_2O_2 was added to each beaker to dissolve any remaining organics. Beakers were placed on hot plates under a fume hood, covered with watch glasses, and left to leach for 10 to 12 hours at a temperature just below boiling. After leaching, the acid was allowed to cool, then poured off into a plastic waste acid barrel; each sample was rinsed several times with Millipore filtered water (MilliQ water), transferred to a smaller beaker, dried, and reweighed.

Leaching the samples in HF serves two purposes. First, most remaining non-quartz mineral grains, including clays, micas, and feldspars, are dissolved and removed

from the sample. Second, the outer surfaces of the quartz sand grains become etched, removing meteoric ^{10}Be adsorbed to the grain surfaces from exposure to rain and groundwater. Calibration curves produced by Kohl and Nishiizumi (1992) demonstrate that two sonicated 1% HF/1% HNO_3 leaches are sufficient to remove meteoric ^{10}Be ; removal of non-quartz mineral matter may require additional leaches. Nitric acid is added to the leach to prevent adherence of mostly dissolved fine material to the quartz grains. Sonication circulates the acid solution through the sample, greatly increasing leaching efficiency (Kohl and Nishiizumi, 1992).

For the first leach, 1 L of acid was used for each 7.5 g of sample; each sample was split into ~28 g portions, each portion placed in a 4 L Nalgene plastic bottle. To each bottle was added 3660 mL of MilliQ water, 83 mL 49% HF, and 54 mL 69% nitric acid; this resulted in 3.8 L of 1% HF/1% HNO_3 solution in each sample bottle. Bottles were submerged in an ultrasonic water bath at 80 C for 12 hours. After leaching, the acid was allowed to cool, then decanted into a plastic waste acid drum; each sample was rinsed several times in MilliQ water, transferred back to its small beaker, dried, and reweighed.

Subsequent leaches of each sample were performed in the same manner, except 15 g sample were added per L of acid. The quartzite samples started as very pure quartz, and so were leached twice only to remove meteoric ^{10}Be . Soil samples needed to be leached 3 to 4 times to remove all additional minerals; some samples contained large amounts of white mica, and so were subjected to a double-strength leach. After each leach, each sample was dried, reweighed, and its mass recorded on its sample sheet. Once samples were free of non-quartz minerals (by visual inspection under a microscope, > 99.5% pure), they were transferred to labeled glass bottles.

3.4.3 Sample spiking and dissolution

A small but unquantifiable amount of sample is unavoidably lost in container transfers during the dissolution, fuming, column separation, and target packing steps of the isotope isolation procedure. This means a final measurement of ^{10}Be will underrepresent the amount of the isotope in the original mass of quartz. To avoid this problem, the sample of quartz with known mass is spiked with a known quantity of ^9Be , allowing determination of a ratio of ^9Be to sample mass. The Accelerator Mass

Spectrometry (AMS) facility then measures and reports the $^{10}\text{Be}/^9\text{Be}$ ratio in the target; from this the original ^{10}Be to sample ratio can be calculated.

The ^9Be carrier solution is created from beryl from a deep mine so that it has an initial ^{10}Be concentration that is 2 or more orders of magnitude less than that expected in the sample. The carrier used had a concentration of 1005 ± 3 mg $^9\text{Be}/\text{L}$. Ideally, the $^{10}\text{Be}/^9\text{Be}$ ratio in the final target will be about 5×10^{-13} , with a standard spike volume of 0.5 mL. To produce this ratio, the amount of quartz sand sample used was adjusted for estimated concentration based on depth and estimated age. Sample sizes ranged from about 20 g for shallow or old samples to about 40 g for deeper or younger samples.

Each sample was measured out using weigh boats on an analytical balance to a precision of 0.1 mg, the mass recorded on the sample's processing sheet. The sample was then placed in a 500 mL Teflon jar. The carrier bottle was placed on the analytical balance, tared, then ~ 0.5 mL was withdrawn using a 1 mL pipette and added to the sand sample. The mass of the withdrawn carrier was recorded to a precision of 0.1 mg, along with the carrier batch number and concentration.

Although ^{26}Al targets were not prepared, samples were also spiked with 1 mL ^{27}Al carrier with a concentration of 999 ± 3 mg/L so targets can easily be prepared for Al analysis from the same samples. The method for spiking with ^{27}Al was exactly the same as that for ^9Be .

3.4.4 Quartz dissolution and removal

To remove SiO_2 from the sample, 5 mL HF and 0.3 mL HNO_3 per gram of sample were added to the teflon jars under a fume hood. The jars were capped and placed on a hot plate at a temperature of about 90 C for 4-8 hours (until all quartz was completely dissolved). The lids were then removed and the samples were allowed to fume away on the hot plate and under a heat lamp. The fuming removes Si from the sample as SiF_6 . The fuming was repeated by adding approximately 25 mL of 3:1 HF: HNO_3 to resuspend the sample, then allowing it to fume until approximately 10 mL remained. The samples were then transferred into 25 mL platinum crucibles and allowed to fume until dry.

Once the samples had dried down in the platinum crucibles, they were transferred to a higher-temperature hot plate and 10 mL sulfuric acid was added to

each. This was allowed to fume away at 400 C under the heat lamp, removing F⁻ from the sample. This fuming was repeated twice, only with 5 mL H₂SO₄ per sample on the second and third fumings. After the third fuming, each sample was resuspended in 25 mL 1.2N HCl plus a drop of H₂O₂ and left on low heat for a short time to ensure complete dissolution. It was then transferred to a tared 50 mL centrifuge tube and sample mass recorded. Platinum crucibles and Teflon jars were acid washed in a solution of HNO₃.

Some very resistant minerals, such as zircon, do not dissolve in the HF and sulfuric fumings. Any mineral grains remaining in the bottom of the crucibles were rinsed several times with MilliQ water and transferred to small plastic bottles for preservation. Zircons retrieved from these samples may be used to reveal provenance of the sediments at the cosmogenic sampling sites.

3.4.5 ICPMS split and column separation

To analyze the samples for ²⁶Al, a split must be taken for Inductively Coupled Plasma Mass Spectrometry (ICPMS) measurement of total ²⁷Al present in the sample and spike. This split was taken by removing 1 mL of sample from each centrifuge tube with a pipette and placing it in a clean, tared 15 or 30 mL plastic bottle. The mass of the withdrawn sample was recorded to a precision of 0.1 mg, then 1.2N HCl was added to the bottle until the mass of the split was approximately 10 g. The exact total mass was also recorded to a precision of 0.1 mg. The remainder of each sample was transferred to a 100 mL Teflon beaker and dried down.

To remove interfering cations from the sample, especially Fe and B, each sample was passed through a 20 mL anion exchange column. These columns contain a resin substrate that maintains an anionic charge. This charge varies with pH, so conditioning with acid of specific normality allows preferential extraction of specific cations from sample filtered through the resin. Columns were conditioned in 9N HCl. Samples were resuspended in 6 mL 9N HCl, transferred to centrifuge tubes, and centrifuged for 2 minutes at high speed to separate any particulate matter, which can ruin the column substrate. Using a pipette, each sample was dropped slowly onto the substrate of one of eight anion columns, then flushed through the column with 34 mL 9N HCl into a 60 mL plastic bottle.

80 mL 0.1N HCl was then run through each column into a 125 mL bottle. This bottle then contained the unwanted portion of the sample; it was saved until the sample ran successfully. The first bottle of each sample was dried down in a Teflon beaker.

Ti, which dilutes the Be beam on the AMS, is separated from the sample when it is passed through cation exchange columns, but it can be more thoroughly removed by adding a precipitation step before the column separation. Ti and Ca precipitate from the sample at a pH of about 4.0, while Be and Al precipitate between pH 8.1 and 8.9. Samples are brought up in 20 mL 1.2N HCl and transferred to 50 mL centrifuge tubes. The pH of each sample was adjusted by adding ammonium hydroxide (NH_4OH) with a pipette until Ti precipitated from the solution. Narrow-range pH paper was used to ensure that the pH did not rise to the point where Be and Al began to precipitate. The tube was then centrifuged at high speed for about 10 minutes. The supernatant was transferred to another centrifuge tube; the original tube with the Ti/Ca pellet was retained until a successful sample run.

The pH of each sample in its new tube was adjusted in a similar manner until Be and Al precipitated. This was centrifuged, the supernatant discarded, and the pellet dissolved in 3 mL of 3N HCl. The sample was transferred to a Teflon beaker and dried down.

The cation columns separate any remaining Ti from the Be in the sample, and separate the Be from the Al. The basic procedure is similar to that of the anion columns; 20 mL drip columns are filled with a cation substrate, conditioned with 200 mL 6N HCl then 60 mL milliQ water.

Samples were brought up in 1 mL 6N HCl, then 5 mL of MilliQ water were added to bring the acid down to 1N. If a sample was cloudy it was centrifuged to remove particulates. It was then dropped onto the cation substrate and run through with 300 mL 1N HCL into a set of bottles. The bottle set separated column volumes 5-8 from those before and after. Calibration curves show 95 to 99% Be recovery in these four column volumes. Once the 1N HCl had all run through, 80 mL 2.5N HCl were run through into a 125 mL bottle, collecting the Al in the sample. The bottles containing the Be were dried down in Teflon beakers. The Al bottles were preserved, as ^{26}Al AMS targets can be prepared easily from these bottles of sample.

3.4.6 Precipitation of Be and Al and target preparation

Samples were resuspended in 2 mL 6N HCl and transferred to centrifuge tubes. Be was precipitated from each sample using exactly the same procedure as before. The supernatant was discarded and the Be gel pellets were rinsed several times and re-centrifuged with MilliQ water to remove any excess OH⁻.

Each sample was transferred by pipette to a labeled ~3 mL quartz crucible that had been cleaned by etching in 10% HF / 25% HNO₃. Crucibles were placed in a hot block in a dry bath at high temperature for 4-8 hours (until dry). Crucibles were then transferred to a metal rack and placed in a muffle furnace at 750 C for 5 minutes to oxidize the Be gel.

The Be oxide in the quartz crucibles is powdered and mixed with niobium powder, then packed into aluminum target holders that act as the cathode in the mass spectrometer. Al targets were not prepared, but the Al oxide is usually mixed with silver powder and packed into stainless steel holders. Target holders are prepared by washing with soap and MilliQ water then are thoroughly rinsed and oven dried.

A ~0.75 cubic meter Plexiglas box provided a clean workstation for target packing. Inside the box, a target holder was labeled and placed on a holding mount, sample opening up. A pin gage was used to scrape the oxide from the sides and bottom of the crucible and grind it into powder. A small spatula was then used to add a volume of niobium powder slightly less than that of the sample to the crucible. The pin gage was used to thoroughly mix the powders together; if very little sample was present, more niobium was added, up to twice the volume of the sample.

The mixed powder was poured from the crucible into the funnel end of the target holder, then guided with the pin gage into the narrow sample hole at the center. The pin gage was used to pack the powder into the hole, then tapped sharply with a ball-peen hammer to ensure a tight packing. The target was removed from the mount and tapped lightly against the mount to ensure no sample would spill during transport. The target was then placed in a cryogenic vial, which in turn was sealed and placed in a holding rack for shipment to Lawrence Livermore National Laboratory. A new pin gage was used for each sample, and the workspace was cleaned with acetone and Kimwipes between samples to prevent cross-contamination.

3.5 AMS Results

31 targets were prepared and analyzed by AMS at Lawrence Livermore National Lab. The first batch of 16 samples was run in October of 2003 and included 2 process blanks. The second batch of 15 samples was run in May of 2004 and included only one blank. Due to a spill, the second blank for this batch failed to produce enough oxide for preparation of the final target. However, the seven samples prepared with this blank were prepared using the same equipment and within a few days of the other seven samples and blank, so the second blank should suffice to correct systematic error in the entire batch.

Raw AMS results are included as Appendix D. The $^{10}\text{Be}/^9\text{Be}$ ratios determined by AMS are shown in Table 3-2 along with the calculated sample ^{10}Be concentrations. Figure 3-10 shows these concentrations plotted against depth for each of the terrace deposits.

3.6 ^{10}Be depth profile analysis

3.6.1 CRN profile methods

Two methods were used to model exposure ages based on measured CRN concentrations. The first is the exponential profile fitting method of Hancock et al. (1999). This method fits an exponential curve to the CRN depth profile, then uses production functions to calculate the exposure time necessary to produce this exponential profile. Ideally, this exponential is asymptotic to a concentration that represents the inventory of CRNs inherited from erosion and transport of the deposit's alluvium.

Some sites exhibit profiles that cannot be fit well with an exponential curve. In these cases, the method used to interpret an exposure age is modified from that of Perg et al. (2001). This method assumes that bioturbation such as treethrow and animal burrowing and soil forming processes such as clay shrink-swell and material translocation mix the deposit to a specific depth, resulting in a uniform concentration of ^{10}Be down to the depth of mixing. It is also assumed that any ^{10}Be mixed upward from below this depth is balanced by ^{10}Be mixed downward from above this depth. Granted

these assumptions, the total depth-integrated inventory of ^{10}Be produced in the mixed interval should be preserved during mixing. CRN production functions can be used to solve for the time required to produce this inventory of ^{10}Be within the mixed interval, revealing the exposure age of the deposit.

Mixing depth is typically chosen by examining the measured concentration vs. depth profile for a transition between uniform concentration and the deeper exponential falloff of concentration with depth (Fig. 3-11). Soils data aids in choosing a mixing depth, as root-limiting layers tend to inhibit mixing and the presence of primary soil stratigraphy such as pebble lines can indicate where mixing has not occurred. Where the lower, exponential part of the CRN-depth profile is retained, it is possible to constrain the amount of CRN inventory inherited from erosion and transport (Perg et al., 2001).

3.6.2 Production systematics

^{10}Be is produced *in situ* by cosmic radiation through three main pathways. Within 2 meters of the surface, neutron spallation is the dominant mechanism of production (e.g., Nishiizumi et al., 1993). Production by spallation falls off exponentially with depth as a function of material density and is negligible in rock and dense alluvium at depths of more than a few meters. ^{10}Be is also produced by nuclear interactions with stopped negative muons and fast muons. Like spallogenic production, muogenic production falls off with depth, but less steeply than spallogenic production. Thus, while muon interactions contribute at most a few percent of production at the surface, they dominate production at depths below ~3 m in rock (e.g., Granger et al., 1997).

The ^{10}Be concentration produced by neutron spallation at depth z as a function of time t is given by:

$$N_N(t,z) = P_0 e^{-\rho z \Lambda^{-1}} [(\tau_{\text{Be}}^{-1} + \rho \epsilon \Lambda^{-1})]^{-1} [1 - e^{-t(\tau_{\text{Be}}^{-1} + \rho \epsilon \Lambda^{-1})}] \quad (1)$$

where P_0 is the latitude and altitude corrected ^{10}Be surface production rate, ρ is terrace material density, Λ is an attenuation length scale, τ_{Be} is the radioactive meanlife of ^{10}Be ,

and ϵ is terrace surface erosion rate. (Granger and Smith, 2000).

The negative muon stopping rate profile with material depth is best fit by a 5th order polynomial (Stone et al., 1998). A pair of functions is therefore required to satisfactorily approximate ^{10}Be production by stopped negative muons over depths appropriate for surficial dating:

$$N_{\mu}(t,z) = YA_1e^{-\rho zL_1^{-1}}[(\tau_{\text{Be}}^{-1} + \rho\epsilon L_1^{-1})]^{-1}[1 - e^{-t(\tau_{\text{Be}}^{-1} + \rho\epsilon L_1^{-1})}] \\ + YA_2e^{-\rho zL_2^{-1}}[(\tau_{\text{Be}}^{-1} + \rho\epsilon L_2^{-1})]^{-1}[1 - e^{-t(\tau_{\text{Be}}^{-1} + \rho\epsilon L_2^{-1})}] \quad (2)$$

where Y is the ^{10}Be yield per stopped negative muon, A_1 and A_2 are production coefficients scaled to local atmospheric attenuation, and L_1 and L_2 are different attenuation length scales (Granger and Smith, 2000).

The ^{10}Be concentration produced by fast muon interactions at depth z as a function of time is closely approximated by:

$$N_{\mu\text{fast}}(t,z) = Be^{-\rho zL_3^{-1}}[(\tau_{\text{Be}}^{-1} + \rho\epsilon L_3^{-1})]^{-1}[1 - e^{-t(\tau_{\text{Be}}^{-1} + \rho\epsilon L_3^{-1})}] \quad (3)$$

where B is a production coefficient scaled to local atmospheric attenuation and L_3 is an attenuation length scale (Granger and Smith, 2000).

The sum $N_N + N_{\mu} + N_{\mu\text{fast}}$ is the total produced concentration of ^{10}Be at depth z after time t . A MATLAB program was used to calculate the age of each deposit based on these production systematics and the measured CRN profile from that deposit. The specific starting value used for each site-independent variable and coefficient is listed in Table 3-3.

3.6.3 Age calculation MATLAB program

For each sampling site, a small MATLAB script file is created that contains the site-specific values for variables such as geographic latitude, altitude, material density, profile mixing depth, and a range of ages to search to best match the measured CRN profile. The script file loads the measured ^{10}Be concentrations from separate files into matrix variables then calls the main program used to calculate exposure ages (G.

Hancock, pers. comm.).

The main program used to calculate the ages from the measured profiles first calls a production rate calculation program and passes to it the user-specified latitude and altitude of the sampling site. This calculator returns the production rate correction factor based on the systematics of both Lal (1991) and Dunai (2000). The more recent Dunai correction factor is used to calculate the surface production rate P_0 , based on a high latitude, sea level production rate of 5.55 atoms ^{10}Be per gram of quartz per year (Perg et al., 2001). The production rate scaling calculator also returns the atmospheric pressure at the site, which is used to scale the muogenic production coefficients.

Next, the program iterates age in steps of 5000 years between a user-specified minimum and maximum age, usually 100 to 2000 ka. For each age iteration, ^{10}Be concentration is calculated by the sum of equations 1, 2, and 3 in a depth profile of 1000 points to a depth of 10 m. For the best-fit exponential method, the program iterates through a user-defined range of cosmogenic inheritance values at each age step. This allows the best fit to depend both on time and inheritance. Using a least-squares type regression, the calculated profile is compared to the measured profile. If the profile calculated in a particular iteration, i.e., for a certain age, fits better than all previous iterations, the age and calculated profile are stored for comparison in further iterations. When the maximum age is reached, the age that produced the best-fitting profile is reported as the age of the deposit. For the mixed-profile method, the profile generated at each age step is integrated to a user-specified mixing depth, resulting in an averaged profile. The calculated profile is compared to the measured profile averaged to this mixing depth and the time step that generated the best-fitting profile is reported as the age of the deposit. Finally, the program plots the mixed or exponential profile on a depth vs. concentration diagram along with the measured ^{10}Be concentrations.

3.6.4 Uncertainties

It has become standard practice in the cosmogenic literature to report error in exposure ages as analytical error only, due to the difficulty in estimating and propagating errors from variables that affect production rate in a specific deposit. Errors on age results reported here represent ^{10}Be measurement error only, propagated by calculating age for profiles defined by the minimum and maximum measured

concentrations within error for each sample (Fig. 3-12). Resulting analytical errors on exposure ages were small, typically less than $\pm 4\%$. It is expected that fully propagated error would be larger than this, but how much larger is unclear.

A major source of error in any cosmogenic exposure technique is the rate of CRN production P_0 . ^{10}Be production rates are constrained by models (Masarik and Reedy, 1995), using measured neutron and muon fluxes (Dunai, 2000), by direct measurement in artificial targets (Nishiizumi et al., 1996), and by calibration against deposits with independent age constraint (Nishiizumi et al., 1986; Brown et al., 1991; Clark et al., 1995). The production rate at any given location fluctuates due to changes in solar output, geomagnetic field configuration, and atmospheric density (Dunai, 2000; Bierman, 1994). Variations of the production rate over different timescales are not well known, but are becoming better constrained as more calibration sites are utilized and better physical models become available (Gillespie and Bierman, 1995). Holocene production rates are generally $\sim 7\text{-}10\%$ lower than those derived for timescales of millions of years (Nishiizumi et al., 1996).

The chosen production rate of $5.55 \text{ atoms/g} \cdot \text{qtz}$ is $\sim 7\%$ higher than short-term rates calibrated from samples $\leq 13 \text{ ka}$ old and $\sim 7\%$ lower than modeled and calibrated rates for timescales of millions of years, so is considered appropriate for timescales of tens to few millions of years (Perg et al., 2001; Clark et al., 1995). Empirically, choosing a higher or lower production rate from among accepted values changes resulting model ages by no more than about 10% . Additionally, erroneous choice of a production rate contributes systematic rather than random error to ages assuming that the true rate does not fluctuate wildly over applicable timescales. Finally, new scaling factors account for non-dipole variability in the geomagnetic field as well as latitude and altitude variations in atmospheric pressure and cosmic ray penetration lengths. These scaling factors are estimated to contribute only 2% uncertainty to scaled production rates (Dunai, 2000).

Additional error is contributed to model ages by uncertainties in target material density, topographic shielding, and vegetative and snow cover. Constraining the magnitude of variations in local variables affecting production is difficult at best in most geologic situations. For this study, average soil density measured at several depths in each site was used for production calculations. While it is impossible to constrain the variability of soil density through time, a lack of correlation between terrace soil density

and relative age indicates that density varies more with parent material composition (e.g., proportion of rock vs. silt and clay in alluvium) than with time. Assuming monotonic change in soil density over long timescales, error due to soil density variation should be systematic. Topographic corrections were applied at each site and are not expected to have varied significantly over the past several million years in a slowly eroding Appalachian landscape. Moreover, these corrections were negligible at most sites. Corrections were not made for snow and vegetation shielding. These effects would be expected to vary most because of glacial-interglacial cyclicity and are thus averaged over timescales longer than several glacial cycles. Therefore, error contributed by these effects is also systematic. Because of the low densities of wood and snow ($< 1 \text{ g/cm}^3$), corrections for their shielding effects are typically very small, a few percent at most (Kubik et al., 1998).

The iterative best-fit process used in this and similar studies does not allow conventional error propagation, even if uncertainties were constrained for all variables. It may be possible to statistically constrain error through a Monte Carlo simulation. This simulation would randomly assign values to each independent variable from within the range of that variable's error or reasonable values, calculate an exposure age, then repeat the process many times, assigning new random values to the variables. After a statistically significant number of iterations, a population of age results will be defined, with a central tendency and associated standard deviation that quantifies the precision of the age values. It should be possible to modify the MATLAB program used to calculate the ages in this study to include this Monte Carlo error propagation. However, to do so was not feasible in the timeframe of this study.

3.7 Age results

Generally, ^{10}Be concentrations were geologically reasonable. As expected, concentrations increased with elevation above the river and decreased with depth in each deposit (Fig. 3-10). Exponential concentration-depth profiles were observed in deposits without significant evidence for mixing, and uniform concentrations with depth accompanied deposits that appear to have been mixed. Once geologic complexities specific to each dated surface were accounted for, it was possible to model ages and rates based on the measured concentrations that are geologically reasonable

and fit well with geomorphic observations.

Because of the variety of parameters needed to constrain cosmogenic exposure ages, and the variability of these parameters between sites within the study area, results are meaningless without some discussion of the choice of parameter values used to generate each age. Therefore, discussion and results on a site-by-site basis follow. A summary of parameters and interpretations is presented in Table 3-4, and Fig. 3-13 presents the best model ages and profiles for each dated surface.

3.7.1 Kentland Farm 10 m terrace

The CRN concentrations measured from the 10 m terrace during the first processing run contained an anomaly. The two deepest samples (200 and 250 cm, 10C and 10A) had concentrations nearly two orders of magnitude higher than those of the three shallower samples (Table 3-2). The concentrations were so high as to be geologically impossible to generate through cosmogenic production at this location; it was suspected that a laboratory error or sample contamination had occurred. To test this, the 225 cm sample (10B) from the same terrace was included in the second sample run. The 225 cm sample had a ^{10}Be concentration near its expected value, slightly lower than the concentrations in the three upper samples. Therefore, the two anomalous measurements were discounted as the result of an error and were not used in interpretation. The remaining four samples were used for profile analysis.

Interpretation of this profile proved difficult, as the profile was weakly exponential with no apparent mixed zone. CRN concentrations in deeper samples were sufficiently high that an exponential profile only fits by allowing for 6.42×10^5 atoms/g•qtz of inherited ^{10}Be . This inheritance corresponds to an average basinwide erosion rate of 10 m/my, and the best fitting exponential corresponds to an exposure age of 130 ± 15 ka (Fig. 3-13a).

An alternative interpretation is that this terrace's profile has been mixed to a depth below the deepest sample. Assuming no inheritance, integration of the CRN concentration to a depth of 250 cm yields an exposure age of 395 ± 15 ka. The unmixed, younger interpretation is better supported by soils data. The top of the C horizon of the 10 m terrace soil is at a relatively shallow depth of 195 cm and pebble lines are found at depths as shallow as 100 cm, both suggesting that extensive, deep mixing has not

occurred. The good exponential shape of the upper profile is not indicative of mixing at shallower depths. An exponential fit only to the upper 2 samples is identical to one fit to all samples. If shallow mixing has occurred, to a depth of no more than 100 cm, the correct age of the terrace should be given by the total integrated CRN inventory over this interval minus this interval's portion of the inherited inventory calculated from the lower part of the profile. This age is 235 ± 15 ka and can be considered as a tentative maximum age for this terrace. Since evidence for mixing is absent, however, the 130 ka age is preferred. The surface of this terrace is perfectly flat for hundreds of meters and no other evidence for erosion is present, so erosion was ignored in the calculation of these ages.

3.7.2 Kentland Farm 20 m terrace

The ^{10}Be concentration in the 75 cm sample (20B) from the 20 m terrace was also anomalously high, two times that of the other three samples and higher than that of any other samples from Kentland Farm. Approximately 2.4 million years of unmixed production at this location would be needed to create this concentration, an unreasonable age for this deposit given the poor development of the soil. Though no further samples were run from this site, it is assumed that this sample was subject to a similar laboratory error to that affecting the deep 10 m terrace samples, and so was disregarded in profile analysis.

The remaining samples above and below the anomaly define a well-mixed profile of nearly constant concentration to the bottom of the alluvium at 125 cm. A mixed profile is supported by the irregular contact between the alluvium and underlying saprolite, including minor mixing between these horizons near the interface. Erosion is considered to be zero for this site, as it is located on the flat tread of a terrace that exhibits a very clear step-tread morphology. The integrated CRN inventory over the alluvial deposit yields an exposure age of 610 ± 20 ka (Fig. 3-13b).

This strath terrace also afforded an unique opportunity to investigate how long the river takes to form terraces. A sample of shale saprolite (20S) was taken from the strath below the 20 m terrace's alluvium at a depth of 150 cm. This sample's ^{10}Be concentration was slightly higher than would be expected at this depth after 610 ka of production, and the strong rock controlled structure of the saprolite precludes any

mixing. This suggests that the strath was exposed for some time before it was covered by alluvium. The time necessary to account for the difference between the measured concentration and that produced since deposition of the alluvium is 35 ± 5 ka. Assuming the density of the saprolite has decreased since the time of initial exposure, this represents a minimum exposure time of the strath prior to alluvial deposition and terrace abandonment. In turn, this implies that the New River had incised to this elevation by 645 ± 21 ka, formed a floodplain, and abandoned this as a terrace by 610 ± 20 ka.

The saprolite sample has additional implications for cosmogenic inheritance. Inheritance was ignored in the age calculation, as it cannot be constrained using the mixed-profile technique unless a deeper, unmixed part of the profile is preserved. However, if inheritance is significant, a lower concentration of ^{10}Be in the saprolite is expected than would be produced over the apparent exposure time of the terrace. Since this concentration is actually higher than expected, inheritance in this deposit is considered to be small.

3.7.3 Kentland Farm 50 m terrace

Like the 10 m terrace, the 50 m terrace's CRN profile is weakly exponential. Concentrations are much higher than those of the 10 m terrace, however, even deep in the profile. The best-fit exponential gives an age of 185 ± 20 ka with a high inherited ^{10}Be concentration of 1.73×10^6 atoms/g•qtz (Fig. 3-13c). This inheritance makes up ~73% of the highest measured concentration at this site. This interpretation is unreasonable for several reasons. First, the strength of soil development and elevation of this terrace imply that it is older than lower terraces. The amount of surface erosion that would be needed to reduce the apparent age of this terrace to 185 ka from an age older than that of the 20 m terrace is ~4.5 m. There is no geomorphic evidence for this much erosion here. Moreover, the calculated inheritance concentration is higher than the maximum concentration measured in the 10 m terrace and approaches the maximum concentration in the 20 m terrace. If a significant amount of erosion has occurred and this terrace is indeed older, the initial inheritance needed is higher still because radioactive decay has reduced the inherited inventory more over the greater amount of time. Finally, this terrace appears to be cut into a thick deposit of alluvial fill. This

alluvium has other, higher terraces cut into it, implying that it was deposited long before the 50 m terrace was exposed. Because of radioactive decay, this means that an extremely high inheritance would be needed at time of deposition to allow the calculated inheritance at the time of exposure.

Since the best-fit exponential method appears to be inapplicable to calculation of the 50 m terrace's age, the mixed-profile approach is employed. CRN concentrations at depth are very uniform, supporting profile mixing to a depth below the deepest sample. Since no break in the CRN profile is observed, the mixing depth is not constrained, but assuming that mixing does not extend into the C horizon of the soil and given that the lowest sample is in a BCt transitional horizon, it is not likely that the mixed zone extends significantly more deeply than the deepest sample. As samples were taken at 50 cm intervals, the profile is integrated to 25 cm below the deepest measurement. Integration of the CRN profile over this mixing depth of 275 cm yields an exposure age of 955 ± 25 ka (Fig 3-13d).

Though there is no evidence for deep (>1 m) erosion at this site, this terrace has a slight slope compared to the lower, flatter terraces. This implies that some surface erosion may have occurred here. The site was carefully located away from shoulder positions and where the slope was a minimum ($\sim 3^\circ$), so any erosion should be minor; even so, the 955 ka exposure age should be regarded as a minimum.

3.7.4 Kentland Farm 128 m terrace

Unlike the lower terraces, the 128 m terrace at Kentland Farm shows a strong exponential CRN concentration-depth profile. The best-fit exponential yields an exposure age of 620 ± 20 ka with no inheritance (Fig. 3-13e). The exponential fit is not ideal, as there appears to be a mismatch between the lower 3 samples and the upper sample. This is suggestive of mixing to a depth between that of the upper two samples. A mixing depth of 62 cm was chosen, which corresponds to the Bt2/2Bt3 soil horizon break. The 2Bt3 horizon here is root-limiting, supporting the idea that most mixing would occur in the overlying horizons. Integrating ^{10}Be concentration over this interval yields an apparent exposure age of 500 ± 15 ka (Fig. 3-13f). Fitting an exponential to the lower 3 samples results in a very good fit and an apparent age of 415 ± 10 ka.

The mismatch between the ages given by the lower exponential and the upper

mixed interval is suggestive of surface erosion over the time of production, as CRNs produced in the upper zone are mixed into the overall inventory as the lower profile remains constant. This helps to explain the young apparent age of this deposit. The extremely strong development of the soil, high elevation above the river, and exposure ages of much lower terraces such as the Kentland Farm 50 m suggest that the age of this terrace is greater than 1 Ma. This site is located at the crest of a terrace remnant hill, on an area that is slightly convex, so it is conceivable that several meters of erosion have occurred here. Estimating this terrace's age by its elevation using the average incision rate of 43 m/my given by the ages of the lower terraces yields 2.98 Ma, though this may be inappropriate if the New River's incision history is stepwise. Approximately 4 m of surface erosion from this terrace are necessary to reconcile its estimated age with its apparent exposure age. Thus, the CRN concentration from this surface is likely governed by the rate of erosion and does not accurately represent the age of the terrace.

3.7.5 Pearisburg 80 m terrace

Like the 128 m Kentland Farm terrace, the 80 m terrace at Pearisburg exhibits a strong exponential CRN profile. The best-fit exponential fits very well without any suggestion of a mixed zone and yields an apparent exposure age of 435 ± 20 ka with 1.45×10^5 atoms/g•qtz of inherited ^{10}Be (Fig. 3-13g). This should be considered to be an extreme minimum age for this deposit; the strong development of the soil is akin to that of the 128 m Kentland Farm terrace, yet the apparent age is less than that of the 20 m Kentland Farm terrace. Though the Pearisburg site is on a level terrace tread with no geomorphic indication that major erosion has occurred, the disconnect between the apparent exposure age of the terrace and the relative age indicators suggests that surface erosion is important here. Estimating this terrace's age by its elevation using the average incision rate gives 1.95 Ma. Approximately 3 m of surface erosion from this terrace are necessary to reconcile its estimated age with its apparent exposure age.

3.7.6 Big Falls bedrock samples

Concentrations measured from the three samples of bedrock from Big Falls were interpreted in two ways: as representing a surface exposure age, with CRN accumulation since exposure, and as representing a steady erosion rate, with constant surface CRN concentration through time.

To estimate a surface exposure age, bedrock sample concentrations were analyzed in the same manner as the terrace deposits. Since samples BF01 and BF02 were taken from the upper cm of rock and subsequently crushed, the mixed-profile technique was used to calculate an age from the average CRN concentration over this 1 cm interval. Sample BF03 was prepared from a crushed joint block 5 cm thick vertically, so a 5 cm mixing interval was used. Water only covers the sampled surfaces during rare high-flow events, much less than 1% of the time. Though this coverage may have been higher in the past as the river lowered its bed around these bedrock ribs, CRN shielding by water since exposure is considered to be negligible. This interpretation assumes that these surfaces were exposed instantaneously rather than gradually. CRN concentration inherited from ingrowth before surface exposure is thus ignored.

Samples BF01 and BF02, taken from similar surfaces a few meters apart on the same rib, yielded exposure ages of 23.0 ± 0.6 and 23.6 ± 0.6 ka, respectively. The joint block BF03 yielded an age of 20.9 ± 0.6 ka.

It is possible to interpret the CRN concentrations in bedrock surface samples as erosion rates (e.g., Hancock et al., 1998). Assuming steady erosion and a constant rate of production, the surface ^{10}Be concentration in an outcrop should be constant through time. In this case, the surface erosion rate should be:

$$\varepsilon = P_0[N\rho\Lambda^{-1} + \lambda]^{-1} \quad (4)$$

where λ is the decay constant of ^{10}Be ($4.6 \times 10^{-7} \text{ yr}^{-1}$) and N is the measured concentration of the isotope in the sample (Bierman, 1994). Here, P_0 is the scaled spallogenic production rate; muogenic production is ignored, but is generally insignificant in surface samples. For BF01, the apparent steady erosion rate is $25.0 \pm 0.8 \text{ m/my}$, and for BF02 this rate is $24.4 \pm 0.7 \text{ m/my}$. BF03 is not strictly a surface sample and due to its thickness exhibits a slightly lower overall CRN concentration than would a surface

sample from the same location, but yields an apparent erosion rate of 28.4 ± 0.7 m/my.

The assumption in question when choosing between these interpretations is whether the rate of erosion is steady (small-block quarrying, abrasion) or stepwise (large-block quarrying) through time (Small et al., 1997). For example, if quarrying removes blocks 1 m in thickness at regular time intervals, ~20% of the surface ^{10}Be concentration at the time of plucking will be inherited from production before the overlying block was plucked. In this case, the surface exposure age will be overestimated by the amount of time needed to produce the value of the inheritance at the rock surface. Thus the surface exposure age will be most accurate near the end of the interval, i.e., just before the next plucking event.

In this example, the magnitude of error when using the erosion rate interpretation depends on how long the surface has been exposed since the last plucking event. As exposure time and CRN concentration increase, estimated erosion rate decreases, initially overestimating then eventually underestimating the average erosion rate (Small et al., 1997). Thus, with long exposure times, the calculated erosion rate can be very inaccurate, or accurate but very imprecise. As plucking recurrence interval decreases, precision increases until it is equivalent to or less than measurement error in the isotope concentration.

For smaller blocks, inheritance will be a much higher proportion of the total surface concentration; a 10 cm block size results in ~86% inheritance. A limit is defined: as block size approaches zero, percentage of inherited CRNs approaches 100. The concentration at which this limit occurs (N) is constant for a steadily eroding surface and is controlled by the erosion rate ϵ (Equation 4), and thus by the plucking interval. The smaller the block size, the less accurate the surface exposure age becomes, as the minimum error is controlled by the proportion of the CRN concentration that is inherited.

To summarize, when interpreting surface CRN concentrations, exposure age calculations become more accurate as quarried block size increases and erosion rate calculations become more accurate as plucking interval decreases. A basic assumption is that block size and plucking interval covary such that smaller blocks are plucked with higher frequency, but it is possible to envision geologic scenarios in which this is not the case. More problematically, and more likely, irregular sizes of blocks and/or variable intervals of plucking make the accuracy of either technique unpredictable. It is thus

necessary to have a detailed understanding of the mechanisms of erosion in an outcrop before an accurate interpretation can be made. This level of understanding may or may not be possible from examination of the outcrop.

If quarrying of large blocks (1 m or more in thickness) is a dominant mode of erosion from the large bedrock ribs at Big Falls, and blocks remain in place for tens of thousands of years between quarrying events, the surface exposure interpretation can be used. This may be reasonable, as the upper surfaces of these ribs (such as that from which BF01 and BF02 were sampled) are smooth and continuous and do not exhibit scars from plucking of small blocks. It is also possible to interpret these surfaces as uneroded since a time when they were constantly below water level; like a strath, they were beveled off at the former riverbed and have since been abandoned. This interpretation is supported by the consistent elevation of the highest rib surfaces across the outcrop. In either case, the 23 ka exposure age interpretation is the most appropriate. If the riverbed was at a maximum height of 2 m, the elevation of this surface, at exposure of the surface, the river is incising around these ribs at a rate up to 87 m/my, even if the rocks themselves are eroding much more slowly.

On thinner ribs or lower surfaces of the large ribs, such as that from which BF03 was collected, the size of quarried joint blocks (represented by plucking scars) varies greatly. Most blocks are significantly less than a meter in vertical thickness when they are removed, and many are small (< 10 cm thick). CRN concentrations between the three samples were uniform, despite the BF03 sample being from a different protruding bedrock rib and a meter lower than the surface sampled for BF01 and BF02. This could indicate that erosion here is steady at ~ 25 m/my across the entire outcrop, whereas the exposure age interpretation would predict a much lower concentration in the lower-elevation BF03 sample.

It is possible that different mechanisms apply to different portions of the outcrop and the similarity of CRN concentrations between the three samples is coincidental. The steady erosion interpretation may apply to areas where small-block plucking is in evidence (BF03), but the concentrations from continuous upper surfaces represent exposure ages (BF01 and BF02). To be certain, more samples need to be analyzed from a variety of surfaces across the Big Falls area and a more detailed examination of the mechanisms of erosion needs to be performed.

3.8 Synthesis

Cosmogenic exposure dating yields good model ages for New River terraces at elevations 10 m, 20 m, and 50 m above modern river level. While exposure ages should generally be considered as minimums because of the possibility of surface erosion, the 10 m and 20 m Kentland Farm terraces are very unlikely to have experienced significant erosion and yield the most accurate terrace exposure results. The 50 m Kentland terrace yields a good minimum age, as morphological observations indicate that minor erosion is possible here. The Kentland 128 m and Pearisburg 80 m terraces did not yield valid exposure ages despite exhibiting strong exponential concentration-depth profiles. This is attributed to significant surface erosion at these locations.

Detailed geomorphic observations were invaluable in selecting between different possible interpretations for each site. The most important observations were those which helped constrain surface erosion from terraces and depth of mixing within terraces. Together with cosmogenic inheritance, these issues were found to have the largest effect on the interpretation applied to each site and on resulting model ages, and thus merit further discussion.

3.8.1 Surface erosion

Though sampling sites were carefully chosen to avoid any locations where a large amount of erosion was likely to have occurred, the progression of cosmogenic exposure ages indicates that surface erosion has occurred to a significant extent on higher, presumably older terraces. The ages of the Kentland Farm 128 m terrace and the Pearisburg 80 m terrace in particular cannot be reconciled with their own strong soil development or with the ages of lower terraces. Without independent constraints on erosion rates from these surfaces, it is impossible to estimate their true exposure age using a single cosmogenic isotope. Measurement of the ratio of ^{26}Al to ^{10}Be in deep samples from these profiles may allow erosion and age constraint (e.g. Granger and Smith, 2000), but to do so was beyond the resources available for this study.

Though a true exposure age cannot be obtained from these deposits using the data currently available, it is possible to estimate current erosion rates on these landforms. Assuming that erosion has occurred at a constant rate for long enough to

generate a steady-state CRN profile, the surface erosion rate from these terraces should be given by equation 4. As this equation requires surface values for N , best-fit exponentials fit to measured CRN profiles were projected to the surface for the 128 m Kentland and 80 m Pearisburg terraces. In the case of the 128 m terrace, the lower, exponential, unmixed part of the profile was used, as the mixed zone may retain CRN inventory from overlying material that has since eroded. The lower profile is thus more representative of the CRN concentration as controlled by the surface erosion rate. The resulting rates of erosion from the upper surfaces of the 128 m and 80 m terrace are 2.02 ± 0.05 m/my and 1.62 ± 0.07 m/my, respectively.

The higher erosion rate on the higher, more convex surface of the 128 m terrace implies that erosion rates increase with time and elevation above the river. Terraces such as the Kentland 10 and 20 m may persist with little or no erosion for hundreds of thousands of years, until dissection of the terrace surface and incision of nearby drainages progress to the point where diffusive hillslope erosion processes become significant. Erosion begins slowly, but increases in rate as terrace remnants become more convex and isolated until a balance is reached between slope and material strength. At this point, the erosion rate should stabilize. If the erosion rate is still accelerating on the 80 m and 128 m terrace surfaces, or if part of the measured CRN concentrations in the profile are retained from exposure before erosion became sufficient to establish a steady-state profile, the rates obtained above will underestimate the true current erosion rate. These rates should therefore be considered as minimums.

3.8.2 Profile mixing

It was necessary during interpretation of cosmogenic results to call on profile mixing at some sites and not others. The Kentland 10 m terrace appeared to be unmixed, the 20 and 50 m terraces mixed, the 128 m shallowly mixed, and the Pearisburg 80 m terrace was unmixed. This variation can be explained geologically. The unmixed low terrace is relatively young. It is possible that deep mixing occurs over longer timescales than the age of this terrace. The middle-aged terraces are old enough for deep mixing. The highest terraces are certainly old enough for deep mixing, but these terraces show evidence of significant surface erosion. This erosion may be fast enough that the upper, mixed zone is constantly being removed, leaving the

exponential profile intact.

A possible drawback to the mixed-profile technique is the assumption that mixing is uniform throughout a part of the profile. This is reasonable when a clear break in profile can be observed between an interval of uniform CRN concentration and one of exponential concentration decrease. In deposits with slightly higher concentrations in the upper profile than the lower, it is conceivable that two zones of mixing may be present: an upper zone of mixing on short timescales and a lower zone mixed on longer timescales. Extending this concept, it seems possible that in diverse ecosystems with many burrowing species with different maximum burrow depths and different tree-root penetration depths, mixing amount and timescale may increase continuously with depth. Consequently, the deposit's mixed CRN profile would retain the semblance of an exponential curve even after mixing. This exponential would be less strongly expressed than in an unmixed deposit, resulting in an underestimation of the exposure age by the best-fit exponential method. The integrated inventory method would remain valid, but it would be difficult to constrain the maximum mixing depth if it is below that of the deepest sample.

3.8.3 Cosmogenic inheritance

Like mixing, cosmogenic inheritance appeared to vary in importance between terrace deposits. Only the youngest, 10 m terrace appeared to have any inheritance, the amount constrained by the deep samples from its exponential concentration-depth profile. The high terraces, exposed potentially hundreds of thousands of years or more after deposition of the alluvium into which they are cut, are not expected to exhibit inheritance. Radioactive decay would have greatly reduced the inherited inventory in this alluvium prior to terrace exposure. This is corroborated by the good fit of exponential profiles from the Kentland 128 m and Pearisburg 80 m terraces even if inheritance is constrained to be zero. Some inheritance is expected in the 20 m Kentland terrace, but cannot be quantified as the alluvium here is mixed thoroughly. However, a large amount of inheritance, equivalent to that calculated from the 10 m terrace, would create a mismatch between the predicted and measured concentration of ^{10}Be in the saprolite sample from below the alluvium. This mismatch is not observed.

This implies that cosmogenic inheritance differs between deposits. Inheritance

may vary between deposits if the source material is different between these deposits. This could vary as a result of minor reconfigurations of the the geomorphic system and may not be reflected in an examination of alluvial provenance. Alluvium consisting of material that was eroded quickly from bedrock outcrops would be expected to have less inheritance than alluvium consisting of reworked material that had been previously exposed in an older deposit.

Sand samples such as that collected for this study will generally exhibit lower inheritance than cobble samples, because erosion and transport time for sand-sized grains should be shorter than those for larger grains (Hancock et al., 1999). The 10 m/my basinwide erosion rate inferred from the calculated inheritance at the 10 m site may actually only represent the erosion rate of sand from terrace deposits farther upstream; basinwide rock erosion rates could be much slower.

This inheritance could also represent exposure over the transport time of the sand. The transport time necessary to create this concentration is ~91 ka (ignoring water shielding during transport, which would be significant). This transport time seems long for sand in continuous motion, but should be considered as a maximum. The inherited CRN concentration in this sand is more likely the sum of production during initial erosion, storage, reworking, and further transport before final deposition. A high concentration may also result in sand that is broken down from larger grain sizes that sat exposed in the riverbed or in point bars for long periods of time, even if transport is rapid once the grain is reduced to sand. Estimation of basin erosion rates from inherited CRNs in terrace deposits is thus prone to a large error, and results should be considered approximate at best.

Figure 3-1: Idealized CRN concentration-depth profile. Cosmogenic inheritance is constrained by shape of exponential curve at depth.

Figure 3-2: Kentland Farm 10 m terrace sampling site. Map contour interval is 20 ft. View in photo is looking NE across terrace surface.

Location (dec. degrees, WGS84)
N 37.19332, W 80.57886

Topography:
Extensive flat (0° slope). Site located ~ 50 m from riser of 20 m terrace, on a cm-scale rise in the surface.

Current land use:
Pasture, cornfield.

Notes:
Lowest prominent terrace above modern floodplain. A classroom GPR and shotgun-source seismic demonstration showed bedrock under 6-8 m of alluvium.

Figure 3-3: Kentland Farm 20 m terrace sampling site. Map contour interval is 20 ft. View in photo is looking NE across terrace surface. More terrace area at this level is visible across the nearby gully.

Location (dec. degrees, WGS84)
N 37.19551, W 80.57892

Topography:
Prominent flat (1° slope) on tread of well-preserved terrace. Terrace riser and small gully within ~25 m of site.

Current land use:
Fescue pasture.

Notes:
Same terrace trenched by Mills (1981): strath with shallow alluvium, saprolite at ~1.5 m depth.

Figure 3-4: Kentland Farm 50 m terrace sampling site. Map contour interval is 20 ft. View in photo is looking ENE across terrace surface. More terrace area at this level is visible in the distance.

Location (dec. degrees, WGS84)
N 37.20026, W 80.58634

Topography:
Large flat ($<4^\circ$ slope) at base of high hill. Site located ~100 m from toe of higher slope.

Current land use:
Fescue pasture.

Notes:
Most extensive terrace level at Kentland Farm, but strongly dissected.

Figure 3-5: Kentland Farm 128 m terrace sampling site. Map contour interval is 20 ft. View in photo is looking north across terrace surface.

Location (dec. degrees, WGS84)
N 37.20727, W 80.59206

Topography:
Crest of highest local hill. Flat open area, about 20x50 m. Several gullies within 150 m.

Current land use:
Pasture, orchard.

Notes:
Highest preserved terrace remnant at Kentland Farm. Soil very red even at shallow depths.

Figure 3-6: Pearisburg 80 m terrace sampling site. Map contour interval is 20 ft. View in photo is looking north across terrace surface.

Topography:

Large flat (0° slope). Site ~25 m from shoulder of terrace at cm-scale rise in surface.

Current land use:

Vegetable garden.

Notes:

Cemetery nearby on same surface with late 19th cen. headstones: this is an original flat surface. Nearby flats have been cut and filled for construction.

Figure 3-7: Sampling locations on Big Falls bedrock ribs. Surface samples BF01 and BF02 were taken from upper, unpolished surfaces of the large rib (bounded in red, right), where abrasion appears to be a minimum. BF03 was a cobble-sized joint block removed from smaller outcropping to the left of the large rib (see Fig. 3-9). Large rib, as shown, protrudes ~1 m from river surface and is ~20 m in length. Ruler is ~30 cm long.

Figure 3-8: Collecting soil samples from marked-out depth intervals in the Kentland 50 m terrace trench

Figure 3-9: Bedrock sampling at Big Falls. Hammer is 40 cm long.

A - BF02 surface sample. Existing crack in surface exploited for sampling because of competence of rock.

B - BF03 joint block sample. This joint block was only loosely held in place; it would have been removed soon by a high-flow event.

Figure 3-10: Measured CRN concentrations and depth-concentration profiles for New River terraces. Error bars on concentrations are smaller than point symbols.

Figure 3-11: Idealized top-mixed CRN profile. Upper zone is homogenized by bioturbation. Below the mixed interval, CRN concentration falls off exponentially with depth. Net transport of CRNs between the mixed and unmixed zones is assumed to be zero.

Figure 3-12: Age uncertainty bounds calculated from minimum and maximum possible concentration profiles, defined by analytical uncertainty. Analytical uncertainty is greatly exaggerated for the purpose of this illustration and is typically $\leq 3\%$.

Figure 3-13: Interpreted ages from best-fit CRN production profiles (solid black lines). Dotted vertical lines represent best inheritance at time of exposure. Dashed horizontal lines represent base of mixed interval. See text for discussion of individual profiles.

Table 3-1: Cosmogenic sample names, depths, and processing status

Sample	Depth (m)	AKA	AKA	Processed?	Run on AMS?
Kentland 128 m					
TRDW01 A	2.50	DW128A	128A	Y	Y
TRDW01 B	2.00	DW128B	128B	Y	Y
TRDW01 C	1.50	DW128C	128C	Y	Y
TRDW01 D	1.00	DW128D	128D	Y	Y
Kentland 50 m					
TRDW02 A	2.50	DW50A	50A	Y	Y
TRDW02 B	2.25			N	
TRDW02 C	2.00	DW50C	50C	Y	Y
TRDW02 D	1.75			N	
TRDW02 E	1.50	DW50E	50E	Y	Y
TRDW02 F	1.25			N	
TRDW02 G	1.00	DW50G	50G	Y	Y
TRDW02 H	0.75			N	
TRDW02 I	0.50	DW50I	50I	Y	Y
Kentland 20 m					
TRDW03 A	1.00	DW20A	20A	Y	Y
TRDW03 B	0.75	DW20B	20B	Y	Y
TRDW03 C	0.50	DW20C	20C	Y	Y
TRDW03 D	0.25	DW20D	20D	Y	Y
TRDW03 S	2.00	DW20S	20S	Y	
Kentland 10 m					
TRDW04 A	2.50	DW10A	10A	Y	Y
TRDW04 B	2.25	DW10B	10B	Y	
TRDW04 C	2.00	DW10C	10C	Y	Y
TRDW04 D	1.75			N	
TRDW04 E	1.50	DW10E	10E	Y	Y
TRDW04 F	1.25			N	
TRDW04 G	1.00	DW10G	10G	Y	Y
TRDW04 H	0.75			N	
TRDW04 I	0.50	DW10I	10I	Y	Y
Pearisburg 80 m					
DWDIRECT A	2.75			Not collected	
DWDIRECT B	2.50	DIRECTB	DIRB	Y	Y
DWDIRECT C	2.25			N	
DWDIRECT D	2.00	DIRECTD	DIRD	Y	Y
DWDIRECT E	1.75			N	
DWDIRECT F	1.50	DIRECTF	DIRF	Y	Y
DWDIRECT G	1.25			N	
DWDIRECT H	1.00	DIRECTH	DIRH	Y	Y
DWDIRECT I	0.75			N	
DWDIRECT J	0.50	DIRECTJ	DIRJ	Y	Y
Big Falls Bedrock					
BF01	0.00			Y	Y
BF02	0.00			Y	Y
BF03	0.00			Y	Y
Process Blanks					
BLK-DW01	N/A	BLK1		Y	Y
BLK-DW02	N/A	BLK2		Y	Y
BLK-DW03	N/A	BLK3		Y	No target oxide
BLK-DW04	N/A	BLK4		Y	Y

Table 3-2: CRN concentrations calculated from AMS results.

Sample name	Depth (cm)	Sample mass (g)	Mass 9Be spike (g)	Atoms 9Be/g sample	10Be/9Be ratio from AMS	Error	Atoms 10Be/g sample	Error
DW50A	250	49.2962	0.4809	6.55131E+17	2.66274E-12	5.0626E-14	1.744E+06	3.357E+04
DW50C	200	29.281	0.4773	1.09469E+18	1.59403E-12	4.35434E-14	1.745E+06	4.795E+04
DW50E	150	29.4108	0.5081	1.16019E+18	1.50646E-12	2.9698E-14	1.748E+06	3.485E+04
DW50G	100	31.4106	0.475	1.01556E+18	2.11442E-12	3.5578E-14	2.147E+06	3.670E+04
DW50I	50	25.3779	0.4775	1.26359E+18	1.8832E-12	4.09054E-14	2.380E+06	5.217E+04
DW20A	100	32.6902	0.4731	9.71901E+17	1.94011E-12	4.48311E-14	1.886E+06	4.393E+04
DW20B	75	32.3634	0.5073	1.05268E+18	3.97388E-12	5.43047E-14	4.183E+06	5.851E+04
DW20C	50	32.7646	0.4922	1.0084E+18	1.97346E-12	4.95976E-14	1.991E+06	5.039E+04
DW20D	25	28.4646	0.5012	1.18248E+18	1.68831E-12	3.76719E-14	1.996E+06	4.494E+04
DW20S	150	24.9684	0.5155	1.38652E+18	5.85984E-13	1.1448E-14	8.125E+05	1.606E+04
DW10A	250	39.8809	0.526	8.85743E+17	1.18658E-11	2.74673E-13	1.051E+07	2.453E+05
DW10B	225	34.642	0.4747	9.20244E+17	7.56122E-13	2.43371E-14	6.958E+05	2.249E+04
DW10C	200	31.5925	0.5267	1.11961E+18	2.47006E-11	3.49206E-13	2.765E+07	3.996E+05
DW10E	150	28.043	0.5349	1.28096E+18	5.60092E-13	2.2453E-14	7.175E+05	2.884E+04
DW10G	100	28.0223	0.5286	1.26681E+18	7.12717E-13	2.47698E-14	9.029E+05	3.149E+04
DW10I	50	28.2326	0.4494	1.06898E+18	1.07969E-12	3.1357E-14	1.154E+06	3.370E+04
DWDIRB	250	34.2815	0.5256	1.02963E+18	2.70851E-13	9.3687E-15	2.789E+05	9.682E+03
DWDIRD	200	25.8536	0.5079	1.3193E+18	2.67419E-13	6.96756E-15	3.528E+05	9.252E+03
DWDIRF	150	26.9478	0.5012	1.24903E+18	3.9397E-13	1.00766E-14	4.921E+05	1.267E+04
DWDIRH	100	23.6888	0.5003	1.41832E+18	6.32883E-13	1.5919E-14	8.976E+05	2.274E+04
DWDIRJ	50	20.4847	0.5054	1.65689E+18	9.92233E-13	3.73887E-14	1.644E+06	6.214E+04
DW128A	200	35.5804	0.5551	1.04772E+18	2.92945E-13	7.21226E-15	3.069E+05	7.612E+03
DW128B	150	30.3693	0.6077	1.34382E+18	3.946E-13	9.28621E-15	5.303E+05	1.258E+04
DW128C	100	27.1608	0.5711	1.41207E+18	6.48827E-13	1.54863E-14	9.162E+05	2.204E+04
DW128D	50	24.7861	0.5717	1.54898E+18	1.62397E-12	3.77732E-14	2.515E+06	5.899E+04
DWBF01	Surface	29.7812	0.5091	1.14802E+18	1.37656E-13	3.61788E-15	1.580E+05	4.180E+03
DWBF02	Surface	30.8973	0.4731	1.0283E+18	1.57061E-13	4.05809E-15	1.615E+05	4.201E+03
DWBF03	Surface	30.2448	0.5218	1.15862E+18	1.19591E-13	3.20169E-15	1.386E+05	3.733E+03

Table 3-3: Default values for site-independent CRN production variables

Variable or coefficient	Default Value	Notes/source
P_0	5.55 atoms/g qtz/year	Perg et al., 2001 SLHL - scaled to each site by age calculation program
Λ	160 g/cm ²	e.g., Bierman, 1994
τ_{Be}	2.17E6 years	e.g., Hancock et al., 1999
Y	5.6E-4	Heisinger, 1998
A_1	170.6	Granger and Smith, 2000; Stone, et al., 1998
A_2	36.75	Granger and Smith, 2000; Stone, et al., 1998
L_1	738.6 g/cm ²	Granger and Smith, 2000; Stone, et al., 1998
L_2	2688 g/cm ²	Granger and Smith, 2000; Stone, et al., 1998
L_3	4360 g/cm ²	e.g., Heisinger, 1998
B	0.026	Granger and Smith, 2000; Heisinger, 1998

Table 3-4: Overview of CRN profile analysis results. Preferred interpretation for each site in **bold**. See text for discussion.

Site	Profile fig.	<u>INHERITANCE/SHIFTED EXPONENTIAL</u>		<u>MIXED</u>			<u>SURFACE EROSION</u>	
		Inheritance (at/g-qtz)	Age, ka (shifted exponential)	Evidence for mixing	Assumed mixing depth (cm)	Age, ka (mixed)	Evidence for erosion	Erosion rate, m/ky (assumes steady)
Kentland 10 m	3-13 A	6.42E+05	130± 15	None; Pebble lines at 100 cm and below	100	235± 15	None	N/A
Kentland 20 m	3-13 B	N/A	N/A	Uniform profile, irregular soil/sparolite interface	125	610± 20	None	N/A
Kentland 50 m	3-13 C,D	1.73E+06	185± 20	High, uniform concentration at depth	275	955± 25	Slight surface slope	N/A
Kentland 128 m	3-13 E,F	0.00E+00	620± 20	Profile mismatch w/upper sample	62	500± 15	Top of convex hill; age mismatch between mixed and unmixed parts of profile; appt. age unreasonably young	2.02± .05
Pearisburg 80 m	3-13 G	1.45E+05	435± 20	None	N/A	N/A	Appt. age unreasonably young vs. relative age indicators	1.62± .07
Big Falls BF01	N/A	N/A	23.0± 0.6	N/A	N/A	N/A	None; unpolished surface rarely submerged	25.0± 0.8
Big Falls BF02	N/A	N/A	23.6± 0.6	N/A	N/A	N/A	None; unpolished surface rarely submerged	24.4± 0.7
Big Falls BF03	N/A	N/A	20.9± 0.6	N/A	N/A	N/A	Small joint block surrounded by plucking scars	28.4± 0.7

Chapter 4: Interpretations

4.1 Introduction

The cosmogenic exposure ages obtained from the New River terraces at Kentland Farm allow construction of a more detailed incision history for the river than has previously been possible. Though previous studies imply relatively steady downcutting over the past 1 Ma, the new results demonstrate a fluctuating rate of incision that may be linked to changes in global climate. These correlations have implications for the dominant controls over the river's behavior, and by extension, for processes of denudation in ancient orogens. Comparing the results of this study to that of other studies of the New River elucidates strengths and weaknesses of different cosmogenic techniques. Comparison to studies of other drainages provides insight into the regional applicability of the interpretations made from the results of this study. Terrace ages also constrain soil development rates, which can be used to deduce the ages of other alluvial surfaces across the Valley and Ridge.

4.2 New River incision history from terrace exposure ages

Prior to 2 Ma, possibly far prior to this time, the New River deposited a large package of alluvial fill in its valley through the Valley and Ridge. Examination of core through 40 m of this fill provides evidence for relatively uninterrupted deposition of at least the lower section of this fill. The core was drilled on a terrace at an elevation ~55 m above the modern river, implying that at this location the river had cut to an elevation ~15 m AMRL. Evidence for incision to this depth at this time is not seen in the Kentland Farm area; however, Bartholomew and Mills (1991) suggest that the river's course above Big Falls may have been different at this time. Nonetheless, aggradation in one or more events continued until alluvium had been deposited to a height of at least 128 m above the modern river. At some point prior to ~1 Ma, the New River incised through this fill in a course similar to its present one, abandoning a terrace surface at 128 m and cutting to 50 m AMRL.

By 955 ka, the New River had cut extensive terraces into the fill at the 50 m level. At 955 ka, the river abandoned these terraces and began downcutting to an elevation 20

m AMRL at an average rate of 97 m/my (Figure 4-1). The presence of several distinct terraces between 50 and 20 m AMRL indicates that this downcutting was not continuous. However, these terraces are not extensive relative to the 50 m and 20 m terraces, so are not likely to represent extended periods of stalled downcutting.

Near 645 ka, the New River began cutting an extensive strath 20 m above the modern river. By 610 ka, this strath had been covered with just over a meter of alluvium and abandoned. Downcutting proceeded to an elevation below 10 m AMRL at a minimum rate of 21 m/my. Another extensive terrace formed at this elevation.

The timing of initiation of the 10 m terrace's formation is not known, so the rate of downcutting between this and the 20 m terrace may have been much higher. The depth to bedrock below the alluvium of the 10 m terrace is at least 6 m, so terrace cutting and filling to the present surface at 10 m AMRL may have taken as many as several hundred thousand years before abandonment at 130 ka. The average incision rate from this terrace to the modern river level was 77 m/my.

Linear regression through the age-elevation data (including the origin) yields a long-term average incision rate of 43 m/my (Fig. 4-2), which is reasonable for a large Appalachian drainage (e.g., Hack, 1965; Matmon et al., 2003). This rate may be skewed, however, because the residence time of the river at elevations of extensive terrace formation is not constrained for any terrace except the 20 m. Long periods of stalled downcutting, such as that suggested by the extent of the 50 m terrace level across the study area, would decrease the long-term average incision rate. Since the 50 m terrace's age is considered a minimum, it too constrains this 43 m/my rate as a maximum.

4.3 Correlation of incision events with climate records

The relationship between New River terrace abandonment ages and glacial-interglacial cyclicity has important implications for the dominant controls on river behavior. Stalled downcutting and terrace formation during sea level lowstand, for example, would disavow a base level control over the New River's downcutting rate. If such a control existed, a sea level drop would be expected to promote incision. The New River's course to sea level is so long and its slope so controlled by lithology that some insulation from base level changes is to be expected; if it did respond to these changes, a significant lag time would be expected. This lag time would take the form of a

headward-propagating knickpoint that could stall upon encountering the steeper slopes and more resistant units of the Valley and Ridge (e.g., Harbor et al., 2004).

By the same token, a sediment supply increase during glacial times due to decrease of stabilizing vegetation, stormier climate, and increased hillslope erosion might reduce the available power of the river to incise (e.g. Molnar, 2001). This would promote alluviation and floodplain formation, creating packages of fill and terraces cut into that fill. Upon deglaciation, meltwater from snow and periglacial ice would increase the river's discharge and stream power, promoting rapid incision.

This hypothesis is supported by evidence that the river is incising during the present interglacial. To test this further, age results from cosmogenic exposure dating are plotted against records of global climate and sea level change, as represented by the marine stable isotope record (Fig. 4-3). Terrace abandonment ages appear to be associated with the onsets of individual negative excursions in the ^{18}O isotope, global warming events, and the onset of sea level rise from lowstand. The abandonment of the 50, 20, and 10 m terraces correspond to the beginnings of Marine Isotope Stages 29, 15, and 5e, respectively. Within the likely uncertainty of these ages, however, such correlations are meaningless. If the Big Falls bedrock rib surface is interpreted as a strath-like surface with a 23 ka exposure age, this surface can be correlated with the last glacial period. As uncertainties are less likely to be large on this younger age, this correlation may be more acceptable than correlations based on terrace ages. If this correlation is real and the rib surface represents a former riverbed elevation, renewed incision since the last glacial period and sediment supply control on the New River are supported.

Whatever the specific correlation between terrace age and glacial cycles, the alternating rapid incision and stalled downcutting implied by terrace ages suggest a climate control on the New River. The thickness of alluvium deposited before about 1 Ma is an order of magnitude greater than that deposited at any elevation since that time. This suggests a drastic change in the river's regime at some point prior to 1 Ma, from extensive aggradation to dominant, if discontinuous, incision. This change may correspond to a greatly increased variability in climate that began near 1.2 Ma or it could be the result of a major drainage reorganization or a more subtle climatic shift. Regardless, it is clear that long-term average incision rates for the New River represent the integration of numerous periods of inferred rapid incision and aggradation, and

that transitions between these states appear to be climate-driven.

4.4 Comparison of incision history above and below Big Falls

Unfortunately, the apparent erosion from the terrace dated at Pearisburg disallows any comparison of incision rate between the reaches upstream and downstream of Big Falls. The young apparent exposure age from this terrace (435 ka) yields a long-term incision rate of 184 m/my, which, in the absence of major tectonic activity, is difficult to reconcile with the 43 m/my long-term rate given by the Kentland Farm terraces. Cosmogenic cave burial ages presented by Granger et al. (1997) are all from locations downstream of the falls, but differences in the techniques invalidate a direct comparison. Generally, burial ages should be interpreted as maximums because any burial of the sediment before emplacement in a cave will increase its apparent emplacement age. Further, sediment may be emplaced in a cave on more than one occasion: during initial incision past the cave, during aggradation of the riverbed near the cave, or during re-evacuation of aggraded sediment. Cave burial ages may thus represent a mixed history; broad age scatter in cave burial dates from four caves at similar elevations demonstrates the validity of this issue. Exposure ages generally should be thought of as minimums because the most likely source of error (surface erosion) decreases apparent age. Thus the long-term incision rate given by cave burial ages of 27 m/my should be thought of as a minimum rate, while the exposure age long-term incision rate of 43 m/my is considered a maximum. While the range of long-term incision rates defined by the two techniques is very reasonable, an attempt to draw geologic meaning from the difference between these rates would be inappropriate.

4.5 Comparison to other regional drainages

The Green River in Kentucky drains the Cumberland Plateau before entering the Ohio River approximately 700 km downstream of the New River. Using cosmogenic burial dating of deposits emplaced in a series of caves, Granger and others (2001) documented a series of aggradation and incision events between 3.5 and 0.7 Ma. With the exception of one event linked to a regional drainage reorganization, Green River incision events are correlated with interglacials and aggradation with glacial times. This

is in good agreement with the cosmogenic exposure results from the New River. The Green River's incision history is not well-constrained during the period of New River history documented in this study, but an aggradation of the Green River between 700 and 800 ka is recorded. This correlates with the cessation of New River downcutting and the initial formation of the 20 m Kentland strath at 750 ka, and suggests that these subglacial Ohio tributaries respond similarly to climatic changes. If this is the case, the Green River aggradation events documented at 3.25 and 2.3 Ma may correspond to deposition of the large packages of New River alluvium into which the high Kentland Farm terraces are cut.

Preliminary results of cosmogenic exposure dating of James River terraces in the Piedmont of Virginia suggest that a transition from river stability and floodplain formation to incision occurred between 1.1 and 1.2 Ma (Hancock et al., 2004). This change may be linked to the increased variability of climate beginning ca. 1.2 Ma. The average rate of incision since this time (35-60 m/my) is comparable to the 43 m/my average rate of New River incision during the same time period, and the prior period of stability may correlate to the period of extensive aggradation on the New River that ended before 955 ka. This supports a climate control over the behavior of subglacial Appalachian rivers across the region, both in the Ohio-Mississippi network and the Atlantic drainage area.

Recent cosmogenic exposure dating of bedrock straths along the Potomac and Susquehanna Rivers by Bierman et al. (2004) and Reusser et al. (2004) indicate a period of rapid incision beginning with the onset of the last glacial period ca. 30-35 ka. This incision is attributed to greatly depressed sea level during this period. These rivers empty to the Atlantic after draining parts of the Appalachians and Piedmont, and exposure ages are from downstream reaches less than ~100 km from the river outlets. The results suggest that at least the distal reaches of these drainages are strongly controlled by base level, in contrast to the lack of evidence for base level control on the New River. Changes in factors affecting sediment supply should be similar to those in the New River's drainage area. This implies that base level change holds a stronger influence on river incision than sediment supply, except in drainages insulated from sea level change by distance and lithology.

4.6 Implications for soil development

Among the terrace soils which were effectively exposure dated, a chronosequence is defined, with a progression of soil development through time. This chronosequence was assumed and used to choose reasonable interpretations for the cosmogenic ages, so using these ages to redefine the chronosequence is somewhat circular. It is appropriate, however, to calibrate the previously documented soil development indicators so long as the relative sequence is not changed. Though detailed soil mineralogical data were not collected in this study, basic soils data such as color and clay content were collected and can be plotted against terrace age. So that soils data from the 128m Kentland and 80 m Pearisburg terrace may be included, ages are estimated based on terrace elevation and the 43 m/my long-term incision rate. The age estimates for these two terraces may be in error by 50% or more, but this should not drastically change the observed trends in soil development.

Figure 4-4a shows the strongest development of B horizon color (as Munsell hue) vs. age for each dated Kentland Farm terrace. Generally, redder colors are associated with stronger development. Redness appears to increase steadily from 10YR to 2.5 YR during the first million years of soil development, then color change slows and levels off at 10R near 2 Ma. This is related to the relative increase in clay content with age (Fig 4-4b). As minerals such as feldspar and mica weather in the soil to unstable clays such as vermiculite then to more stable clays such as kaolinite, iron is freed into the soil, and under oxidizing conditions, the soil is reddened. As more stable clays such as kaolinite predominate, weathering rate and reddening slow. The difference in clay content in Bt horizons and as measured at 50 cm depth is a result of soil horizonation and translocation of clays to deeper horizons. The difference is large on younger terraces, but becomes small with increasing age, suggesting that erosion has removed clay-poor upper layers of soil from the oldest terraces.

Figure 4-4c shows Bt horizon depth and thickness vs. age. Though Bt horizon upper depth shows no correlation with age, thickness appears initially to increase steadily through time. The decreased Bt thicknesses on terraces older than 1 Ma is attributed to erosion: as soil development progresses deeper into the parent material, erosion removes upper layers, keeping the overall Bt thickness from increasing.

Though some clear trends in development of basic soil properties through time

are documented here, more complete soils data should be examined to refine rates of soil development in Valley and Ridge alluvium. Integration of data from previous studies (e.g. Harris et al., 1980; Mills and Wagner, 1985) and more detailed examination by soil scientists of terraces dated in this study should allow a wider range of soil development indicators to be calibrated against cosmogenic exposure ages.

Figure 4-1: Schematic profile of terraces and elevations AMRL at Kentland Farm, with terrace ages and incision rates.

Figure 4-2: Age-elevation plot of cosmogenic exposure ages from Kentland Farm terraces. Regression fit is poor due to the intermittent nature of incision over the last Ma.

Figure 4-3: Exposure ages in context of $\delta^{18}\text{O}$, Marine Isotope Stages, and global climate and sea level. Because uncertainties are unconstrained on exposure ages, both propagated analytical uncertainty (black error bars) and $\pm 15\%$ ranges (gray boxes) are shown. Correlations are not meaningful within $\pm 15\%$ for all except the very youngest ages. Based on public data from ODP hole 677, courtesy of the Delphi Project, <http://delphi.esc.cam.ac.uk/>; isotope stage numbers after Bowen et al., 1986.

Figure 4-4: Soil attributes vs. age. A - Munsell hue. B - Clay %. C - Depth and thickness of Bt.

Chapter 5: Conclusions

The New River's course through the core of the Appalachians places it across a variety of rock types that affect its ability to incise toward base level. Knickpoints and riffles, formed where the river crosses extremely resistant units such as the Tuscarora sandstone, bear the focus of much of the river's energy. Active bedrock incision features such as flutes, potholes, and plucking scars demonstrate that the New River is currently in a state of incision, despite abundant evidence in the form of alluvial fill deposits that the river has undergone significant periods of aggradation in the past.

Cosmogenic exposure ages from a series of fill-cut and strath terraces reveal the episodic nature of the incision history of the New River. Since 955 ka, the New River has incised 50 m through alluvial fill and bedrock at an average rate of 43 m/my. During short-term periods of incision, downcutting rates have reached at least 97 m/my. Between periods of incision, extended periods of aggradation and terrace formation are documented, ending with terrace abandonment events at 955, 610, and 130 ka. On Tuscarora sandstone at Big Falls, erosion is currently proceeding at a rate of at least 25 m/my; incision rates at this location may be as high as 87 m/my. These results demonstrate the variability in process rates that can occur in Appalachian drainages and suggest a strong climatic influence on the New River, possibly by way of changes in sediment supply.

The cosmogenic exposure dating technique used in this study greatly benefitted from detailed descriptions of terrace soils. These descriptions allowed more appropriate selection of values for crucial parameters such as surface erosion and depth of mixing by bioturbation. In return, soil development rates can be calibrated against terrace exposure ages, quantifying the effect of time on alluvial soils in the Valley and Ridge. Very strongly developed Paleudults with 10R colors and >50% clay in the Bt horizons formed over time spans of 1.5-5 Ma. Strong soil development was aided by extremely slow rates of erosion from terrace surfaces. Even high, convex terrace remnants yielded cosmogenic erosion rate estimates of ~2 m/my or less. This implies a state of landscape disequilibrium, in which river incision rates far outstrip rates of erosion of surrounding landforms. These findings echo recent results from other subglacial Appalachian drainages and demonstrate the dynamic nature of erosional processes in an ancient orogen on a passive margin.

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APPENDIX A: Logs of sample site soil profiles

SOIL AND SITE DESCRIPTION FORM

Persons Describing the Soil: John Galbraith Pedon # K1-Wheeling
Date 8/15/03 Lat. 37.19332 Lon. -80.57886 (decimal degrees)
County Montgomery USGS Quad Sheet(5) Radford N MLRA 128

Site Properties:

Current land use and vegetation: fescue pasture

Elevation (m): 518 m (1699 ft) Aspect (slope direction) (0° to 360°): 300

Slope gradient (%): 1 Slope length: (m) 100

Boulders on/in surface (%) --- Stones on/in surface (%) ---

Geomorphic surface --- Flood Plain X Stream terrace (level) --- Stream terrace (dissected)
--- Upland --- Closed Depression --- Drainageway

Landform position:

--- Summit --- Shoulder --- Backslope
--- Footslope --- Toeslope X Not Appl. (on < 2% slopes in coastal plains)

Land surface shape: (First letter is down-slope profile, --- LL X LV
--- LC second letter is cross-slope profile) --- VL --- VV --- VC
L = linear V = convex C = concave --- CL --- CV --- CC

Hydrology:

Saturation type: endo or epi? endo Wetland indicator plants? y/n --- Artificial drainage: y/n ---

Depth of observed water: (cm) >8' Flooding evidence? y/n --- Ponding evidence? y/n ---

Soil Properties:

Soil Drainage Class: moderately well

Depth Class: very deep

Parent Material(s): Alluvium

Pedon # K1-Wheeling

Ap1--0 to 13 cm; dark brown (10YR 3/3) moist loam, brown (10YR 5/3) dry; top 5 cm very friable; moderate granular structure, 5 to 13 cm moderate subangular blocky structure; (3%) gravel (brick fragments), (1%) cobbles; many very fine & fine roots; very few pores; common Mica flakes.

Ap2--13 to 31 cm; dark brown (10YR 3/3) loam; includes (15%) pieces of Bt1 horizon by volume; weak, subangular blocky structure; very friable; (5%) gravel (brick fragments); many fine & very fine roots; very few pores; common Mica flakes.

Bt1--31 to 41 cm; yellowish brown (10YR 5/6) loam; moderate, subangular blocky structure; very friable; clay films; common roots; very few pores; common Mica flakes; (5%) A horizon in worm holes.

Bt2--41 to 59 cm; dark yellowish brown (10YR 4/6) loam; moderate, subangular blocky structure; very friable; (1%) cobbles; clay films; (50%) Mn stains in lower 5 cm; common roots; very few pores; common Mica flakes.

Bt3--59 to 87 cm; dark yellowish brown (10YR 4/6) loam; moderate, subangular blocky structure; friable; (2%) reddish brown (2.5Y 5/3) and (2%) weak red (2.5Y 5/2) Fe depletions; (15%) yellowish brown (10YR 5/6) masses of Fe concentrations; (5%) gravel; clay films; (25%) Mn concretions; (5%) Mn stains; few roots; few pores; common Mica flakes.

Bt4--87 to 117 cm; dark yellowish brown (10YR 4/6) loam; weak, subangular blocky structure; friable; (2%) reddish brown (2.5Y 5/3) and (2%) weak red (2.5Y 5/2) Fe depletions; (10%) yellowish brown (10YR 5/6) masses of Fe concentrations; (5%) gravel; clay films; (10%) Mn concentrations; (10%) Mn stains; few roots; few pores; common Mica flakes, pebble lines (70%) sandstone, (15%) shale, (15%) quartz at 100 cm.

BCt--117 to 150 cm; dark yellowish brown (10 YR 4/6) loam; weak prismatic structure; friable; (2%) reddish brown (2.5Y 5/3) and (2%) weak red (2.5Y 5/2) Fe depletions; (10%) yellowish brown (10 YR 5/6) masses of Fe concentrations; (5%) gravel, (1%) cobbles; clay films; (5%) Mn concentrations; (10%) Mn stains; very fine roots; very fine pores; many Mica flakes, pebble lines (70%) sandstone, (15%) shale, (15%) quartz at 150 cm.

BC--150 to 195 cm; (40%) dark yellowish brown (10YR 4/4) and (60%) yellowish brown (10YR 4/6) fine sandy loam; structureless, massive; very friable; (2%) reddish brown (2.5Y 5/3) Fe depletions; (5%) red (10R 5/6) Fe concentrations; (5%) gravel; (1%) Mn stains; many Mica flakes, pebble lines (70%) sandstone, (15%) shale, (15%) quartz at 175 cm.

C--195 to 250 cm; (75%) dark yellowish brown (10YR 4/4) and (25%) dark yellowish brown (10 YR 4/6) loamy fine sand; structureless, massive; very friable; (2%) reddish brown (2.5Y 5/3) Fe depletions; (5%) red (10R 5/6) Fe concentrations; (5%) gravel; (1%) Mn stains; many Mica flakes.

SOIL AND SITE DESCRIPTION FORM

Persons Describing the Soil: John Galbraith Pedon # K2-Zoar

Date 8/15/03 Lat. 37.19551 Lon. -80.57892 (decimal degrees)

County Montgomery USGS Quad Sheet(5) Radford N MLRA 128

Site Properties:

Current land use and vegetation: fescue pasture

Elevation (m): 526 m (1726 ft) Aspect (slope direction) (0° to 360°): 90

Slope gradient (%): 1 Slope length: (m) 20

Boulders on/in surface (%) --- Stones on/in surface (%) ---

Geomorphic surface --- Flood Plain X Stream terrace (level) --- Stream terrace (dissected)
--- Upland --- Closed Depression --- Drainageway

Landform position:

X Summit --- Shoulder --- Backslope
--- Footslope --- Toeslope --- Not Appl. (on < 2% slopes in coastal plains)

Land surface shape: (First letter is down-slope profile, second letter is cross-slope profile)
L = linear V = convex C = concave X LL --- LV --- LC
--- VL --- VV --- VC
--- CL --- CV --- CC

Hydrology: ditch 100 yds away

Saturation type: endo or epi? epi Wetland indicator plants? y/n n Artificial drainage: y/n ---

Depth of observed water: (cm) >8ft Flooding evidence? y/n --- Ponding evidence? y/n ---

Soil Properties:

Soil Drainage Class: moderately well

Depth Class: deep

Parent Material(s): Alluvium - ancient
Calcareous siltstone or silty limestone

Pedon # ____ K-2 Zoar _____

Ap--0 to 18 cm; very dark grayish brown (2.5Y 4/2) loam; upper 5 cm is moderate granular, 5-18 cm is moderate, subangular blocky structure; very friable; (5%) round gravel; many fine & very fine roots.

E/A--18 to 30 cm; (66%) light yellowish brown (2.5Y 6/4) and (34%) dark grayish brown (2.5Y 4/2) loam or fine sandy loam in earthworm holes; moderate, subangular blocky structure; very friable; (5%) round gravel; many fine & very fine roots.

E--30 to 50cm; light yellowish brown (2.5Y 6/4) fine sandy loam; moderate, subangular blocky structure; very friable; (10%) round gravel; common fine & very fine roots.

2Bt1--50 to 90 cm; light yellowish brown (10YR 6/4) in upper 8cm and 58 to 90 cm dark yellowish brown (10YR 4/6) gravelly loam below; (5%) light brownish gray (2.5Y 6/2) Fe depletions and (10%) strong brown (7.5YR 4/6) and (5%) yellowish brown (10YR 5/6) masses of Fe concentrations; moderate, subangular blocky structure; friable; (2%) sandy bleached pockets; (5%) brittle; (25%) round gravel, (2%) round cobbles; clay films; few fine & very fine roots.

2Bt2--90 to 105 cm; dark yellowish brown (10YR 4/6) extremely gravelly clay loam; (5%) pale brown (10YR 6/3) and (10%) reddish brown (2.5Y 5/3) Fe depletions; (15%) yellowish brown (10YR 5/6) and (10%) dark yellowish brown (10YR 4/6) masses of Fe concentrations; moderate, angular blocky structure; firm; (5%) sandy bleached pockets; (15%) brittle; (50%) round gravel, (20%) round cobbles; clay films; few fine & very fine roots.

3Bt3--105 to 125 cm; (70%) brown (7.5YR 4/4) channery clay, moderate, prismatic structure; (30%) strong brown (7.5YR 4/6) channery clay, strong, platy structure; firm; (10%) rock controlled structure; perching layer; root limiting; (15%) yellowish red (5YR 4/6) masses of Fe concentrations; (2%) round gravel, (15%) channers; clay films; few fine & very fine roots on prism faces.

3Bt4--125 to 165 cm; (60%) brown (7.5YR 4/4) channery clay, moderate, prismatic and (40%) strong brown (7.5YR 4/6) channery clay, strong, platy structure; friable; (20%) rock controlled structure; (15%) channers; clay films.

3BCt1--165 to 180 cm; (50%) brown (7.5YR 4/4) and (40%) strong brown (7.5 YR 4/6) very channery clay; moderate, platy structure; friable; (50%) rock controlled structure; (5%) pale brown (10YR 6/3) Fe depletions; (15%) yellowish red (5 YR4/6) and (5%) yellowish red (5YR 5/8) masses of Fe concentrations; (50%) channers; clay films.

3BCt2--180 to 212 cm; brown (7.5YR 5/4) extremely channery loam; weak, platy structure; friable; (70%) rock controlled structure; (15%) yellowish red (5YR 5/6) and (20%) red (2.5YR 4/6) masses of Fe concentrations; (70%) flat gravel; clay films.

3Cr--212 to 262+ cm; light yellowish brown (10YR 6/4) weathered siltstone (leached of carbonates) probably formerly limestone or calcareous siltstone, 15 degrees oriented; (25%) red (10R 4/6) and red (2.5YR 4/6 and 4/8) colored rock fragments; (100%) rock controlled structure; (98%) channers; (15%) brown (7.5YR 4/3) Mn films concentrations.

SOIL AND SITE DESCRIPTION FORM

Persons Describing the Soil: Andy Jones, John Galbraith, Lee Daniels Pedon # K-3 Low Shottower

Date 8/25/03 Lat 37.20026 Lon. -80.58634 (decimal degrees)

County Montgomery USGS Quad Sheet(5) Radford N MLRA 128

Site Properties:

Current land use and vegetation: fescue pasture

Elevation (m): 556 (1824 ft.) Aspect (slope direction) (0° to 360°): 140

Slope gradient (%): 4 Slope length: (m) 21

Boulders on/in surface (%) --- Stones on/in surface (%) ---

Geomorphic surface ☐ Flood Plain ☐ Stream terrace (level) ☒ Stream terrace (dissected)
☐ Upland ☐ Closed Depression ☐ Drainageway

Landform position:

☐ Summit ☐ Shoulder ☒ Backslope
☐ Footslope ☐ Toeslope ☐ Not Appl. (on < 2% slopes in coastal plains)

Land surface shape:

(First letter is down-slope profile,
second letter is cross-slope profile)

L = linear V = convex C = concave

☐ LL ☐ LV ☐ LC
☐ VL ☐ VV ☒ VC
☐ CL ☐ CV ☐ CC

Hydrology:

Saturation type: endo or epi? --- Wetland indicator plants? y/n --- Artificial drainage: y/n n

Depth of observed water: (cm) n Flooding evidence? y/n n Ponding evidence? y/n n

Soil Properties:

Soil Drainage Class: somewhat well

Depth Class: very deep

Parent Material(s): Alluvium

Pedon # K-3 Low Shottower

Ap--0 to 12 cm; dark yellowish brown (10YR 3/4) loam; moderate granular structure in upper 5 cm, weak subangular blocky structure below; very friable; (1%) gravel; many fine & very fine roots; common pores.

E/Bt--12 to 35 cm; E (65%) light yellowish brown (10YR 6/4) loam; Bt (65%) yellowish brown (10YR 5/6) clay loam; moderate subangular blocky structure; friable; (10%) brownish yellow (10YR 6/6) masses of Fe concentrations; (1%) gravel; clay films; many fine & very fine roots; common pores; (5%) worm holes filled with Ap horizon.

Bt1--35 to 49 cm; yellowish brown (10YR 5/6) clay loam; moderate, subangular blocky structure, (10%) prism surfaces with Fe depletions; friable, (5%) brittle; (5%) strong brown (7.5YR 5/6) masses of iron concentrations; (2%) gravel; clay films; (1%) Mn concentrations and Mn stains; common fine & very fine roots; common pores.

Bt2--49 to 97 cm; yellowish brown (10YR 5/6) clay; moderate, subangular blocky structure, (10%) prism surfaces with Fe depletions; friable, (10%) brittle; (5%) light olive brown (2.5Y 5/6) and (2%) light brownish gray (2.5Y 6/2) iron depletions; (5%) yellowish red (5YR 5/8) and (25%) strong brown (7.5YR 5/6) masses of iron concentrations; (3%) gravel; clay films; (1%) Mn concentrations and Mn stains; few roots & very fine roots; few pores.

Bt3--97 to 150 cm; yellowish red (5YR 5/6) clay; weak, subangular blocky structure; firm; (10%) brittle; (20%) yellowish brown (10YR 5/6) and (2%) light brownish gray (2.5Y 6/2) iron depletions; (5%) yellowish red (5YR 5/8), (10%) light olive brown (2.5Y 5/6), and (10%) red (2.5YR 4/6) masses of Fe concentrations; (3%) gravel; clay films; few fine & very fine roots; few pores.

Bt4--150 to 197 cm; red (2.5YR 4/6) clay; weak, subangular blocky structure; firm; (10%) light brownish gray (2.5Y 5/6) Fe depletions; (10%) yellowish brown (10YR 5/6) masses of Fe concentrations; (5%) gravel; clay films; few fine & very fine roots; common pores.

2BCt--197 to 260+ cm; red (2.5YR 4/6) clay loam; (5%) light brownish gray (2.5Y 5/6) Fe depletions; (5%) yellowish brown (10YR 5/6) masses of Fe concentrations; weak subangular blocky structure; firm; (2%) gravel; clay films; common pores.

SOIL AND SITE DESCRIPTION FORM

Persons Describing the Soil: John Galbraith & W. Lee Daniels Pedon # K-4 High Shottower
Date 8/25/03 Lat. 37.20727 Lon. -80.59206 (decimal degrees)
County Montgomery USGS Quad Sheet(5) Radford N. MLRA 128

Site Properties:

Current land use and vegetation: Fescue pasture

Elevation (m): 611 (2005 ft) Aspect (slope direction) (0° to 360°): 60
Slope gradient (%): 3 Slope length: (m) 10
Boulders on/in surface (%) --- Stones on/in surface (%) ---

Geomorphic surface ☐ Flood Plain ☐ Stream terrace (level) ☒ Stream terrace (dissected)
☐ Upland ☐ Closed Depression ☐ Drainageway

Landform position:

☒ Summit ☐ Shoulder ☐ Backslope
☐ Footslope ☐ Toeslope ☐ Not Appl. (on < 2% slopes in coastal plains)

Land surface shape: (First letter is down-slope profile, second letter is cross-slope profile)
L = linear V = convex C = concave ☐ LL ☐ LV ☐ LC
☒ VL ☐ VV ☐ VC
☐ CL ☐ CV ☐ CC

Hydrology:

Saturation type: endo or epi? ☐ Wetland indicator plants? y/n ☐ Artificial drainage: y/n ☐
Depth of observed water: (cm) ☐ Flooding evidence? y/n ☐ Ponding evidence? y/n ☐

Soil Properties:

Soil Drainage Class: well
Depth Class: very deep
Parent Material(s): Alluvium

Pedon # K-4 High Shottower

Ap--0 to 15 cm; dark brown (10YR 3/3) gravelly loam; moderate, fine and medium granular structure; very friable; (15%) gravel; many fine and medium roots.

Bt/E--15 to 28 cm; Bt (65%) yellowish red (5YR 4/6) and E (35%) dark yellowish brown (10YR 4/4) gravelly loam; moderate, medium subangular blocky structure; friable; (15%) gravel; (1%) cobbles; clay films; common medium and few fine roots; about (50%) of this horizon has an 8 cm thick layer of pure E material right under the Ap horizon.

Bt1--28 to 40 cm; Bt (40%) yellowish red (5YR 4/6), (40%) red (2.5YR 4/6), and (20%) dark yellowish brown (10YR 4/4) gravelly clay loam; weak to moderate, coarse to medium subangular blocky structure; friable; (15%) gravel; (1%) cobbles; clay films; few fine and very fine roots.

Bt2--40 to 62 cm; (70%) red (2.5YR 4/6) and (30%) yellowish red (5YR 4/6) clay; weak, coarse to medium subangular blocky structure; (15%) gravel; clay films; few fine and very fine roots.

2Bt3--62 to 97 cm; dark red (10R 3/6) gravelly clay; weak, fine subangular blocky structure; friable and firm; (5%) brown (7.5YR 5/4) Fe depletions; (10%) strong brown (7.5YR 5/8) masses of Fe concentrations; (30%) gravel; clay films.

2Bt4--97 to 138 cm; dark yellowish brown (10R 3/6) gravelly clay; weak, fine subangular blocky structure; friable and firm; (10%) brown (7YR 5/4) Fe depletions; (15%) strong brown (7.5YR 5/8) masses of Fe concentrations; (25%) gravel; clay films.

2BCt--138 to 250+ cm; (70%) dark red (10R 3/6) and (30%) red (2.5YR 4/6) sandy gravelly clay loam; weak medium to coarse subangular blocky structure; friable; (20%) gravel; clay films.

APPENDIX B: Detailed log of Pembroke terrace core 1

LOGGING NOTES: Intervals are measured from top of the core. Interval boundaries are always somewhat gradational; measurements are ± 1.5 cm. All colors are measured in the dry condition (unless otherwise noted), as the core material has been in storage for 6 years. Color codes are Munsell. Sand is quartz sand unless otherwise noted. Grain distribution is estimated by eye and feel and is likely to be accurate only to $\pm 15\%$. Grain shape is based on examination of sand grains under a 10x hand lens. Dry strength is noted only when soil peds or clay clumping is identified. Much of the gravel-sized fraction looks freshly broken from larger cobbles (often represented by intervals where clean, unstained white sandy material dominates), likely by the drilling equipment. It is therefore possible that the gravel fraction is over-represented relative to the cobble fraction. Clay-rich material is commonly clumped into gravel-sized pieces which may be mistaken for gravel, increasing the chance for overestimation of the gravel fraction. Marbling of colors, where noted, appears to be a result of the drilling procedure.

16 June 2003

Section 1 - 0-5 ft.

Brown cobble-rich modern soil at top, followed by bands of yellow ochre and reddish-purple in sandier material grading into purple with white patches of sand from disintegrated cobbles.

0-14 cm.

10YR 8/2 Very pale orange to grayish orange.

Poorly sorted. 30% cobbles, 15% gravel, 40% sand, 15% fines.

Dry strength high to very high. Peds cannot be broken with fingers, but break against a hard surface.

Peds and root material abundant. Many pebbles break easily into sand under pressure. Grains subangular to subrounded.

14-35 cm.

10YR 7/4 to 10YR 6/6 Grayish orange and dark yellowish orange, varying.

Moderately to poorly sorted. 10% cobbles, 10% gravel, 50% sand, 30% fines.

Dry strength medium.

Material smaller than gravel is in peds. Many crumbling pebbles, some with dark grayish brown rinds. Root material common. Grains subangular to subrounded.

35-41 cm.

5YR 2.5/2 Grayish to dusky brown with some grayish orange material.

Poorly sorted. 70% gravel, 20% sand, 10% fines. Gravel remnants of hematite-cemented sst. cobbles.

Few peds. Provenance of hematitic material likely Silurian Rose Hill Fm. Grains subrounded.

41-50 cm.

10YR 8/6 Dominantly pale yellowish orange sand, with some brownish pebbles.

Moderately sorted. 45% gravel, 45% sand, 10% fines.

Gravel is mostly broken material from cobbles and disintegrates easily. Grains subangular.

50-68 cm.

5YR 2/2 to 5RP 2/2 Dusky brown to very dusky purple. 6-cm dia. patch of 10YR 8/2 very pale orange to white sand.

Moderately sorted. 40% gravel, 40% sand, 20% fines.

Gravel and sand seem to be from disintegrated cobbles of Silurian sandstones (Rose Hill [purple] and Tuscarora [white] Fms.). grains subrounded.

68-80 cm.

5YR 3/2 Grayish brown with patches of 10YR 8/2 very pale orange to white sand.
Moderately sorted. 40% gravel, 40% sand, 20% fines.
Grains angular to subrounded.

80-108 cm.

5YR 3/2 Grayish brown with minor 10YR 8/2 sand and gravel. Cement and stain 5YR 5/6 to 5YR 3/4, light to moderate brown.
Moderately sorted at top grading to poorly sorted, with increasing cobbles. 50% gravel, 30% sand, 20% fines at top grading to 30% cobbles, 30% gravel, 10% sand, 30% fines.
Many coarse sand to gravel grains cemented together and stained by reddish shiny clay. This increases toward the bottom of the interval. More yellowish sand toward bottom of interval, corresponding with large cobbles of similar material. Grains subangular to rounded.

108-120 cm.

5YR 5/6 and 5YR3/2 Dominantly light brown Fe-stained sand and gravel and grayish brown sand. Some 5YR 5/2 pale brown clasts.
Poorly sorted. 35% gravel, 40% sand, 25% fines.
Grains subangular to subrounded.

120-123 cm.

5RP 2/2 Very dusky purple.
Moderately sorted. 40% gravel, 40% sand, 20% fines.
Grains subrounded.

123-134 cm.

10YR 6/2 to 10YR 8/2 Pale yellowish brown to very pale orange; sand mixed from purplish and white sources. Minor reddish-brown and yellowish sand.
Poorly sorted. 10% cobbles, 30% gravel, 40% sand, 20% fines.
Fe-staining on outside of white cobbles and pebbles. Grains angular to subrounded.

134-142 cm.

10YR 8/2 Very pale orange sand, pebbles, and cobbles. Little reddish staining. Very color-homogeneous interval.
Poorly sorted. 15% cobbles, 35% gravel, 20% sand, 30% fines.
Very homogeneous interval in terms of provenance. Grains subrounded

142-152 cm. (END OF SECTION)

10YR 7/4 Grayish orange overall color, varying from pale yellow to reddish-orange with iron staining.
Poorly sorted. 10% cobbles, 25% gravel, 25% sand, 40% fines.
More Fe-staining and clumping suggests abundant clay in fines. Grains subrounded to rounded.

17 June 2003

Section 2 - 5-10 ft.

Dominantly poorly sorted reddish-brown material punctuated by short intervals of more cobble-rich, lighter brown material.

152-170 cm.

5YR 2/2 to 10YR 8/6 Dusky brown to pale yellowish orange, varying. Overall color is 5YR 5/2, pale brown. Mixed material.

Poorly sorted. 10% cobbles, 30% gravel, 25% sand, 35% fines.

Subangular grains. Yellowish Fe-stained grains interspersed with brown-purple hematite-cemented grains.

One piece of woody organic material at base of interval.

170-179 cm.

5YR 7/2 Grayish orange pink.

Poorly sorted. 30% cobbles, 40% gravel, 10% sand, 20% fines.

Subangular to subrounded grains. Scarce organic debris - small rootlets. Very porous and permeable interval.

179-206 cm.

5YR 2/2 to 10YR 8/6 Dusky brown to pale yellowish orange, varying. Overall color is 5YR 5/2, pale brown. Mixed material.

Poorly sorted. 15% cobbles, 30% gravel, 25% sand, 30% fines.

Subangular grains. Yellowish Fe-stained grains interspersed with brown-purple hematite-cemented grains.

Fe-staining most near top of interval, diminishing toward the bottom. Increasing cobbles toward bottom of interval.

206-214 cm.

5YR 2/2 to 10YR 8/6 Dusky brown to pale yellowish orange, varying.

Moderately sorted. 40% cobbles, 40% gravel, 10% sand, 10% fines.

Subrounded grains. Individual clasts show banding and marbling of color - red-orange, yellow, and purple.

Many appear to be from one large decomposing sandstone cobble. Very porous and permeable interval.

214-228 cm.

5YR 2/2 to 10YR 8/6 Dusky brown to pale yellowish orange, varying. Mixed material.

Poorly sorted. 15% cobbles, 30% gravel, 25% sand, 30% fines.

Subrounded grains. Yellowish Fe-stained grains interspersed with brown-purple hematite-cemented clasts.

Individual clasts show banding and marbling of color - red-orange, yellow, and purple. Yellow Fe-staining least near top of interval, increasing toward the bottom.

228-258 cm.

5YR 2/2 to 10YR 8/6 Dusky brown to pale yellowish orange, varying. Overall color is 5YR 5/2, pale brown.

Moderately sorted. 40% cobbles, 45% gravel, 5% sand, 10% fines.

Subangular grains. Yellowish Fe-stained grains interspersed with brown-purple hematite-cemented grains.

Increasing cobbles and decreasing finer material toward bottom of interval.

258-277 cm.

5YR 2/2 to 10YR 8/6 Dusky brown to pale yellowish orange, varying. Mixed material.

Poorly sorted. 10% cobbles, 15% gravel, 40% sand, 35% fines.

Subangular to subrounded grains. Yellowish Fe-stained grains interspersed with brown-purple hematite-cemented grains. Individual clasts show banding and marbling of color - red-orange, yellow, and purple.

Many gravel-sized clumps of material with moderate dry strength.

277-293 cm.

10YR 8/2 Very pale orange.

Poorly sorted. 50% cobbles, 20% gravel, 15% sand, 15% fines.

Subangular to subrounded grains. Cleaner white sandstone and derivative sand/gravel from several decomposing cobbles. Low degree of Fe staining. Some clumps with moderate dry strength.

293-304 cm. (END OF SECTION)

5YR 5/2 to 5YR 3/2 Pale brown to grayish brown. Isolated yellowish or whiteish patches.

Moderately sorted. 20% gravel, 30% sand, 50% fines.

Gravel-sized lumps with moderate to high dry strength. Grains subrounded to rounded.

Section 3 - 10-15 ft.

Dark brown loose material with few cobbles grading into light brown and yellow material with many large cobbles, top to bottom. Also, increasing sand toward bottom of section.

304-337 cm.

5YR 5/2 Pale brown overall, variable to darker brown and lighter yellowish orange.

Moderately sorted. 10% gravel, 45% sand, 45% fines.

Grains angular to subangular. Gravel-sized clumps with low dry strength. Minor organic woody debris near base of interval.

Provenance white clean sandstones and purple hematite-cemented sandstones.

337-375 cm.

5YR 2/2, 5YR 5/2, and 10YR 8/6 Dusky and pale brown and pale yellowish orange, varying, with local 5RP 2/2, very dusky purple.

Poorly sorted. 40% cobbles, 30% gravel, 15% sand, 15% fines.

Grains subrounded to rounded. Several boulder-sized clasts rounded and broken by the drill (counted as cobbles) near base of interval. Most large clasts are white sandstone with Fe-staining. Some clumps with low dry strength.

375-381 cm.

5YR 7/2 Grayish orange pink.

Well-sorted. 80% sand, 20% fines.

Grains rounded to well rounded. Different provenance - lightly purple-stained sandstone source cobble.

Few, small clumps only, with very low dry strength.

381-400 cm.

10YR 8/2 to 5Y 8/4 Very pale orange to grayish yellow with patches of 5RP 2/2, very dusky purple.
Poorly sorted. 20% cobbles, 40% gravel, 30% sand, 10% fines.
Grains rounded to well-rounded. Gravel is mostly fragments of one or more larger white sst. cobbles, cut by drill. Fe-stained yellow. Few, gravel-sized clumps have low dry strength.

400-414 cm.

10YR 7/6 Yellowish orange.
Moderately sorted. 30% gravel, 60% sand, 10% fines.
Grains subrounded to well rounded. Sand from disintegrating cobbles and pebbles - very crumbly, very Fe-stained.

414-431 cm.

10YR 8/2 Very pale orange, with a darker orange patch near top of interval.
Poorly sorted. 10% cobbles, 40% gravel, 30% sand, 20% fines.
Subrounded to rounded grains. Gravel mostly sst. cobble fragments. A few clumps, with very low to low dry strength.

431-456 cm. (END OF SECTION)

10YR 8/2, 5YR 7/2, and 5RP 7/2 Very pale orange, grayish orange, and pink.
Poorly sorted. 20% cobbles, 40% gravel, 25% sand, 15% fines.
Common rounded, coarse sand. Gravel is fragments of larger pinkish fine sandstone cobbles.

18 June 2003

Section 4 - 15-20 ft.

Loose sandy mixed material grading downward into clay-rich, cobble-rich, orange-yellow material, with increasing pinkish purple toward bottom of section. First 25 and last 15 cm of this section are loose in the liner, not packed, and have probably been mixed. They have also slumped so are overrepresenting the vertical length of their respective intervals.

456-482 cm.

5YR 5/2 Pale brown overall, but variable between 5YR 3/2, grayish brown, and 10YR 7/6, yellowish orange.
Poorly sorted. 35% gravel, 45% sand, 20% fines.
Grains subangular to subrounded. Very loose material, composed of grains of different colors and sources. Little clay.

482-537 cm.

10YR 7/6 Yellowish orange, with local minor purplish patches.
Poorly sorted. 25% cobbles, 25% gravel, 15% sand, 35% fines
Cobble-rich silty orange clay. Grains angular to subrounded. Clumps are common and have moderate dry strength.

537-592 cm. (END OF SECTION)

10YR 7/6 and 5RP 7/2 Yellowish orange and pink, mixed evenly in cm-scale patches. Increasing orange

near base of interval.

Poorly sorted. 10% cobbles, 25% gravel, 25% sand, 40% fines.

Grains angular to subangular. Many pebbles well rounded, however. More and smaller clumps than section above. Orange clumps more clay-rich with moderate dry strength, pink clumps more sand/silt rich with low dry strength. Some clumps mixed colors/materials.

Section 5 - 20-25 ft.

Orange and purple cobbly clay, with increasing purple and decreasing cobble size downsection. First 20 and last 20 cm of this section are loose in the liner, not packed, and have probably been mixed. They have also slumped so are overrepresenting the vertical length of their respective intervals.

592-644 cm.

10YR 7/4 to 10YR 7/6 Grayish orange to yellowish orange, with patches of 5RP 6/2, pale red purple.

Poorly sorted. 50% cobbles, 20% gravel, 10% sand, 20% fines.

Grains angular to subangular. Pebbles and cobbles well rounded. Fewer intact cobbles toward bottom of interval. Many clumps, size ranging from coarse sand to small cobble-sized. Dry strength moderate. Very clay-rich.

644-657 cm.

10YR 6/6 and 10YR 8/2 Dark yellowish orange and very pale orange to white, with minor pink, varied.

Poorly sorted. 30% cobbles, 30% gravel, 25% sand, 15% fines.

Grains subrounded to well rounded. Some coarse sand, from decomposing white sst. cobble, very well rounded and etched.

657-670 cm.

5RP 7/2 Pink is dominant. Minor 10YR 7/6, yellowish orange.

Poorly sorted. 30% cobbles, 30% gravel, 25% sand, 15% fines.

Grains subrounded to well rounded. Zone of decomposing pinkish cobbles. Sand is mostly fine sand. clumps have low to moderate dry strength.

670-710 cm. (END OF SECTION)

10YR 7/4 Grayish orange overall, variable from 5YR 7/2 to 10YR 8/6, grayish orange pink to pale yellowish orange. Grayer/pinker toward base of interval.

Moderately sorted. 10% cobbles, 60% gravel, 15% sand, 15% fines.

Grains subrounded. Mixed provenance; purplish, pinkish, white sandstone sources.

Section 6 - 25-30 ft.

Entire section uniform material. Orangish clay supporting well rounded cobbles and pebbles. First 20 cm of this section is loose in the liner, not packed, and has probably been mixed. It has also slumped so it is overrepresenting the vertical length of this interval. At about 818 cm. is an 8 cm. section of core that retained its shape and is clearly rotated wrt the liner, presenting evidence for mixing within the core boxes.

710-841 cm. (END OF SECTION)

10YR 5/4 to 10YR 8/6 Moderate yellowish brown to pale yellowish orange, with subordinate 5RP 7/2, pink, which decreases in abundance toward bottom of section.

Poorly sorted. 30% cobbles, 15% gravel, 15% sand, 40% fines.

Subrounded grains. Pebbles and cobbles well rounded. Most of the finer grains are in gravel-sized clumps with low to moderate dry strength. Matrix is silty clay. Cobbles are dominantly white with some pink sandstones. Pinkish cobbles are weaker and more crumbly than white cobbles.

Section 7 - 30-35 ft.

Orangish clay with rounded cobbles changing downward into dominantly purplish sandy clay, then looser, sandier yellowish material with increasing purple to end of section. First 20 cm of this section is loose in the liner, not packed, and has probably been mixed. It has also slumped so it is overrepresenting the vertical length of this interval. Intact core in correct orientation starts at 864 cm.

841-874 cm.

10YR 6/2 to 10YR 8/6 Pale yellowish brown to pale yellowish orange.

Poorly sorted. 30% cobbles, 15% gravel, 15% sand, 40% fines.

Grains subangular to subrounded; cobbles/pebbles well rounded. Similar to interval above it.

874-909 cm.

5RP 7/2 to 10YR 5/4 Pink dominant grading to moderate yellowish brown. Minor 10R 6/6, moderate reddish orange.

Poorly sorted. 50% cobbles, 15% gravel, 10% sand, 25% fines.

Grains subrounded. Clumping prevalent, clumps have moderate dry strength. A zone of concentrated purplish cobbles.

909-930 cm.

5Y-10YR 8/6 Pale yellow to pale yellowish orange.

Moderately sorted. 15% gravel, 45% sand, 40% fines.

Grains subrounded to rounded. Sand is mostly fine sand. Many small clumps with low dry strength.

930-969 cm. (END OF SECTION)

5RP 5/2, 10YR 8/6, and 10YR 8/2 to N9 Red purple, pale yellowish orange, and very pale orange to white, mixed. Decreasing purple and increasing white toward bottom of interval.

Poorly sorted. 10% cobbles, 30% gravel, 40% sand, 20% fines.

Grains subangular to subrounded. Sand increasingly coarse toward bottom of interval. Common clumps with moderate dry strength. Overall loose material.

19 June 2003

Section 8 - 35-40 ft.

Dominantly cobbly material in light brown clay, retaining the shape of the core, with one ~40 cm. sandier, looser interval near the base of the section.

969-1058 cm.

10YR 7/4 to 10YR 6/6 Grayish orange to dark yellowish orange, homogenous, with rare streaks of 5RP

5/2, red purple.

Poorly sorted. 10% cobbles, 20% gravel, 30% sand, 40% fines.

Grains subangular to subrounded. Pebbles well rounded. Sandy clay; entire interval retains cylindrical shape; clumps have moderate dry strength. Very minor component of sand (~1-2%) appears to be dark minerals - probably hematite.

1058-1091 cm.

10YR 6/6 and 10R 6/6 Dark yellow orange dominant with subordinate moderate reddish orange, variegated.

Poorly sorted. 10% cobbles, 30% gravel, 40% sand, 20% fines.

Grains subrounded. Clumps are small and have moderate dry strength.

1091-1114 cm. (END OF SECTION)

10YR 7/4 to 10YR 6/6 Grayish orange to dark yellowish orange, homogenous.

Poorly sorted. 10% cobbles, 20% gravel, 40% sand, 30% fines.

Grains subrounded. Clumps have moderate dry strength. Most of interval retains core's shape. Very minor component of sand (~1-2%) appears to be dark minerals - probably hematite.

Section 9 - 40-45 ft.

Orange cobbly clay, downward across a sandier whitish band into purplish clay, then grading into cobblier, grayer material at the base of the section.

1114-1132 cm.

10YR 5/4 to 10YR 6/6 Moderate yellowish brown to dark yellowish orange, homogeneous.

Poorly sorted. 20% cobbles, 20% gravel, 35% sand, 25% fines.

Grains subrounded. Clumps have moderate dry strength.

1132-1147 cm.

10YR 8/4 and 10YR 6/6 Very pale orange to pale yellowish orange with dark yellowish orange, variegated.

Poorly sorted. 25% gravel, 50% sand, 25% fines.

Orangish clumps scattered in a zone of mostly whitish, sandy clumps with moderate dry strength. Grains subrounded to well rounded.

1147-1195 cm.

5YR 5/2 to 10YR 6/6 Pale brown to dark yellowish orange, variegated.

Poorly sorted. 10% cobbles, 20% gravel, 30% sand, 40% fines.

Grains subangular to subrounded. Clumps have moderate dry strength. Many small pebbles are darkly stained purplish-gray.

1195-1240 cm. (END OF SECTION)

10YR 8/2 to 10YR 6/6 and 5RP 5/2 Very pale orange to dark yellowish orange with patches of red purple.

Poorly sorted. 30% cobbles, 20% gravel, 20% sand, 30% fines.

Grains subangular to subrounded. Large white sst. cobbles, some cut by drill. Clumps have moderate to high dry strength. Yellowish clumps are sandier than purplish clumps.

Section 10 - 45-50 ft.

Entire section uniform material. Yellow-orange clay, retaining the shape of the core wrapper (flattened in places from cylindrical by the box). Wrapper coated on the inside with clay - this was wet clay.

1240-1355 cm. (END OF SECTION)

10YR 6/6 Dark yellowish orange, homogeneous. Rare spots of 5R 6/6, light red.

Poorly sorted. 20% cobbles, 20% gravel, 30% sand, 30% fines.

Grains subrounded. Decreasing sand, increasing fines toward bottom of section. Increasing occurrence of pink/purple material toward bottom, but it is still minor. One small pebble of feldspar identified near base of section - seems to be Na-plag - squarish, w/rounded corners. Majority of cobbles are hard quartz sst. or quartzite.

Section 11 - 50-55 ft.

Orange clay interrupted by a short section of sandier purple and yellow material. Entire section retains core shape. Clay still retains some moisture. Whitish-purple veneer on outside of core - breakdown products of original core material. This veneer wipes off easily revealing actual colors.

1355-1395 cm.

10YR 5/4 to 10YR 6/6 Moderate yellowish brown to dark yellowish orange.

Poorly sorted. 10% cobbles, 25% gravel, 20% sand, 45% fines.

Grains subangular to subrounded. Slightly pliable clay (no dry strength estimate).

1395-1427 cm.

5RP 4/2 to 5R 5/4, 10YR 8/4, and 10YR 5/6 Grayish red purple to moderate red, very pale orange to yellowish orange, and dark yellowish orange, mixed.

Moderately sorted. 20% gravel, 30% sand, 50% fines.

Grains subangular to subrounded. Whitish clay, whitish sand interspersed with purpleish and yellow clay. Less coherent than the rest of the section. Slightly pliable clay (no dry strength estimate). Whitish clay seems to be from feldspar pebbles

1427-1478 cm. (END OF SECTION)

10YR 6/6 Dark yellowish orange with streaks of 5R6/2, pale red.

Moderately-well sorted. 10% gravel, 15% sand, 75% fines.

Grains subangular. Common feldspar pebbles (not abundant).

Very coherent clay. Slightly pliable.

20 June 2003

Section 12 - 55-60 ft.

Short interval of light yellow clay with feldspar pebbles down into dark yellow-orange clay for the rest of the section. Orange clay is still moist. Entire interval retains the shape of the core. Few, if any, cobbles in this section.

1478-1503 cm.

5Y 8/4 to 10YR 8/4 Pale grayish yellow orange, homogenous.

Moderately-well sorted. 10% gravel, 10% sand, 80% fines.

Grains angular to subangular. Pebbles squarish, not rounded. Majority of pebbles feldspar. Clumps have moderate dry strength.

1503-1630 cm. (END OF SECTION)

10YR 6/6 to 10YR 7/4 Dark yellowish orange to grayish orange, with common streaks of 5R 6/2, pale red. Reddish streaks decrease in abundance toward base of interval.

Well sorted. 5% gravel, 5% sand, 90% fines.

Grains angular to subangular. Pebbles are squarish or subangular. Quartz, feldspar grains dominant with some hematite grains. Clay is moist.

Section 13 - 60-65 ft.

Lighter orange clay downward into darker orange clay with red streaks. Decomposed feldspar grains throughout. Entire section retains core shape and is very moist, sticky.

1630-1681 cm.

10YR 6/6 Dark yellowish orange dominant, with minor streaks of redder or lighter color.

Moderately-well sorted. 10% gravel, 10% sand, 80% fines.

Grains subangular to angular. Pebbles dominantly qtz and feldspar. Whitish patches mark decomposing feldspar grains.

1681-1764 cm. (END OF SECTION)

10YR 5/4 and 5YR 4/6, Moderate yellowish brown and moderate brown, streaked. Minor patches of dark gray or whitish.

Moderately-well sorted. 15% gravel, 10% sand, 75% fines.

Grains subangular. Common decomposing feldspars and minor hematite.

Section 14 - 65-70 ft.

Reddish clay except where decomposing feldspar cobbles are intersected - large whitish patches - and increasing hematite toward bottom of section. Core has a lighter orange "rind" and is mostly dry.

1764-1916 cm. (END OF SECTION)

10YR 6/6 Dark yellowish orange with patches of 5Y 8/4 and 5YR 3/2, grayish yellow and grayish brown.

Well sorted. 5% pebbles, 95% fines. Virtually no sand.

Very abundant light patches from large feldspar cobbles, decomposed into soft material. Dark patches appear to be hematitic. Dry strength is moderate to high.

Section 15 - 70-75 ft.

Orange-brown clay, moist, with decomposing feldspar and hematite. Similar to overlying section.

1916-2061 cm. (END OF SECTION)

10YR 5/4 to 10YR 6/6 Moderate yellowish brown to dark yellowish orange. Darker orange, more brown toward base of section.

Well sorted. 5% gravel, 5% sand, 90% fines.

Grains subangular. Abundant light patches from large feldspar cobbles, decomposed into soft material.

Dark patches appear to be hematitic.

10 September 2003

Section 16 - 75-80 ft.

Orange-brown clay, dry, with decomposed feldspar and chert pebbles.

2061-2152 cm. (END OF SECTION)

10YR 7/4 to 10 YR 6/6 Grayish orange to dark yellowish orange.

Well sorted. 5% gravel, 10% sand, 85% fines.

Common angular chert pebbles. Common clay films in cracks and on pebbles. Abundant light patches. Dry strength moderate to high.

Section 17 - 80-85 ft.

Orange clay, slightly moist, with chert pebbles increasing toward base of section.

2152-2271 cm.

10YR 6/6 Dark yellowish orange. Some redder and browner mottling.

Well sorted. 5% pebbles, 5% sand, 90% fines.

Common subangular to angular chert pebbles. Common clay films in cracks and on pebbles.

2271-2296 cm. (END OF SECTION)

10YR 5/4 and 5YR 5/6 Moderate yellowish brown surrounding light brown material.

Moderately well sorted. 10% gravel, 5% sand, 85% fines.

Abundant angular chert pebbles and granules. Abundant clay films in cracks and on pebbles. Seems to exhibit angular blocky soil structure.

Section 18 - 85-90 ft.

Dark brown clay with light section at base.

2296-2409 cm.

10YR 4/4 Dark yellowish brown with minor reddish and yellowish mottling.

Moderately well sorted - 10% gravel, 10% sand, 80% fines.

Abundant chert pebbles.

2409-2421 cm. (END OF SECTION)

10Y 8/2 Pale greenish yellow, with streaks of 10YR 4/2 dark yellowish brown and reddish clay films.

Cohesive in platy structure with common dark veins and clay films.

Section 19 - 90-95 ft.

Mottled light yellow platy material grading to orange and brown clay.

2421-2490 cm.

10YR 8/2 Very pale orange, with streaks of 10YR 4/2 dark yellowish brown and reddish clay films.

5% gravel, 25% sand, 70% fines.

Blocky subangular structure, eluvial horizon from paleosol?

Gradational to more light brown clay.

2490-2539 cm. (END OF SECTION)

10YR 6/6 Dark yellowish orange with ~15% marbling of 10YR 4/2 dark yellowish brown at top of interval.

Lighter and darker mottling throughout.

5% gravel, 20% sand, 75% fines.

Blocky structure apparent at base of interval. Minor component of clay films. Illuvial horizon assoc.

w/overlying pale horizon?

7 October 2003

Section 20 - 95-100 ft.

Dry orange clay with a pale whitish horizon in the middle of the section.

2539 - 2592 cm.

10YR 6/6 Dark yellowish orange with common clay films.

5% gravel, 5% sand, 90% fines.

Gravel is mostly angular chert pebbles.

2592 - 2649 cm.

N9 White to 10YR 8/2 very pale orange, with common clay films.

5% gravel, 20% sand (fine), 75% fines.

Not calcic. No reaction to HCl.

2649 - 2691 cm. (END OF SECTION)

10YR 6/6 Dark yellowish orange with common clay films.

5% gravel, 20% sand (fine), 75% fines.

Small component of white material.

Section 21 - 100-105 ft.

Very moist dark orange silty material.

2691-2820 cm. (END OF SECTION)

10YR 5/4 Moderate yellowish brown, with common redder clay concentrations.

Moist enough to texture - textures as silt loam.

5% gravel, 15% sand (fine), 80% fines (mostly silt - perhaps 20% clay).

Section 22 - 105-110 ft.

Very moist, dark, silty/sandy material.

2820-2916 cm. (END OF SECTION)

10YR 4/4 Moderate yellowish brown, with few redder clay concentrations.

Moist enough to texture - textures as fine sandy loam.

55% sand, 45% fines (mostly silt - perhaps 15% clay).

Coarse-sand sized chert fragments abundant at top of section, decreasing to rare at the bottom. Pickets of increased sandiness at bottom of section.

Section 23 - 110-115 ft.

Dark orange silty material, coarsening and more mottled toward base of section.

2916-2975 cm.

10YR 6/6 Dark yellowish orange, with darker patches.

Textures as silt loam.

35% sand, 50% silt, 15% clay.

Abrupt lower boundary.

2975-3014 cm.

10YR 6/6 Dark yellowish orange to 10YR 4/2, dark yellowish brown, varied.

Vast increase in coarse sand and gravel - textures as sandy loam.

15% gravel, 45% sand, 40% fines.

Sand is angular quartz.

3014-3035 cm. (END OF SECTION)

10R 1/2 Very dusky red, 10YR 4/2 dark yellowish brown, and 10YR 6/6 dark yellowish orange, variegated.

10% gravel, 50% sand, 40% fines.

Orange patches are dominated by clay-coated, angular, coarse quartz sand. Purplish patches are hematitic fine sandstone fragments, highly decomposed.

9 October 2003

Section 24 - 115-120 ft.

Brown sand into white fine sand with angular gray sandstone fragments, gradational to dark brown sandy clay.

3035-3066 cm.

10YR 5/4 Moderate yellowish brown.

80% sand (dominantly fine-v. fine), 20% silt and clay.

Abrupt lower boundary.

3066-3102 cm.

10YR 8/2 Very pale orange to white.
40% gravel/cobbles, 50% sand (fine-v.f.), 10% fines.
Abundant angular gray sandstone fragments.

3102-3131 cm.

10YR 8/2 Very pale orange to 10YR 5/4 moderate yellowish brown, mixed, with marbling of darker brown.
20% gravel, 50% sand, 30% fines (silt).
Mixed material - intermediate between layers above and below.

3131-3167 cm. (END OF SECTION)

10YR 2/2 Dusky yellowish brown dominant, with common patches of lighter brown sand.
50% sand (fine-v. fine), 50% fines.

Section 25 - 120-125 ft.

White and brown sand with darker, finer material at the base of the section.

3167-3189 cm.

10YR 8/2 Very pale orange to 10YR 5/4 moderate yellowish brown, mixed, with marbling of darker brown.
40% gravel, 40% sand, 20% fines (silt).
Mixed material - intermediate between layers above and below.

3189-3222 cm.

10YR 8/2 Very pale orange to white.
40% gravel/cobbles, 40% sand (fine-v.f.), 20% fines (silt dominated).
Abundant angular gray sandstone fragments.

3222-3240 cm.

10YR 8/2 very pale orange to grayish orange.
40% gravel/cobbles, 40% sand (fine-v.f.), 20% fines (silt dominated).
Abundant angular gray and light brown sandstone fragments.

3240-3265 cm. (END OF SECTION)

5YR 3/4 Moderate brown, variable, with abundant patches of lighter brown.
15% gravel, 35% sand (fine-v. fine), 50% fines.

Section 26 - 125-130 ft.

Brown fine sandy material with clean white sand/silt at very base of interval.

3265-3352 cm.

10YR 6/4 Grayish orange, fairly uniform.
75% sand (v.f.), 25% fines (dom. silt).
Few angular coarse sand fragments.

3352-3364 cm. (END OF SECTION)

N9 White, partially mixed with 10YR 6/4 grayish orange.
70% sand, 30% fines (dom. silt).

13 October 2003

Section 27 - 130-135 ft.

Fine white powder surrounding quartzite fragments into brown silty material at base.

3364-3469 cm.

N9 White with light gray rock fragments.
40% rock/gravel, 35% sand (v. fine), 25% fines.
Angular rock fragments, cut into whole or partial cylinders by drill. 3386-3402 cm. is a continuous core section through hard, light gray, fine grained sandstone/quartzite. Other fragments are of the same rock. The occurrence of this clean white powder probably marks the destruction of such rocks by the drill and is thus not a depositional feature.

3469-3515 cm. (END OF SECTION)

10YR 5/4 Moderate yellowish brown, some lighter brown patches.
10% gravel, 50% sand (fine-v. fine), 40% fines.
Gravel fragments dominantly angular to subangular gray sst/qtzite.

Section 28 - 135-140 ft.

Fine brown material into gravelly, light brown and white material.

3515-3594 cm.

10YR 5/4 Moderate yellowish brown, some lighter and darker brown marbling.
10% gravel, 50% sand (fine-v. fine), 40% fines.

3594-3667 cm. (END OF SECTION)

10YR 5/4 Moderate yellowish brown and N9 white, mixed roughly evenly but not homogeneously.
50% gravel, 30% sand, 20% fines.
Gravel is mostly subangular hard sst. fragments, with some more rounded pebbles.

Section 29 - 140-144 ft.

White powdery/gravelly material into brown fines surrounding rock fragments.

3667-3736 cm.

N9 White with light gray rock fragments and few light brown coatings

20% rock/gravel, 45% sand (v. fine), 35% fines.

Less gravelly than similar horizons (less competent rock?).

3736-3790 cm. (END OF CORE)

10YR 5/4 Moderate yellowish brown surrounding gray rock pieces.

50% rock, 20% sand (v. fine), 30% fines.

Cobble-sized fragments of gray rock suspended in finer material. Rock is hard sandstone, but light patches could be decomposed limestone bedrock.

APPENDIX C: Soil density data from cosmogenic sampling sites

SITE	TRDW01	TRDW01	TRDW01	TRDW01	
Elevation (m)	128	128	128	128	
Sample depth (m)	2.0	1.5	1.0	0.5	
Weight of sand (lbs)	2.13	2.19	2.00	3.38	
Mass of sand (g)	963.88	992.23	907.18	1530.87	
Volume of hole (cc)	655.70	674.99	617.13	1041.41	
Wet mass of soil (g)	1442.80	1267.10	1290.30	1428.70	
% Water	16.73	18.70	23.70	18.61	
Dry mass of soil (g)	1201.42	1030.15	984.50	1162.82	
Wet density of soil (g/cc)	2.20	1.88	2.09	1.37	
Dry density of soil (g/cc)	1.83	1.53	1.60	1.12	
SITE	TRDW02	TRDW02	TRDW02	TRDW02	TRDW02
Elevation (m)	50	50	50	50	50
Sample depth (m)	2.5	2.0	1.5	1.0	0.5
Weight of sand (lbs)	2.63	2.25	2.13	1.94	1.75
Mass of sand (g)	1190.68	1020.58	963.88	878.84	793.79
Volume of hole (cc)	809.99	694.27	655.70	597.85	539.99
Wet mass of soil (g)	1560.50	1513.90	1241.50	1252.50	1097.10
% Water	16.80	18.80	17.70	16.79	12.80
Dry mass of soil (g)	1298.34	1229.29	1021.75	1042.21	956.67
Wet density of soil (g/cc)	1.93	2.18	1.89	2.10	2.03
Dry density of soil (g/cc)	1.60	1.77	1.56	1.74	1.77
SITE	TRDW03	TRDW03			
Elevation (m)	20	20			
Sample depth (m)	1.5	0.5			
Weight of sand (lbs)	1.68	1.88			
Mass of sand (g)	759.77	850.49			
Volume of hole (cc)	516.85	578.56			
Wet mass of soil (g)	1064.60	1398.40			
% Water	27.20	12.55			
Dry mass of soil (g)	775.03	1222.90			
Wet density of soil (g/cc)	2.06	2.42			
Dry density of soil (g/cc)	1.50	2.11			
SITE	TRDW04	TRDW04	TRDW04	TRDW04	TRDW04
Elevation (m)	10	10	10	10	10
Sample depth (m)	2.5	2.0	1.5	1.0	0.5
Weight of sand (lbs)	3.00	2.06	1.94	1.81	1.94
Mass of sand (g)	1360.78	935.53	878.84	822.14	878.84
Volume of hole (cc)	925.70	636.42	597.85	559.28	597.85
Wet mass of soil (g)	1697.40	1402.50	1410.60	1307.50	1200.70
% Water	21.06	20.82	20.58	15.10	20.10
Dry mass of soil (g)	1339.93	1110.50	1120.30	1110.07	959.36
Wet density of soil (g/cc)	1.83	2.20	2.36	2.34	2.01
Dry density of soil (g/cc)	1.45	1.74	1.87	1.98	1.60
SITE	DIRECT1	DIRECT1	DIRECT1	DIRECT1	DIRECT1
Elevation (m)	70	70	70	70	70
Sample depth (m)	2.5	2.0	1.5	1.0	0.5
Weight of sand (lbs)	2.44	2.31	2.19	2.50	2.81
Mass of sand (g)	1106.77	1047.80	993.37	1133.98	1274.59
Volume of hole (cc)	752.90	712.79	675.76	771.42	867.07
Wet mass of soil (g)	1746.70	1609.40	1585.20	1843.60	1991.80
% Water	8.82	13.16	16.98	9.39	8.84
Dry mass of soil (g)	1592.66	1397.60	1316.03	1670.43	1815.80
Wet density of soil (g/cc)	2.32	2.26	2.35	2.39	2.30
Dry density of soil (g/cc)	2.12	1.96	1.95	2.17	2.09

APPENDIX D: AMS results

VITA

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Research Interests

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Publications

Ward, Dylan, Gregory Hancock, and James Spotila (2004). Testing the roles of climate, tectonics, and bedrock lithology in the late cenozoic incision history of the new river. *GSA Abstracts with Programs*, 36.

Ward, Dylan, Gregory Hancock, James Spotila, and Richard Law (2003). Testing the roles of climate, tectonics, and bedrock lithology in the late cenozoic incision history of the new river. *GSA Abstracts with Programs*, 35.

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