Extrinsic terrace formation processes and tectonically driven river incision along the South Anna River, Virginia

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Extrinsic terrace formation processes and tectonically driven river incision along the South Anna River, Virginia

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(Matthew McGavick)
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Abstract

Deep residual soils, saprolite, erosion rates inferred from alluvial terrestrial cosmogenic nuclide (TCN), and long-term river incision rate data all point to a slow pace of landscape evolution for the Appalachian Piedmont west of the Fall Zone measured in rates of $10^0$ – $10^1$ m/My. New data collected as part of a mapping and geochronologic study following the 2011 M 5.8 Mineral earthquake in Louisa County, central Virginia challenges this notion of a uniformly slowly evolving landscape, and also helps to demonstrate the exogenic impacts of climate change and active tectonics on the South Anna basin. This paper documents the ages and characteristics of the terrace stratigraphy in the hanging wall of the Quail Fault that ruptured in 2011, measured with respect to channel elevation, for the South Anna River. Six mostly paired strath terraces (Qt1 – Qt6) are incised into the hanging wall. Qt1 and Qt2 lie > 27 m in elevation, are highly dissected, and characterized by alluvium mixed with residual soil thought to be middle-early Pleistocene age. From Qt3 through Qt5, alluvial deposits underlie mappable terrace landforms and preserve distinct, locally cumulic soils. The Qt3 terrace strath lies ~25 m and has a deeply weathered, red (2.5YR) gravelly silty clay soil with mid-Pleistocene Infrared Stimulated Luminescence (IRSL) and TCN ages. Qt4a lies ~20 m and has an orange (7.5 YR) gravelly clay loam soil with Optically Stimulated Luminescence (OSL) ages between 120-150 ka. Qt4b lies ~15 m and has a reddish brown (10YR) clayey silt soil with OSL and IRSL constraining ages of 75-100 ka, respectively. Qt5 lies ~3 m and has a brownish yellow (10 YR – 2.5 Y) loamy clay soil with an OSL age of 45-65 ka. The relatively thick terrace fills and their age distribution are collectively consistent with exogenic climatic changes driving terrace formation. Furthermore, the elevations of the
terrace straths in the hanging wall are in sharp contrast to the footwall terrace elevations, where Qt4a-Qt6 all lie close to the modern river level. Long-term river incision varies from ~17 - 88 m/my in both the hanging wall and footwall when averaged over middle Pleistocene time scales (~400 ka). However, distinct exogenic tectonic forcing on incision unsteadiness is apparent in an acceleration of rapid incision at rates of ~340 m/My recorded only in the hanging wall from ~100 - 60 ka.

Introduction

Fluvial terraces are inset into river valleys in a wide range of tectonic and climatic settings and are commonly used as important geomorphic and stratigraphic markers in geologic, geodynamic, and paleo-environmental studies. The distribution of terraces engenders several global models for their formation that can be organized into two groups: (1) those that appeal to extrinsic forcings such as changes in climate or base level (tectonics) that drive drainage basin-wide unsteadiness in discharge, sediment supply, and sediment transport (Bull, 1991), and (2) those that appeal to intrinsic forcings related to intrinsic unsteadiness in fluvial processes (Hadley and Schumm, 1957; Finnegan and Dietrich, 2011; Limaye and Lamb, 2016). Processes related to intrinsic unsteadiness and stochastic distributions of fluvial incision are currently experiencing a resurgence in interest as they explain apparent incision acceleration in many well-mapped terrace sequences (Finnegan et al., 2013). These ideas stand in contrast with more traditional models that appeal to extrinsic forcings that can be temporally correlated to well-documented environmental changes, providing a mechanism for applying an age model
in the absence of numeric ages (Bull, 1991, reviewed in Pazzaglia, 2013) and provide a basis for understanding stratigraphic architectures in basin sedimentary sequences.

Most likely, both extrinsic and intrinsic processes build terraces segregated by scale, with the intrinsic terraces restricted to small time (millennial) and space < 1 km scale, that collectively contribute to a coarser, but more spatially continuous extrinsically-produced stratigraphy at long time ($10^5$ yrs) and space (> 1 km) scales. Extrinsically formed terraces should be paired, long-traceable landforms that are sub-parallel with the river channel, have a common tread age reflected in soil development, and have clear temporal correlation to known climate changes. Depending on the accommodation space related to local crustal deformation, these terraces have the potential to be well preserved in the geologic record. Intrinsically formed terraces are unpaired, not long and traceable or sub-parallel to the river channel, have treads with highly variable soils, and have no systematic temporal coincidence to well-documented climatic changes. It is challenging to preserve intrinsic-processes in the geologic record, so a deep time record of these terraces can be difficult to analyze.

Natural experiments exist that may help quantify the respective contributions of the intrinsic and extrinsic unsteadiness in terrace formation. For example, recent detailed geologic and geomorphic observations, including the completion of a 1:24,000 scale map of the South Anna River, central Virginia Piedmont, in response to the 2011 Mineral earthquake, reveal a datable terrace stratigraphy with the potential to apportion the relative contributions of intrinsic and extrinsic unsteadiness in terrace formation (Malenda, 2015; Pazzaglia, 2015). Although thorough in its coverage of terrace alluvium and local, relative stratigraphic relationships, the work to date lacks clear confirmation of
terrace ages spatially, how they correlate longitudinally along the river profile, and the influence of active tectonics on terrace genesis and river incision rates. The goal of this thesis is to test previous terrace genesis hypotheses and to determine the relative contributions of extrinsic and intrinsic forcings on the South Anna terraces. Secondarily, within the context of these external forcings on South Anna river processes, this thesis addresses historical river incision rates and attempts to document evidence for tectonic activity prior to the 2011 Mineral earthquake.

In an active tectonic setting, the history of terrace formation and incision rates is both a direct consequence of and has a dynamic interaction with rock deformation (Bull, 1991; Merritts et al., 1994; Pazzaglia et al., 1998; Wegmann et al., 2002). A key debate is how tectonic processes can be isolated from the myriad of climatic and intrinsic river processes that also influence the genesis and subsequent preservation of fluvial stratigraphy (Schumm et al., 1993; Bull, 1991; Hancock and Anderson, 2002). For example, rapid rates of rock uplift, similar to what may occur in the hanging wall of the Quail Fault, and changes in base level that accompany both co- and interseismic deformation introduce the potential for rivers to incise and abandon their valley bottoms as the relative base level changes. (Bull, 1991). The precise manner in which the rivers accomplish that incision and what terrace record will be left behind, however, appears to be dominated by how the watershed responds to changes in climate shifts (Bull, 1991; Wegmann et al., 2002). Due to age constraints on both terrace formation and climate shifts in the region and vertically separated terrace deposits, the South Anna River leaves behind a relatively high-resolution record of its incision. The rate of incision is commonly interpreted in terms of the rate of rock uplift with the assumption that terrace
formation is the result of a short-term disruption of river equilibrium, followed by a river
adjustment back to near-equilibrium conditions (Mackin, 1948).

With these ideas in mind, this paper seeks to provide a better understanding of
terrace formation and chronology and incision rates in the uplifting hanging wall of the
Quail Fault. Specifically, the thesis will build off of previous work dating and analyzing
the soil of terrace deposits in the footwall of the Quail Fault. Additionally, this thesis will
document how and why terraces form in the hanging wall of the reverse fault and explain
differences in incision rates both spatially and temporally. Secondarily, this paper seeks
to develop a soil chronosequence of the terrace deposits along the South Anna. Terraces
are well exposed along the South Anna River, allowing for the unique opportunity to
analyze and date the terrace deposits in order to build a terrace stratigraphic model. OSL
and IRSL absolute dating techniques of the terrace deposits are supplemented by relative
dating techniques such as heavy mineral analysis, soil stratigraphy and morphology, and
iron chemistry. These numeric and relative dating methods, in addition to previous work
in the subsiding, footwall of the Quail Fault, allows for the interpretation of the extrinsic
and intrinsic process conditions under which the South Anna terraces form and
establishes limits to some assumptions as to how these terraces can be used to interpret
the nature and rates of active tectonic processes.

Setting and Background

Location, Geology, Topography, Climate

The study area is located in Louisa County, Virginia in the Appalachian Piedmont
geologic and physiographic province approximately 65 km northwest of Richmond and
150 km south of Washington D.C. This part of the central Virginia Piedmont is underlain by meta-volcanic, volcanioclastic, and igneous rocks emplaced and deformed during the early Paleozoic Taconic Orogeny (Pavlides 1989; Horton, 1989; Hughes et al., 2013, Fig. 1 and 2). The structural grain of these rocks strikes northeast, and from the northwest to southeast is characterized by the middle Ordovician Chopawamsic Formation, composed of amphibolite-grade mica schist and gneiss intruded by Ordovician-Silurian aged Ellisville biotite-bearing granodiorite, the late Ordovician aged Quantico Formation, composed of phyllite, schist and quartzite, and the Middle Ordovician aged Ta River Metamorphic Suite, composed of amphibolite and biotite gneiss. The Proterozoic aged Goochland Terrane, consisting of deformed and metamorphosed gneiss, amphibolite, granite, and anorthosite (Spears, 2004) borders the study area to the southeast (Fig. 2). Although there are a variety of lithologies, erodibility in the region is largely uniform. (Malenda et al., 2015).

Elevations above sea level in the central Virginia Piedmont range from ~50 m for the valley bottoms to ~150 m for the upland interfluves. These interfluves define a rolling upland with 10-20 m of relief that contrasts with the locally deeply incised, steep river valleys. The South Anna River basin stands higher, on average, with respect to the North Anna drainage to the northeast and the James River to the southwest. The headwaters flow at an elevation of approximately 305 m and fall to sea level east of the Fall Zone following a steep, gently concave profile (Fig. 3). In the study region around Louisa County, the river falls from ~ 85 m to 70 m.
Figure 1: A map of the eastern United States geology with an inset topographic map of the study region (Pazzaglia et al., 2015)
Figure 2: A geologic map showing the major geologic units that the South Anna River (blue) traverses. The study area is highlighted in red. CZm and PzYm are metaclastic passive margin sediments. Yp, Ya, and Yg are Proterozoic granatoids and gneiss. Pzg and Pzgp are Paleozoic intrusives. Oc, Oq, and SOg are Taconic metavolcanics and volcaniclastics. N are Neogene Coastal Plain sediments.

**South Anna River and Geomorphologic setting**

The South Anna River drains ~1,025 km² of the central Virginia Piedmont. The river heads on the east flank of the Blue Ridge and flows southeast for ~160 km before crossing the Fall Zone north of Richmond where it joins the North Anna River to become
the Pamunkey River/Estuary (Fig. 1, inset). The longitudinal profile of the South Anna River is concave in the headwaters and continuing downstream for ~25 km to a prominent knickpoint at Byrd’s Mill (Fig. 3). Downstream from the Byrd’s Mill knickpoint the profile is linear for another 40 km, punctuated by several knickpoints, the largest of which is at Yancey Mill (Fig. 3). Historically milldams were sited at these knickpoints that generated long shallow impoundments extending kilometers upstream. Further downstream the profile is convex featuring a large drop at the Fall Zone. The linear gradient-portion of the South Anna River traverses the central Virginia seismic zone in Louisa County, VA, the site of the recent 2011 M 5.8 Mineral earthquake.

![Figure 3: Longitudinal profile of the South Anna River identifying the hanging wall study site in relation to the footwall study site of Malenda et al., (2014) and Pazzaglia et al. (2015), and the surface projection of the Quail fault (Pazzaglia et al., 2015).](image)

The earthquake ruptured a steeply southeast-dipping, blind reverse fault, the Quail Fault, above which the river runs orthogonal, that has a surface projection west of the Yanceyville knickpoint. There is no inferred connection between the knickpoint and the fault. The upper (west) half-segment of the South Anna River lies in the footwall of this
fault whereas the lower (east) half-segment traverses the hanging wall. The straths of the South Anna terraces across the fault are well preserved, with increased vertical separation between terrace straths in the hanging wall. At this site, the individual meander and the cut-off are similar in size to the meanders studied and modeled as produced by intrinsic base level fall processes by Finnegan et al. 2013.

Figure 4: The two study sites along the South Anna River. The Footwall study area is referred to as Horseshoe Farm, while the Hanging Wall study area is broken up into three different sites, A, B, and C. Intersecting the two study regions is the surface projection of the Quail Fault, that ruptured in 2011 at a depth of ~6 km.
Figure 5: A hillshade map assembled from a LiDAR DEM, of the footwall site, Horseshoe Farm. Terraces are labeled by color and the sites where data was collected are labeled as well. Local roads are shown in purple.

Hanging wall data are collected from three valley reaches ~ 12-15 km downstream of the Horseshoe study site. AH is the furthest upstream in the region marked A on Figure 4, (Fig. 6a), followed by Cox, AF1, and AF2 (Fig. 6b), all part of a wide meander loop at B in Figure 4, and lastly BB1, BB2, LZ1, and LZ3 (Fig. 6c) marked as C on Figure 4.
Throughout the hanging wall study reach, the South Anna River sinuosity increases, as does the width of the valley bottom and floodplain. Terraces here are largely paired, being particularly well preserved at the confluence of the trunk channel and major tributaries (Malenda et al., 2014). The mid-late Pleistocene aged terraces at Horseshoe Farm, in the footwall, lie close in elevation to the modern channel, which flows at 85 m above sea level (Fig. 3, Fig. 5). At the downstream sites in the hanging wall, the similarly aged, correlated terraces lie tens of meters above the modern channel, which flows at ~70-75 m above sea level (Fig. 3).
Figures 6a,b,c: Hillshade maps of the hanging wall sites. Figure 6a is the furthest upstream, followed by 6b and then 6c. Terraces are labeled by color and the sites where data was collected are labeled as well. Local roads are shown in green.
Fluvial Terrace Formation

River terraces form as a consequence of unsteady processes of fluvial erosion and sediment transport, manifest as alternating periods of low vertical incision rates and floodplain widening with periods of high vertical incision rates and floodplain abandonment (Bull, 1991). As a result of this unsteadiness, terraces are frequently interpreted to reflect drainage basin-scale responses to changing external drivers, including tectonics, sea level, and climate (Bull, 1991). Terraces produced this way would necessarily have a similar age along the river profile. Tectonic studies, in particular, take advantage of terraces as geomorphic markers to quantify the uplift and deformation of rocks with respect to a channel long profile, which is typically assumed to maintain a steady elevation. In contrast, some studies have pointed out that the process of lateral migration in meandering rivers leads to meander cutoffs and local base level falls, driving unsteady vertical incision and terraces by a completely autogenic mechanism (Finnegan and Dietrich, 2011; Limaye and Lamb, 2015). These terraces may be similar in scale and extent to those created by extrinsic forcing, but their ages would differ significantly along the river profile (Fig. 7).

Both fill and strath terraces and their smaller derivatives like fill-cut terraces are preserved along the South Anna River (Fig. 7). Fill terraces form when the amount of sediment generated in the drainage basin temporarily exceeds the river’s ability to transport that sediment (Bull, 1991, Maddy et al., 2001). The channel aggrades its valley bottom, raising the level of the floodplain, in order to steepen the transport slope. When the sediment flux from the drainage basin subsides, the channel gradient exceeds that which is necessary for transport, triggering incision and exposing the alluvial fill as a
terrace. Fill terraces have irregular unconformable bases with the underlying bedrock including buttress unconformities. The treads of fill terraces are typically wide and sub-horizontal (Bull, 1991, Maddy et al., 2001).

In comparison, strath terraces reflect alternating periods of widening and narrowing of the valley and floodplain superimposed on continuous, if unsteady, vertical incision into bedrock (Bull, 1991). Similar to fill terraces, unsteady sediment flux from the drainage basin is thought to drive the alternations in widening and narrowing. Strath terraces have sub-horizontal erosional contacts with the underlying bedrock and thin alluvial covers, typically less than 2 meters in thickness (Pazzaglia, 2013). Both fill and strath terraces formed by external drivers are commonly paired in the river valley (Fig. 7).

Figure 7: A conceptual valley cross-section illustrating a complex sequence of aggradational (fill) and degradational (fill-cut and strath) terraces.

The terraces at the upstream, footwall Horseshoe Farm location, are characterized by a few meters of alluvium beneath terrace treads, which indicates fill terraces. At the hanging wall sites, the fills are not as thick, likely due to accommodation space.
differences, but are still a 2-4 meters thick, which is too much alluvium to be classified as a strath terrace. An effective way to determine the type of terrace would be to observe the contact between the surface and underlying alluvium. An irregular surface-alluvium contact is indicative of a fill terrace while a uniform contact is indicative of a strath terrace. Additionally, along the South Anna, there are likely nested-fill terraces. These terraces form when the valley fills, incises, and refills to a lower level than before. This fill, cut, fill sequence, however, would require a large amount of sediment to not only repeatedly enter the fluvial system, but also to be transported downstream.

**Extrinsic (climatic) processes**

Terraces formed by extrinsic drivers, such as climate change, should be preserved basin wide, paired, and isochronous for a given terrace along the valley profile. Significant climatic events such as a shift from a glaciated landscape to a more temperature climate would likely increase the stream power and decrease the sediment supply from adjacent hillslopes on a basin-wide scale. Therefore, terrace formation would be similar on both sides of the river (paired, Bull 1991). When in the field, there should be evidence of paired terraces with similar ages and soil profiles that would likely represent a climatic shift. Furthermore, the abundance of terraces formed from a river impacted primarily by extrinsic processes would be irregular, but predictable with time. These terraces would not be as predictable; they would form when the climate shifts, causing a change in base level. The formation of terraces as a result of a shift from a glacial to interglacial time period is well demonstrated (e.g. Pazzaglia, 2013).
It has been observed that incision rates increase during the warming period of a glacial to interglacial transition (Maddy et al., 2001). Evidence for this is the field observation of the usual stratigraphic position of interglacial sediment close to the bottom of each terrace sediment profile. During climatic warming, slopes are stabilized primarily by vegetation, limiting mass-wasting and sediment supply to the valley floor. In addition, it is believed that precipitation typically will increase during interglacial periods. More precipitation will result in increased stream discharge. Higher discharge, combined with a low sediment supply should cause the river to vertically incise, and abandon its floodplain, creating a distinct terrace strath (Maddy et al., 2001). In cooling periods, initial climate instability will likely lead to heightened flood frequency and magnitude promoting an increase in erosion rates in the river. As cooling continues, vegetation will be limited from valley slopes which, in combination with increasing freeze-thaw activity, promotes mass-wasting of sediments to the valley floor and an increase in hillslope erosion rates. These sediments should comprise fine-grained interglacial weathering products and coarser sediments connected to freeze-thaw processes (Maddy et al., 2001). With increased sediment supply and lower stream discharge (due to hypothesized drier conditions in glacial periods), the channel will backfill and start the terrace forming process.

During the Pleistocene, the mid-Atlantic region experienced multiple glacial-interglacial cycles, with glaciers reaching as close as 350 km north of the study area. The waxing and waning of the continental ice sheets is well recorded in the marine isotopic record of sea water and represented through marine isotope stages (MIS), with odd numbered stages representing interglacial periods and even numbered stages representing
glacial periods (Fig. 8). It is important to note that glacial and interglacial cycling has increased in amplitude and frequency over the past 300 ka. As previously noted, terraces typically form when the climate shifts from a glacial time period to an interglacial time period. A Quercus (Oak) pollen core taken from the nearby Potomac River is used to observe climatic shifts in this region over the last ~120 ka. Prominent climatic shifts from interglacial to glacial periods within this time frame occur at 100 ka (MIS 5c -5b), 82 ka (MIS 5b – 5a), 55 ka (MIS 4 -3) and possibly 18 ka (MIS 2 -1, the pollen resolution is low in the last 20 ka).

Figure 8: (Top) A plot using Quercus (oak) populations as a proxy for climate change over the last 120 ka. Low Quercus densities occur during glacial periods and high populations occur in interglacial periods (Litwin et al., 2013). (Bottom) A plot using marine \( \delta^{18} \)O concentrations as a proxy for climate change in the past 500 ka (Lisiecki & Raymo, 2005).
To observe climatic unsteadiness at a longer timescale, a global marine $\delta^{18}$O isotope record is used to determine shifts over the past 500 ka. On this scale, applicable climate shifts occur at 140 ka (MIS 6-5) and 425 ka (MIS 12-11, Fig. 8).

**Intrinsic (local base level fall) processes**

The intrinsic unsteadiness of lateral migration in rivers may generate terraces even under constant rates of vertical incision without external forcing. A few characteristics have been attributed to terraces formed by unsteady channel or knickpoint migration, including: (1) seemingly random ages of formation (2) a lack of correlation of terraces across the channel (unpaired); and (3) limited and varying terrace length along-valley. It is difficult to verify these terrace properties, however, through direct field observations, numerical modeling, or experiments (Limaye and Lamb, 2015). Additionally, when determining the process that drives terrace formation, it is important to note that the South Anna has a relatively small channel and therefore, it likely cannot supply enough sediment even during floods to create a thick fill terrace from an intrinsic terrace genesis event. Therefore, intrinsically forced terrace formation should result in strath terraces or thin fill terraces.

Knickpoints and knick zones are steep reaches in river longitudinal profiles that typically form in bedrock channels in response to a base-level fall or where the channel encounters a relatively resistant substrate. Knickpoints are commonly convex or vertical reaches, in the extreme case of waterfalls, that interrupt the typically concave profiles of graded rivers where fluvial erosive power is maximized by the steep channel gradients (Frankel, et al., 2007). Localized base level fall creates a knickpoint that slowly migrates...
upstream due to the subtle increase in erosion as the river tries to reach a state of equilibrium. As the knickpoint migrates upstream, it will translate that base level fall signal throughout the drainage network in the form of smaller, localized fluvial terraces. These terraces form parallel to the steady-state profile and the result will be a strath terrace carved into the wall of the gorge that dips upstream and is time-transgressive; the downstream portion is higher and older than the upstream portion, which has a zero age where it merges with the active channel (Frankel et al., 2007). Therefore, if a terrace is present throughout a stream, decreases in age upstream, and it is parallel to the channel profile, it is possible that this terrace was formed through knickpoint migration.

Knickpoint migration velocity for the South Anna River is calculated to be \( \sim 7-14 \text{ km/ma} \) (Malenda, 2015). If the age and channel distance between two terraces is known, the migration speed can be used to determine if the terraces were possibly formed through knickpoint migration upstream.

In addition to terraces that form via knickpoint migration upstream, Finnegan et al. (2014) argue that the internal mechanisms of river meander migration and cutoff can generate unsteady incision, local knickpoints and longitudinally traceable unpaired strath terraces. Finnegan et al. discuss the process of stream cutoff due to significant stream meandering and the manner in which this intrinsic process can produce terraces. For example, if the vertical erosion rate is proportional to channel slope, then meander bend growth and cutoff should cause abrupt changes in channel slope (i.e., knickpoints) that propagate upstream and cause pulses of vertical incision that abandon terraces (Finnegan and Dietrich, 2011). Other studies (Malatesta et al., 2017) hypothesize that intrinsic processes can enhance vertical incision rates, leading to the abandonment of terraces and
channel entrenchment. The two primary intrinsic processes are (1) high banks reduce the channel’s lateral migration rate, then vertical incision occurs over the same area and is enhanced and (2) large banks collapse and the excess sediment cannot be immediately removed by the river, that prevents erosion while vertical incision ensues. These processes occur without any external forcing and must be considered when determining how terraces formed along the South Anna River. In the hanging wall of the fault, the South Anna River becomes increasingly sinuous, so terrace formation resulting from meander cutoffs may be more prevalent.

Soil Chronosequence

Soils chronosequences are valuable tools for investigating rates and directions of soil and landscape evolution. Through both relative and numeric geochronology, a soil chronosequence can be created for the terrace deposits along the South Anna River. There are five primary factors that affect soil formation: climate, topography, parent material, vegetation, and time (Jenny, 1941). A soil chronosequence focuses on the integrated effect of the duration of pedogenesis while keeping the other four variables relatively steady and consistent. The soils along the South Anna River have experienced numerous climatic shifts since the mid-Pleistocene, but the impact of these shifts on the soils is believed to be similar throughout the landscape. Chronosequences help to translate variability in soil characteristics that result from spatial differences into temporal differences. In this regard, a soil chronosequence can be used to correlate similar terrace fills in the absence of absolute geochronologic constraints. Soil
chronosequences can provide important information about the timing and processes of landscape response, such as stream or knickpoint migration, to external forcing such as climate or anthropogenic change and can help support hypotheses regarding pedogenesis (Hugget, 1998). There are relatively few chronosequence studies of soil geomorphology constrained by absolute geochronology in the central Virginia region, so this study will provide insight into soil development in an area with an unstable climatic and tectonic history. This study develops a soil chronosequence of terrace deposits through the use of OSL geochronology, heavy mineral analysis, and soil color. Heavy mineral analyses provide relative dating criteria using the relative abundances of minerals resistant or susceptible to chemical alteration. The labile minerals, such as epidote and serpentine, should still be plentiful in the younger soils, while minerals such as zircon and garnet, which will not weather away, will dominate older soils. The NRCS soil survey of Louisa County, VA (Carter et al., 1976) has grouped a variety of alluvial soils along the South Anna River into several soil series, distinguished primarily by on texture, color, and clay content. Older alluvial soil and topographically higher terraces (Qt3) are weathered into red-colored gravel-rich Turbeville soils. Intermediate-aged and elevation terraces are weathered into orangish-red colored Masada soils that range in texture from silty to gravelly sand. The youngest terrace treads that are only a couple of meters above the modern channel are underlain by yellow-tan silty sand and loam-textured soils of the Alta Vista and Forks series.
Methods

Field Methods

Field data were collected over a 1-week period in the summer of 2015, and an 8-week period spanning the Spring through Fall of 2016 following traditional field approaches of mapping, stratigraphic section measuring, soil morphologic description, and sampling for sediment composition and deposit geochronology. Data were collected on 1:24,000 scale, 10 ft contour interval paper maps also reproduced on field computers. The topographic data were supplemented further by 1-m resolution LiDAR digital topography publicly available from the U.S.G.S. Data were primarily assembled from a 8 km long section of the South Anna River flowing from Yanceyville to South Anna, VA through the uplifted footwall reach of the Quail Fault that ruptured in August of 2011 (Fig. 4). Identification of alluvial deposits (Raup, 2014) and extension of a lithographic model previously developed for the footwall was aided by published maps (Malenda et al., 2015) and shallow auguring using a 1-m long by 12-cm wide bucket auger. Deposits containing rounded gravel interbedded with (stratified) sparsely micaceous sand and silt were identified as alluvium, which contrasts with residual soil, colluvium, and saprolite that are dominated by angular gravel, and red, abundantly micaceous, unstratified matrix. Natural exposures of alluvial deposits are restricted almost entirely to the outside meander bends of the South Anna River. These exposures are supplemented by hand-dug pits on the treads of terraces, typically in wide, flat, cultivated fields.

Soil descriptions follow standard NRCS soil taxonomy protocols where a pit or outcrop face is measured, sketched, described, and sampled at soil horizon intervals. Soil colors are quantified using a Munsell soil color chart. At least two descriptions are
collected for each alluvial deposit in order to capture the natural range of textures, colors, and soils. Bulk samples of ~2 kg were collected from the base of the B horizons for textural and heavy mineral analyses. Relatively unweathered alluvial parent material was sampled for OSL/IRSL geochronology. The OSL sample collection process follows the Utah State Luminescence Laboratory’s guidelines (Nelson et al., 2015) and online protocols (http://www.usu.edu/geo/luminlab/howto.html). Steel tubes (1.5” x 8”) were hammered into a sandy bed ideally overlying a gravelly channel facies indicating the base of the fluvial deposit. Parent material from ~20 cm surrounding the tube were sampled for dose rate and water content (in an air tight container). After the dose rate and water content samples were collected, the steel tube was removed and immediately wrapped in duct tape. Ten deposits were sampled for OSL analysis in the hanging wall study region, and of these ten, the six most important samples to this study were sent to the Utah State Laboratory for analysis. Relative importance of each sample was determined through analysis of previous data collection and a desire to obtain samples from each terrace tread. The Utah State OSL Lab procedures are described in Nelson et al. 2015.

Alluvium from the South Anna River’s main channel and its tributaries were sampled in order to determine modern rates of erosion using \(^{10}\)Be terrestrial cosmogenic nuclides (TCN). The sampling protocol involved collecting ~10 kg of naturally washed and sorted sand from sand bars and channel banks during summer low-water conditions. Sample locations were chosen to represent erosion rates of both the hanging wall and footwall portions of the Quail Fault. The sampling sites are nested to determine the erosion rates of an entire tributary basin for where it enters the South Anna River trunk stream as well as erosion in the headwaters of tributary basins. This sampling method
should provide a diverse geologic substrate, relief, and shielding that will end up providing accurate average erosion rates for the entire South Anna basin.

*Heavy Mineral Provenance Analyses*

Heavy mineral identification were completed on bulk samples collected from the middle of the B-horizon from each described alluvium. Coarse sediment and vegetation were initially removed by sieving through a 2Φ sieve. Clay-sized materials were removed using a 1-gallon bucket to suspend the clay and decant it away. The remaining sample was dried and used in the separation analysis.

Separatory funnels filled two-thirds with Lithium Metatungstate (LMT, density of 2.9) was used to float and separate the quartzo-feldspatic portion from the heavy minerals. The samples in the separatory funnel were stirred vigorously to ensure that they were completely saturated with the LMT. Heavy mineral separation took roughly 4-6 hours to complete. Both the heavy and light fractions were collected, washed free of the heavy liquid with acetone, and subsequently dried under heat lamps.

The highly magnetic minerals (ferromagnetics), such as magnetite, were readily separated from the heavy mineral component by use of a magnet, the poles of which were covered by KimWipes. The sample, now de-magnetized, was placed in a petri dish and placed under a light microscope. Here, ~100 grain subsets of the sample were created and point counts were manually performed to create a rough composition of each sample based primarily on the grains’ color, shape and luster. The 4-6 most common minerals from each sample were then placed on a mount to be analyzed in a scanning electron microscope (SEM). In the SEM, each grain was analyzed to observe the shape and to
determine the elemental composition. Mineral species were then identified mainly using a combination of their physical properties and elemental compositions. Elemental compositions of each mineral were obtained from the SEM. The SEM uses a focused beam of high-energy electrons to generate a detailed and precise elemental profile of a specific spot on each grain.

Soil PSDA

Soil particle size distribution analysis (PSDA) was completed using wet sieving and Stoke’s Law settling under controlled temperature conditions. Soil samples were weighed, dried, and then re-weighed to determine the moisture content. The dried sample was wet sieved using a -1 Φ sieve to separate the >2mm grains. The >2mm portion was then dried and then weighed. Approximately 10 g of the <2mm portion was placed in a 100ml beaker to be analyzed for organic content, followed by sand, silt, and clay content. Accordingly, deionized water was used to wet the sample and then 5mL of peroxide was added and the sample was placed on a hot plate for 30 minutes to start organic oxidation. After 30 minutes, a second 5 mL dose of peroxide was added to complete the oxidation, and then the sample was dried and weighed. The now organics-free sample was placed in a centrifuge tube with 10mL of HMP (hexametaphosphate) dispersant and deionized water. The samples were mixed for 16-24 hours. When finished, the sample was wet sieved through a 4 Φ sieve, and into a 1000 mL fleaker. The portion of the sample retained on the sieve was dried, weighed, and reported as the sand component. The fleaker was then topped off to 1000mL with deionized water and mixed thoroughly in order to suspend the sediment. The sample rests for 8 hours and then 25mL of the sample was pipetted 10 cm from the water surface to represent the <2 mm clay-sized fraction.
This sample was dried and weighed to provide the clay component. With the >2mm, sand and clay fractions known, the remaining percentage was assumed to be the silt component (Burt, 2014). The raw PSDA data can be found in Appendix A.

Iron Oxide Crystallinity

Measuring iron oxide crystallinity provides an insight into the relative time of soil development within a specific profile given that secondary iron oxide formation is dependent on weathering processes over time (Dykman, 2015; Ciolkosz et al., 1993). The ratio of FeO (oxalate-extractable iron, representing ferrihydrite and iron associated with organic matter) to FeD (dithionite extractable iron, representing the total secondary iron) in soils decreases with the duration of pedogenesis due to increasing iron oxide crystallinity (Dykman, 2015; Lair et al., 2009). Dithionite-citrate-bicarbonate (DCB)-extractable iron (Fed) is determined using the method of Mehra and Jackson (1960) at 80°C in a hot block. Ammonium oxalate extractable iron is determined using the procedure of McKeague and Day (1996). Both iron extractions are diluted for analysis on the ICP-MS (Markley, 2017).

OSL and IRSL Geochronology

Alluvial deposits were dated using optically stimulated luminescence (OSL) and infrared stimulated luminescence (IRSL) techniques in collaboration with the Utah State Luminescence lab. One OSL sample was extracted from a natural exposure next to the South Anna River channel; the other five samples were extracted from hand-dug soil pits. The OSL technique provides an age for sediment deposition by determining the amount
of time that has passed since the sediment was last exposed to sunlight, presumably during transport. Minerals, such as feldspars, can be used for luminescence dating, however, due to properties such as anomalous fading and internal dosimetry, quartz is more effective in samples younger than 250,000 years. It is possible that the quartz sediment from this system is not suitable for OSL dating due to poor luminescence properties of the quartz grains and dominant intermediate to slow components of the signal that can lead to an age underestimation (Jain et al., 2003). Potassium feldspar has a much brighter luminescence signal than that of quartz and can measure higher dose equivalents because it does not saturate as quickly as quartz (Buylaert et al., 2009.)

Sample preparation for quartz OSL analysis followed the preparation method used by the Utah State OSL Laboratory. The AF1, BB2, LZ1 and AH2 sites yielded samples with enough acceptable quartz after preparation. Samples from sites LZ3 and BB1, however, did not contain enough usable quartz and the dates are from IRSL dating of feldspars. The alluvial samples transported by the South Anna River tend to be first cycle material lacking in well-conditioned electron traps necessary for good OSL ages with small uncertainties. As a result, the feldspar fractions were extracted and used in the similar IRSL technique that has the opportunity to date buried materials up to ~250 k.y. with an uncertainty as low as 5-10% (Nelson et al., 2015). The standard operating procedures (SOP) of the USU Lab for processing samples and reporting results can be found in Nelson et al, (2015) or the USU OSL website.

\textit{TNC}^{10}Be Erosion Rates

Seven samples were taken from terrace alluvium of the South Anna River and its
tributaries in both the footwall and hanging wall for cosmogenic analysis. Samples were collected across the watershed not only to gather data that encompassed a variety of drainages, but also to compare erosion rates in the footwall and hanging wall of the Quail Fault. The samples directly from the South Anna River should provide an average erosion rate for the watershed, whereas samples from tributaries will provide a more localized signal. Samples were also collected directly above and below knickpoints in order to observe how these fluvial features affect the channels erosion rates. The intent is that the sites selected represented a variety of conditions to produce erosion rate data that is not biased.

Bulk channel alluvium samples for $^{10}$Be TCN analysis were washed, dried, and sieved in order to retain grain sizes in the range of 0.125-0.7mm. The samples were then taken to the University of Pennsylvania cosmogenic analysis lab under the direction of Jane Willenbring to have the $^{10}$Be extracted. The standard operating procedures (SOP) of the UPenn Lab can be found in Appendix B. The $^{10}$Be was analyzed at the PRIME lab at Purdue University. Resulting $^{10}$Be concentrations were modeled for erosion rate using the online CRONUS dating calculator (http://hess.ess.washington.edu/). In the calculations, the shielding factor was not changed between samples because the Piedmont is fairly flat, so the shielding correction is small. Sample input for using the online calculator can be found in Appendix C.

Results

South Anna channel and terrace stratigraphy

Alluvial deposits have long been recognized and mapped in the central Virginia
Piedmont, (Weems, 1988) but there is little consensus on the appropriate geomorphic model for their identification and formation. Bedrock is rarely seen at the surface along the South Anna River, typically only at steep slopes or the outside of large meanders. This bedrock has been weathered over time into saprolite, the mean residence time of which, in the Piedmont landscape, is reported to be approximately 800 ka (Pavich et al., 1985). Terrace alluvium is deposited by rivers and streams that recruit weathered and eroded materials from saprolite, residual soils, or older alluvial deposits. The typical stratigraphy of the floodplain is <2m of clast supported, stratified sandy gravel overlain by 1-2m of stratified, sand silt and clay overbank facies. These deposits unconformably overlie bedrock straths, which serve as key geomorphic markers when exposed at the base of the terrace deposits (Malenda, 2015). The alluvial deposits underlying fluvial terrace treads contain sub-rounded to rounded gravel of primarily Piedmont provenance.

The combination of textural and compositional analysis, color, terrace geomorphology, and elevation allowed for the identification of distinct terrace deposits in the field. The two oldest and highest elevation terrace deposits, Qt1 and Qt2 are represented by mostly unstratified, strongly colluviated alluvial parent material. They are deeply weathered, which makes it difficult to determine much about the terrace soils and depositional history.

The Qt3 terraces likely consist of two or three distinct straths vertically separated by ~1-5 meters and are characterized by the Turbeville soil series. These deposits are the oldest (mid-Pleistocene) and highest in elevation that are preserved well enough to confidently analyze the soil properties. The Qt3 sites Pit F and COX (Figs. 9b, 13), consist of clast-supported gravel ~ 0.5-1 m thick. It is overlain by a deeply weathered,
sandy, red 2.5YR color, soil ~ 1-3 m thick. The average FeO/FeD ratio of the Qt3 soils is 0.387 (Fig. 9a). The terrace strath lies at an elevation of 98-102 m and is approximately 20-25 m above the modern river channel.

Inset into the Qt3 deposit are 2-3 intermediate elevation terraces grouped into the Qt4 suite of terraces. There is enough detail in the mapping of these terrace to separate them into a higher, Qt4a, and lower, Qt4b. The Qt4a deposits, sites BB2 and AH2, contain a <0.5 m thick basal bed with sub-angular to sub-rounded cobbles and smooth, rounded quartz cobbles. The deposits are composed of rounded to sub-rounded quartz and quartzite clasts local to the area. The soils are orange-tan-yellow 7.5 YR color and are associated with the Masada soil series. The average FeO/FeD ratio of the Qt4a deposit is 0.375 (Fig. 9b). The terrace deposit is 3-4 m thick and the strath lies at an elevation of 89-92 m, approximately 14-17 m above the modern river channel.

Qt4b deposits, represented by BB1 and AF1, are increasingly gravel-rich with depth, and is overlain by a sandy-loam and silty overbank deposits. The Qt4b treads are 2-3 m thick, slightly thinner than the Qt4a treads. The soils have a yellow-tan 2.5Y to 5Y color and are associated with the Masada soil series. The average FeO/FeD ratio of this deposit is 0.436 (Fig. 9c). The terrace lies at an elevation of 85-90 m and is typically 12-14 m above the modern channel.

Qt5 and possibly Qt6, represented by LZ1 and Site D, are the lowest deposits above the modern floodplain. The base of the deposits is grey-silty-clay with some red mottling. This deposit is overlain by a yellow-tan sandy-loam with sub-rounded quartz pebbles. LZ3 is likely the base of the LZ1 Qt5 deposit, and shows minimal weathering and a sandy composition. The soil is associated with the Alta Vista and Fork soil series
and the average FeO/FeD ratio of this deposit is 0.661 (Fig. 9d). The terrace strath lies at an elevation of 72-77 m, approximately 1-3 m above the modern floodplain (Fig. 10).

These newly documented terrace deposit properties in the hanging wall are notably different than the terrace stratigraphy and properties in the footwall of the Quail Fault. Qt4a and Qt4b show two distinct terrace straths in the hanging wall with different soil colors, textures, and mineralogy. In the footwall, however, the Qt4a and Qt4b terrace treads and straths are at approximately the same elevation, similar to what is observed in the modern valley bottom today. Qt6 is also distinctly inset into Qt5 in the hanging wall. In the footwall, Qt5 and Qt6 combine to make a thick, consistently upward-younging fill. Additionally, the younger Qt5 deposits in the footwall are red, orange and grey in the footwall and are primarily yellow-tan in the hanging wall. Lastly, the terrace fills are thinner in the hanging wall compared to the fills in the footwall.
Figure 9a,b,c,d: A field photo, sketch, PSDA and FeO/FeD plots of a Qt3 deposit (top), Qt4a deposit, Qt4b deposit, and Qt5 deposit (bottom) (Additional field photos, sketches, PSDA and FeO/FeD plots can be found in Appendix D).

Figure 10: (Top) A summary terrace stratigraphic model of the South Anna River for the uplifting hanging wall of the Quail Fault. The site labels are listed adjacent to the corresponding terrace deposit labels.
Terrace parent materials and heavy mineral analysis

South Anna River terraces are composed of quartzo-feldspathic sand and gravel, with variable amounts of silt and clay that reflect the local mineralogy of the underlying bedrock, particularly that of the Chompawamsic Formation and Ellsville Pluton. Typically, alluvial materials are not micaceous, or contain minor amounts of mica, which contrasts sharply with saprolite that tends to be rich in micaceous content. The heavy mineral spectra of the terrace deposits along the South Anna River are dominated by epidote, serpentine, andalusite, kyanite, zircon, rutile and garnet (Fig. 11). The younger, Qt5 deposits, LZ1 and LZ3 (hanging wall) and Site D (footwall) contain primarily epidote and serpentine with some alumino-silicates present. Zircon, rutile, and garnet were not noticeable in these deposits. The Qt4b deposits, BB1 and AF1 (hanging wall), HS Cut AGL/BGL (footwall), also contain epidote and serpentine with some alumino-silicates. The Qt4a deposits, AH2 and BB2 (hanging wall), contain predominantly alumino-silicates with small amounts of epidote and serpentine. AH2 contains little epidote and serpentine and a significant amount of garnet, while BB2 contains a similar amount of garnet but more epidote and serpentine (Fig. 11).
Figure 1: A ternary diagram showing the heavy mineral analyzed from the B-horizon at each site. The three sections of the ternary diagrams represent the labile minerals (epidote and serpentine), intermediate weathering resistant minerals (alumino-silicates), and the most refractory minerals (garnet, rutile and zircon). The yellow points represent Qt5 (youngest) deposits, the brown and orange represent Qt4a and Qt4b (intermediate) deposits, respectively, and the red deposits represent Qt3 deposits (oldest).

The Qt3 deposits COX (hanging wall) and Pit F (footwall) contain no epidote and serpentine and are dominated by zircon, garnet and rutile (Fig. 11). COX contains almost 40% alumino-silicates whereas Pit F contains almost none. The heavy mineral percentages for each sample site can be found in Appendix E.

**Terrace geochronology**

Six samples were collected for optically stimulated luminescence dating. Each of
the samples was obtained from manually excavated pits except for sample LZ3, which was obtained from a natural exposure along the riverbank. The depth of the samples taken from pits ranged from 0.6 m to 1.0 m, while LZ3 was taken from 1.5 m below the surface (Table 1). Quartz OSL ages commonly underestimate the age of deposits in this region due to problems with the luminescence signals. Feldspars can also underestimate the age of deposits because it loses signal over time due to anomalous fading. The results of the OSL measurements and dosimetry data are shown in Table 1. The OSL ages represent the time of deposition, with the terrace straths having older ages and the terrace treads having younger ages. Some of the ages contain large uncertainties, likely due to weathered quartz grains and fading of feldspars. The dose-rate data reflects the sediment type found within the deposit as well as the differences in the water content of the sediment. The OSL and IRSL age uncertainty overlap of similar terraces was used as a likely age of burial to observe how terrace deposit ages align with historical climatic shifts.
Table 1: OSL ages and relevant lab information. The ages highlighted in blue are more reliable due to the underestimate of the other mineral fraction.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth (m)</th>
<th>Dose Rate (Gy/ka)</th>
<th>Age (ka)</th>
<th>Mineral</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF1 (Qt4b)</td>
<td>37.899588</td>
<td>-</td>
<td>0.85-0.7</td>
<td>1.12 ± 0.12</td>
<td>97.3 ±  21.2</td>
<td>Quartz</td>
</tr>
<tr>
<td>AF1 (Qt4b)</td>
<td>37.899588</td>
<td>-</td>
<td>IRSL 50C</td>
<td>2.74 ± 0.4</td>
<td>58.0 ± 18.2</td>
<td>Feldspar</td>
</tr>
<tr>
<td>AF1 (Qt4b)</td>
<td>37.899588</td>
<td>-</td>
<td>pIRIRSL 225C</td>
<td>2.74 ± 0.4</td>
<td>62.0 ± 13.5</td>
<td>Feldspar</td>
</tr>
<tr>
<td>BB1 (Qt4b)</td>
<td>37.888900</td>
<td>-</td>
<td>0.6</td>
<td>±</td>
<td>±</td>
<td>Quartz</td>
</tr>
<tr>
<td>BB1 (Qt4b)</td>
<td>37.888900</td>
<td>-</td>
<td>IRSL 50C</td>
<td>2.54 ± 0.29</td>
<td>60.7 ± 31.6</td>
<td>Feldspar</td>
</tr>
<tr>
<td>BB1 (Qt4b)</td>
<td>37.888900</td>
<td>-</td>
<td>pIRIRSL 225C</td>
<td>2.54 ± 0.29</td>
<td>75.9 ± 16.5</td>
<td>Feldspar</td>
</tr>
<tr>
<td>BB2 (Qt4a)</td>
<td>37.886507</td>
<td>-</td>
<td>0.75-0.6</td>
<td>1.37 ± 0.12</td>
<td>119.3 ± 51.7</td>
<td>Quartz</td>
</tr>
<tr>
<td>BB2 (Qt4a)</td>
<td>37.886507</td>
<td>-</td>
<td>IRSL 50C</td>
<td>3.3 ± 0.44</td>
<td>53.4 ± 13.4</td>
<td>Feldspar</td>
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<tr>
<td>BB2 (Qt4a)</td>
<td>37.886507</td>
<td>-</td>
<td>pIRIRSL 225C</td>
<td>3.3 ± 0.44</td>
<td>57.1 ± 11.6</td>
<td>Feldspar</td>
</tr>
<tr>
<td>LZ1 (Qt5)</td>
<td>37.876913</td>
<td>-</td>
<td>0.9</td>
<td>1.87 ± 0.14</td>
<td>52.1 ± 35.7</td>
<td>Quartz</td>
</tr>
<tr>
<td>LZ1 (Qt5)</td>
<td>37.876913</td>
<td>-</td>
<td>IRSL 50C</td>
<td>3.87 ± 0.49</td>
<td>61.4 ± 11.3</td>
<td>Feldspar</td>
</tr>
<tr>
<td>LZ1 (Qt5)</td>
<td>37.876913</td>
<td>-</td>
<td>pIRIRSL 225C</td>
<td>3.87 ± 0.49</td>
<td>64.3 ± 11.4</td>
<td>Feldspar</td>
</tr>
<tr>
<td>LZ3 (Qt5?)</td>
<td>37.866968</td>
<td>-</td>
<td>1.5</td>
<td>±</td>
<td>±</td>
<td>Quartz</td>
</tr>
<tr>
<td>LZ3 (Qt5?)</td>
<td>37.866968</td>
<td>-</td>
<td>IRSL 50C</td>
<td>2.85 ± 0.34</td>
<td>47.1 ± 15.2</td>
<td>Feldspar</td>
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<tr>
<td>LZ3 (Qt5?)</td>
<td>37.866968</td>
<td>-</td>
<td>pIRIRSL 225C</td>
<td>2.85 ± 0.34</td>
<td>47.1 ± 15.2</td>
<td>Feldspar</td>
</tr>
<tr>
<td>AH2 (Qt4a)</td>
<td>37.91952445</td>
<td>-</td>
<td>0.9</td>
<td>0.97 ± 0.08</td>
<td>149.2 ± 23.6</td>
<td>Quartz</td>
</tr>
<tr>
<td>AH2 (Qt4a)</td>
<td>37.91952445</td>
<td>-</td>
<td>IRSL 50C</td>
<td>2.55 ± 0.31</td>
<td>241.28 * ± 76.2</td>
<td>Feldspar</td>
</tr>
</tbody>
</table>

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Incision Rates

Incision rates are calculated using the OSL/IRSL terrace ages and the elevations above the modern channel. The incision rates are incremental, meaning the incision rates are calculated between successively younger deposits stepping down to the channel. With the exception of one interval with an accelerated incision, rates of vertical incision across the South Anna basin range from 23 – 88 m/My (Fig. 12). The average incision rate in the footwall is 42 m/My, while the average incision rate (excluding the one period of accelerated incision) is 48 m/My. Accelerated incision occurs between terraces Qt4b (~97.3 ± 21.2 ka, and 90-92 m above the modern channel) and Qt5 (~61.4 ± 11.3 ka, and ~76-78 m above the modern channel) in the hanging wall. The incision rate between these two terraces is 339 m/My, which is approximately 9.5 times higher than the average of the other incision rate intervals along the South Anna River (Fig. 12).

Cosmogenic Erosion Rates

Seven samples were collected from the surface of the South Anna River channel and its tributaries in order to obtain a basin wide erosion rates. The seven river surface samples have an average $^{10}\text{Be}$ concentration of 5.33 x 10$^5$ atoms/g. Calculated erosion rates from these samples and concentrations range from 2.38 to 96.06 m/My, with an average erosion rate of 22.62 m/My. The average erosion rate in the footwall, samples SA1, SA2, SA3, SA5, of the Quail Fault is 33.28 m/My and the average erosion rate in the hanging wall, samples SA8, SA10, and SA12, of the fault is 8.41 m/My (Table 2). In the footwall, sample SA2 is significantly higher than the other six samples with an erosion rate of
96.06 m/My. This sample was obtained from Roundabout Creek, right below a knickpoint. There was no noticeable difference between erosion rates taken from the South Anna channel, SA1, SA5 and SA10 and samples taken from tributaries of the South Anna River, SA2, SA3, SA8, and SA12. Differences in shielding likely would impact the calculated erosion rates, but during the erosion rate calculations, the shielding factor was kept constant throughout.

Figure 12: A plot showing the incision rates calculated from terrace ages and elevations in the footwall (grey) and hanging wall (black) of the Quail Fault. The incision rate numbers shown are in meters per million years. The inset plot shows the relationship between erosion rates (red) and incision rates in the footwall (grey) and hanging wall (black). The blue vertical lines are the error bars associated with calculating time-weighted average incision rates.
<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (m)</th>
<th>Sample density (g/cm³)</th>
<th>Shielding correction</th>
<th>Production Rate (muons) (atoms/g/yr)</th>
<th>$^{10}$Be nuclide concentration (atoms/g)</th>
<th>Erosion Rate (m/My)</th>
</tr>
</thead>
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<tr>
<td>SA1</td>
<td>37.97181</td>
<td>-78.02943</td>
<td>85.344</td>
<td>1.9</td>
<td>1</td>
<td>0.077</td>
<td>1.62E+05</td>
<td>27.31</td>
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<tr>
<td>SA2</td>
<td>37.94791</td>
<td>-78.04725</td>
<td>100</td>
<td>1.9</td>
<td>1</td>
<td>0.077</td>
<td>4.96E+04</td>
<td>96.06</td>
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<tr>
<td>SA3</td>
<td>37.94091</td>
<td>-78.08202</td>
<td>115.824</td>
<td>1.9</td>
<td>1</td>
<td>0.078</td>
<td>5.54E+05</td>
<td>7.35</td>
</tr>
<tr>
<td>SA5</td>
<td>38.11889</td>
<td>-78.19833</td>
<td>132.588</td>
<td>1.9</td>
<td>1</td>
<td>78</td>
<td>1.48E+06</td>
<td>2.38</td>
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<tr>
<td>SA8</td>
<td>37.85252</td>
<td>-77.95891</td>
<td>82.296</td>
<td>1.9</td>
<td>1</td>
<td>0.077</td>
<td>4.03E+05</td>
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<td>37.88521</td>
<td>-77.9155</td>
<td>73.152</td>
<td>1.9</td>
<td>1</td>
<td>0.077</td>
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<td>9.00</td>
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<td>37.88573</td>
<td>-77.85383</td>
<td>82.296</td>
<td>1.9</td>
<td>1</td>
<td>0.077</td>
<td>6.34E+05</td>
<td>6.11</td>
</tr>
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</table>

Table 2: $^{10}$Be cosmogenic erosion rates from various sites along the South Anna River and its tributaries and relevant information.
Discussion

The sedimentology, stratigraphy, soils, and geochronology of alluvial materials preserved in fluvial terraces of the South Anna River hanging wall reach collectively can be interpreted in terms of extrinsic and intrinsic terrace formation processes. In addition, as passive geomorphic markers, they also record variable incision into the Virginia Piedmont that can be interpreted in terms of crustal deformation consistent with, or in contrast to the observed rupture of the Mineral earthquake along the Quail Fault.

Terrace Chronology and Classification

Terrace formation in the footwall and hanging wall of the Quail Fault is unsteady through time; however, each terrace observed in the field has a thick alluvial fill overlying the terrace strath (Figs. 13,14). Terrace chronology and field observations are used to determine the types of terraces along the South Anna. IRSL and cosmogenic ages have been more effective in dating the Qt3 terraces because OSL ages are ineffective with soils older than 250,000 years. Although Qt3 ages have been reported as less than 100 ka through OSL dating (Pazzaglia et al., 2015), IRSL and cosmogenic methods more accurately constrained the Qt3 terrace ages in the footwall, at the Pit F site, to be approximately 400 ka. The soil weathering, soil properties, heavy mineral composition and elevation above the modern channel allow for age correlation between the Qt3 Pit F footwall site and Qt3 COX hanging wall site. The colors are both a 2.5R deep red, the FeO/FeD ratios are similar, and the heavy minerals observed are zircon, garnet, rutile and other minerals that do not readily weather away. Using the field and lab observations of
the two Qt3 fill deposits, the two terraces can be confidently correlated across the landscape (Fig.5, Fig 6b).

Since the Qt4a soils formed 130-150 ka and are stratigraphically above the Qt4b deposits, which developed 75-100 ka, the Qt4 suite of terraces needs to be divided into two separate Qt4a and Qt4b fill deposits. This idea is supported through the soil analysis at each terrace. The heavy minerals in the Qt4a deposits are dominated by more weathering resistant minerals, the FeO/FeD ratios are lower in Qt4a, and the soil color in the Qt4a terraces is a red-orange, while the Qt4b terraces are a yellow-grey color. The Qt5 terrace deposits contain a distinct alluvial soil that is at a consistent elevation above the modern channel. The heavy mineral composition and soil color, however, are very different in the footwall and hanging wall. The Qt5 terrace deposits contain a distinct alluvial soil that is at a consistent elevation above the modern channel. The heavy mineral composition and soil color, however, are very different in the footwall and hanging wall. The ages range from 27 ka to 64 ka in the footwall and hanging wall sites. The younger Qt5 ages of approximately 18-27 ka are observed in the footwall site, while older ages between 47-64 ka are observed in the hanging wall valley bottom. At the Horseshoe footwall Qt5 site, the OSL dating targeted sandy alluvium, and returned ages of approximately 18 ka and 27 ka. It is possible that alluvium was in fact sampled with the OSL tube, but due to subsidence, the fill continues to be buried with younger sediment.
Figure 13: A detailed terrace stratigraphic model in the hanging wall of the Quail Fault. Included are OSL and IRSL ages, soil color, and common heavy minerals.
In this scenario, the area sampled could be observed as the top of a thick Qt5 fill. This idea is supported by the soil characteristics at each site. The Site D soil and LZ1 soil are a similar yellow color and have similar iron chemistries (Figure 9d, Appendix D), while the base of the Qt5 deposit in the hanging wall is red, indicating a range of soil development and possible fluvial reworking recently.

A stepwise account of terrace formation, following from the above stratigraphic model assumes that the South Anna River channel both incises and aggrades in response to variable upstream sediment supply, and local uplift or subsidence of the bedrock in response to tectonics. The formation of the Qt3 terraces was caused by an influx in sediment, which caused the river to aggrade, leaving behind a 2-4 m thick fill. Qt3 is labeled as a fill terrace because of the deposit thickness, especially considering that some alluvium has likely been eroded from the tread. The river then incised, over the next 250 ky to roughly 160 ka, and cut down to the base of the Qt4a deposit, a total incision of approximately 10 m. The river then aggraded, leaving behind another 2-3 m thick fill (the Qt4a deposit). The Qt4 suite of terraces has enough mapping and geochronologic detail to distinguish two separate terraces, a higher Qt4a, and a lower inset Qt4b terrace. The formation of these terraces likely started earlier than 150 ka when the river cut down to the base of the Qt4a deposit and then backfilled with sediment. Next, the river incised to the base of Qt4b until approximately 85 ka and then backfilled with sediment. This incision and immediate backfill created the stacked fill terraces labeled Qt4a and Qt4b. The OSL and IRSL dates do not indicate that the Qt4b terraces formed through a fill-cut sequence of one large Qt4 alluvial fill. In this scenario, the older sediments would be located at the bottom of the fill, overlain by progressively younger sediments.
Following the deposition of the Qt4b fill approximately 75 ka, the river incised approximately 12 m in only ~30,000 years to the base of the Qt5 valley at an elevation of approximately 80 m. The channel then filled with 2-3 m of sediment until approximately 60 ka. From ~60 ka to close to present, the river has either been slowly cutting down to the current river level, or potentially formed a small Qt6 terrace approximately 15-20 ka (Fig. 13).

**Extrinsic vs. Intrinsic forcing on terrace genesis and South Anna River incision history.**

Terraces are thought to form during the transition from a glacial to an interglacial time period. In warm, wet periods, plants typically cover the landscape, and sediment supply is low; enhanced moisture increases stream flows, and streams draining mountainous regions will vertically incise. During cold and dry periods of an ice age, plants do not provide enough cover to prevent intense erosion during infrequent storms (Bull, 1991; Merrits et al., 1994). *Quercus* (Oak) pollen isotope records measured in a core extracted from the nearby Potomac River allow for the opportunity to test the climatic forcing hypothesis by comparing terrace ages with regional climate shifts over the past ~115 ka. Oxygen marine isotopes were used as a proxy to observe how terrace deposit ages align with climate shifts over a longer timescale, approximately ~500 ka (Fig. 15). The overlap in age uncertainties in OSL and IRSL data of similar deposits was used to develop an age range of when sediment of a specific terrace was buried.
Figure 14: A detailed terrace stratigraphic model in the subsiding footwall of the Quail Fault. Note that at the Horseshoe Farm location, terraces Qt4a-Qt6 all lie close to the modern river level.
It is likely that the Qt3 suite of terraces formed during the transition from MIS 12 (glacial) to MIS 11 (interglacial) approximately 400-450 ka. The Qt3 terraces occur at similar elevations throughout the watershed (~102-104 m.), are present on both sides of the river, are typically much larger spatially than the other observed terraces, and have similar observable color and weathering across the South Anna. These watershed-wide correlations indicate that this terrace valley formed during a large-scale event such as a climatic shift. It is likely that more detail is inherent in this terrace suite that is no longer observable due the mid-Pleistocene age of the Qt3 terraces. Additionally, because of the soil’s mid-Pleistocene weathered soil conditions, dating the terrace deposits has resulted in a wide range of age estimations. It is possible that the Qt3 suite of terraces is composed of terraces formed not only during the MIS 12 to MIS11 transition, but also during the MIS 10 to MIS 9 transition, approximately 325-350 ka (Fig. 15). Additionally, around 400-450 ka, it is possible that the river was incising very slowly and depositing gravel and sand that collectively make up the observed Qt3 valley bottom. In this scenario, the river was not incising fast enough to generate terraces at different elevations, and they all formed at approximately the same elevation over a range of time.

The Qt4 suite of terraces formed during the transition from MIS 6 (glacial) to MIS 5 (interglacial), approximately 120-140 ka (Fig. 15). The OSL and IRSL ages of the Qt4 terraces, divided into Qt4a and Qt4b, are within the MIS 5 time frame of ~130 ka to ~70 ka. The Qt4a age uncertainties from AH and BB2 overlap at approximately 135-155 ka. This age coincides with the transition from the glacial MIS 6 to the interglacial MIS 5 (Fig. 15). The timeframe of Qt4b terrace genesis falls in the middle of MIS 5 (Fig. 15). This would appear to contradict the hypothesis that climate shifts resulted in the
formation of fill deposits along the South Anna, however the MIS 5 climate was unstable through time. It is often divided into MIS stages beginning with a warm 5a period and alternating between warm and cold periods between stages 5b, 5c, 5d, and 5e. Therefore, it is likely that the Qt4b terraces formed during a different climatic event within the highly variable climatic conditions of the MIS 5 interglacial period. The AF1 and BB1 Qt4b OSL sample age uncertainties overlap at approximately 80-90 ka. This age aligns with the transition from the cold 5b climate to the warm MIS 5a climate (Fig. 15). This hypothesis is supported by the fact that in the hanging wall, the Qt4a deposit is thicker than the Qt4b deposit and likely formed as a fill terrace during a larger climatic shift. The Qt4b terrace is thinner fill terrace supporting the hypothesis that it formed during a smaller climatic transition (Fig. 13).

Another scenario is that the smaller Qt4b terrace deposits formed from a variety of intrinsic processes. South Anna River has reaches that are highly sinuous, and as the river flows and erodes its banks over time, meanders will get cut off. Meander cutoff will create a localized fall in base level. A fall in base level will cause the river to incise and abandon its floodplain, resulting in the formation of a small, localized terrace. Terraces can also form through a similar process as a knickpoint migrates upstream. The knickpoint represents an abrupt change in base level that the river will try to combat by incising, thereby abandoning its floodplain. There are a few sizable knickpoints in the South Anna River, most notably the Byrd Mill knickpoint, which lies just upstream from Horseshoe Farm, the footwall site. Additionally, the river’s complex response to climate change or tectonic forcing, as described in Bull et. al (1991), could have resulted in localized, terrace formation. The two Qt4b terraces deposit ages, AF1 and BB1 are
approximately 30 ka apart. The heavy mineral composition and color at the AF1 and BB1 sites differ significantly (Fig. 11). AF1 contains a large amount of alumino-silicates and is a grey-tan-yellow color with red mottling. The BB1 deposit contains a high amount of epidote and serpentine and is much more yellow. While this is a possibility, there is not enough resolution in the Qt4 valley to determine the influence of intrinsic river processes on terrace formation.

The Qt5 suite of terraces was initially formed through a climatic shift, and subsets of Qt5 terraces were likely formed due to intrinsic processes. The Qt5 suite of terraces formed during the transition from MIS 4 (glacial) to MIS 3 (interglacial) approximately 50-60 ka (Fig. 15). The Qt5 terrace in the hanging wall, with OSL samples labeled LZ1 and LZ3, formed between 47 and 64 ka, which aligns with this climatic shift. The Qt5 terrace age in the footwall, ranges from approximately 27-54 ka. The 27 ka sample would appear too young to be considered in the Qt5 suite of terraces. It is possible that the OSL sample could have been extracted from colluvial material that unconformably buries the terrace tread. The 54 ka sample age correlates with the hanging wall ages and the MIS 4 to MIS 3 climate shift. The two, footwall Qt5 samples, however, do not correlate with the hanging wall Qt5 samples in regards to elevation above the modern channel, soil color and development. The ages and heavy mineral composition, however, correlate strongly with the LZ1 and LZ3 Qt5 hanging wall terrace (Fig. 13, 14). The difference in color could be a result of varying rates of weathering because the footwall samples were taken directly from the modern riverbank and have been flooded often. The varying elevations above the modern channel indicate potential tectonic influences. Due to increased accommodation space from subsidence, the river does not incise and create vertical
terrace separation. With little incision, alluvium will continue to be deposited on top of the Qt5 deposit. Additionally, instead of creating a new Qt6 strath, the river could deposit a younger Qt6 deposit alluvium on top of the Qt5 deposit. This idea is supported by the Qt5 deposits in the hanging wall.

Figure 15: (Top) A plot using *Quercus* (oak) abundances as a proxy for climate change over the last 120 ka. Low *Quercus* abundances occur during glacial periods and high populations occur in interglacial periods. (Bottom) A plot using marine $\delta^{18}O$ concentrations as a proxy for climate change in the past 500 ka. High $\delta^{18}O$ values, and even numbered Marine Isotope Stages, indicate a glacial period, while low values indicate an interglacial period. On both plots, ages of the terrace deposits are shown as orange dots, with horizontal error bars. Grey sections represent glacial periods and white sections represent interglacial periods. The blue lines represent the age range for when sediment of the listed terrace was buried, which is defined by the overlap in age uncertainties in OSL and IRSL data of similar deposits.
At the LZ1 and LZ3 sites, there is a thick Qt5 fill with 47-64 ka ages and the younger Qt6 terrace deposit is inset into Qt5, stratigraphically below.

Similar to the Qt4 suite of terraces, there appears to be multiple terrace forming events during the Qt5 period. Since the Qt5 valley lies only a few meters above the modern channel, terraces formed during the transition from MIS 2 to MIS 1 approximately 15-25 ka could be considered in the Qt5 suite of terraces. It is more probable, however, that the younger terraces simply represent the age minimum of the Qt5 treads or they are fill-cut terraces within the larger Qt5 fill.

**Incision Rates and Tectonic Processes**

Incision rates are calculated from the reconstructed terrace formation and river incision history. The incision rates are more or less steady ~40 m/m.y. for the past 0.5 Ma, for both the hanging wall and footwall reaches, except for one period in the late Pleistocene where accelerated rates approaching 300 m/m.y. are observed (Fig. 12). Footwall and hanging wall incision rates are comparable between ~400 ka (Qt3) and ~100 ka (Qt4b in the hanging wall), and then again from ~60-70 ka to present day. Therefore, the background, long term rate of incision is measured to be approximately 45 m/My (Fig. 12).

The difference in incision rates can be interpreted as differential rock uplift consistent with the sense of rupture during the Mineral earthquake. Between ~100 ka and ~60-70 ka (Qt4b and Qt5 in the hanging wall, respectively), however, there is an acceleration in the incision rates in the hanging wall with respect to the footwall. Differences in incision rates across the Quail Fault result in discrepancies in the elevation
Figure 16: Terrace stratigraphic models in the footwall, the upstream hanging wall, and the downstream hanging wall sites.
above the modern channel of each terrace deposit (Fig. 16). Footwall incision rates between ~100 ka and ~60-70 ka are approximately 25 m/My, while hanging wall incision rates are approximately 340 m/My (Fig. 12). Climate shifts would result in a basin wide response, so it is likely that movement along the Quail Fault caused the variance in incision rates along the South Anna River. The acceleration in fault slip along the Quail Fault between 97 ka and 64 ka created accommodation space in the footwall. Now, instead of the river incising in order to maintain equilibrium, localized subsidence allows for the river to create a new terrace fill, Qt4b, which buries Qt4a.

Increased subsidence is shown in the terrace stratigraphy at Horseshoe Farm in the footwall of the fault (Fig. 14). Here, the Qt4a and Qt4b terrace straths are roughly the same elevation because the river did not incise due to crustal subsidence. Also, Qt6 appears to have buried Qt5. The lack of incision, due to subsidence, between the formation of the Qt4a and Qt4b and Qt5 and Qt6 terraces, results in buried fill terraces. In contrast, the river is rapidly incising in the hanging wall during this time period, creating vertical separation between Qt4a and Qt4b and Qt5 and Qt6 (Fig. 13, Fig. 16). The South Anna River incised approximately 12 m in the hanging wall between 97 ka and 64 ka. In the hanging wall region, the South Anna River previously incised 12 m between 391 ka and 97 ka. The river incising a similar amount in such a short period of time indicates a strong tectonic influence. The tectonic signal has not propagated to the hillslope erosion rates, however, as the $^{10}$Be cosmogenic data from the main channel and tributaries do not correlate with the channel incision rates. Erosion rates are faster in the footwall than the hanging wall, with average rates of 33.28 g/cm$^2$/yr and 8.41 g/cm$^2$/yr, respectively (Table 2, Fig. 12). Upstream, in the footwall, the elevation is higher and the overall relief is
greater. The hillslopes adjacent to the river will thus be steeper, which will cause erosion rates to increase. With lower relief in the hanging wall, the hillslopes are more stable, resulting in less erosion. It is important to note that the erosion rates show how the hillslopes are eroding, not the river. It is possible that erosion of the hillslopes is simply lagging behind and will increase in the future to reflect the tectonic processes. Sample SA2 was collected just downstream of the Byrd’s Mill knickpoint and the erosion rate here is 96.06 g/cm$^2$/yr. Additionally, erosion rates and incision rates are both relatively slow in the subsiding footwall, while in the uplifting hanging wall, erosion rates are slow and incision rates are high (Fig. 12). This relationship supports the idea that the footwall is 1) subsiding, resulting in low incision rates and 2) the entire landscape activity is also slow, and in agreement with river processes. The hanging wall erosion and incision rate relationship supports the idea that incision rates due to uplift are so high that the landscape simply cannot respond immediately. This demonstrates that hillslopes adjacent to the river can reflect river processes (such as incision), but it could take hundreds of thousands of years for the hillslopes to respond.

**Conclusions**

Tectonic and climatic processes are the primary drivers behind river incision and formation of fill terraces along the South Anna River and result in a complex terrace stratigraphy. All of the terrace straths observed in the field are overlain by a 2-4 m thick alluvial fill indicating a large influx of sediment from adjacent hillslopes. Each terrace likely formed from a period of aggradation during the glacial period, followed by a period of incision during an interglacial period. Thick fill terraces dominate the
landscape, with some smaller fill-cut terraces present due to intrinsic river processes. Terrace OSL and IRSL ages in the hanging wall of the Quail Fault reinforce the climate-induced terrace genesis hypothesis. The Qt3 age aligns with the transition from MIS 12 to MIS 11; the Qt4a age aligns with the transition from MIS 6 to MIS 5; the Qt4b age aligns with climatic shifts within MIS 5; and the Qt5 ages align with the transition from MIS 4 to MIS 3. These ages are supported by heavy mineralogy, soil color, FeO/FeD ratios, and terrace elevations. Throughout the last ~400 ky the incision rates in the hanging wall and footwall have been similar and consistently around 40-50 m/My. The exception to this is from approximately 100 ka to 60 ka in the hanging wall. During this period, incision rates increase to ~340 M/My, about 12 times the average historical river incision rate. The increased vertical separation of terrace straths in the hanging wall and the transient pulse in river incision rate indicate that tectonic processes, in the form of rock uplift, have played a role in the South Anna River terrace stratigraphy and landscape evolution along the South Anna River.
References


**Appendices**

**Appendix A.** The raw data used in the particle size distribution analysis of the terrace deposits.

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Appendix B. Standard Operating Procedures for cosmogenic sample analysis. PennCIL Lab, Jane Willenbring, updated 05 July, 2013

Separation and Purification of Quartz from Whole Rock

The following sections describe methods for obtaining clean quartz from a sample of whole rock using a combination of both physical and chemical preparation steps. The physical preparation involves sawing, crushing, grinding and magnetic separations. The chemical methods involve leaching the crushed rock sample in acids.

PHYSICAL PREPARATION OF QUARTZ FROM ROCK

Safety information: The crushing, grinding and sieving of rocks produces high amounts of dust, and inhalation of dust particles should absolutely be avoided. Review the procedures for operating the ventilation systems for these pieces of equipment and procedures. ALWAYS WEAR A DUST MASK, safety goggles, work gloves, long pants and closed shoes.

1. Rock samples may need to be cut using the small or large saw in the basement of Hayden Hall.

2. The samples are crushed into small pieces (less than 4 cm$^3$) using a crusher. Place the protective plastic ring around the rock sample during crushing to contain rock pieces.

3. Samples are then crushed using a disk mill. Crush rock pieces into sand-sized grains (generally < 0.7 mm). It is necessary to put the sample through the disk mill numerous times and progressively move the disks closer together to achieve the desired grain size without producing excess fine-grained sediment. WEAR a DUST MASK!

4. The crushed rock can then be put though a column of sieves to sort the sample by grain size.

Cleaning: Saws and rock crushing machines should be thoroughly cleaned after each sample. Rinse saws with water and dry them completely afterward. Use oil-spray to protect the metal pieces from oxidation. Empty water collection buckets below saws.
Rinse and dry the plates of the hydraulic press. Clean the disk mill using a vacuum, air compressor and small broom or brush. After cleaning the disk mill, turn it on and let it run for a few seconds without putting a sample in and observe to see if grains are in the pan. Clean sieves with a brush and dental pick if necessary.

5. Dry sieves in an oven and inspect them for cleanliness. If grains are still present in sieves, clean further with a brush or air compressor or a pick.

**Magnetic Mineral Separation**

1. An initial rough non-magnetic from magnetic separation can be achieved by putting the sample through a chute magnet (Frantz Magnetic Separator) found in. The grain size used is generally between 0.125-0.7 mm. Dusty samples make this step difficult.

2. The non-magnetic fraction attained using the chute magnet is then put through a Frantz Isodynamic separator located in Room 268 of Hayden Hall. Put sample through the Frantz Isodynamic separator (generally at 0.5 Amps and a 5 degree tilt) until about 150 g of non-magnetic grains are obtained. Collect magnetic and non-magnetic fractions and store in well-labeled Ziploc bags. Store all fractions of samples in a small well-labeled plastic container.

3. Cleaning: Clean the chute magnet and Frantz isodynamic separator thoroughly after each sample. Rinse and dry the chute magnet. All parts of the Frantz isodynamic separator should be taken apart and cleaned using paper towels and the vacuum. Rinse and dry the cups used to collect samples.

**NOTE:** Magnetic separations are not always needed, but when they are, we often do this step after the phosphoric acid boiling and before the first two hydrofluoric acid leaches so as to reduce the total sample size before the acid step.

**Quartz Purification – Chemical Preparation Steps**

**VERY IMPORTANT Safety Information**

The following steps require the use of strong acids that present skin and inhalation exposure risks, and for HF, systemic toxicity. Understand the risks associated with handling the chemicals you are working with, the procedures for reducing any risks and emergency procedures in the event of an accident.

- Verify that emergency eyewash/shower/spill kit is accessible and tested within last month.
- Verify that fume hoods are currently certified.
- Check the location and expiration of the Calcium Gluconate and that a copy of the
MSDS for HF is available.

- Always work in a fume hood with the sash as low as practical.

- It is essential that you wear a face shield over your safety glasses, double neoprene gloves, and a neoprene apron to ensure proper protection for concentrated acid spills.

- Wear appropriate gloves. For work with hot acids, use heavyweight (22 mil) neoprene gloves. For work with HF, you must wear HF resistant gloves – not all materials are HF resistant (for example, latex). Use heavyweight neoprene or nitrile gloves with a thin pair of the blue nitrile gloves underneath. Check your gloves regularly for holes and excessive wear and replace as needed. The thin gloves get holes in them very easily.

- You must wear long pants and closed shoes. Shorts, skirts, and open toed or fabric shoes are not permitted in the lab. Wear a lab coat or Tyvek™ suit over your long pants.

- Small spills contained in a hood, we can clean up. In the event of a large spill or accident, call 3-3333.

- All HF exposures must be treated as a medical emergency. Flush the exposed area with water until medical help arrives.

- Strong chemical waste is collected in labeled containers and picked up as hazardous waste. Understand the procedures for collecting, labeling and disposing of your waste.

- Empty bottles must be thoroughly rinsed out. Fill the bottle with water in the hood to avoid breathing vapors, and then rinse out at least 3 times in the sink. Remove the label, and write very clearly on the bottle, “RINSED”.

**Waste Acid Neutralization**

1. Weak acids (1-5%) may be neutralized to pH neutral conditions (pH>7) in the hood and neutral solutions may be poured down the sink. As with all work with bases and acids (especially hydrofluoric acid!), you must wear proper safety equipment.

2. Add 100 ml NaOH to the bottom of the 5-gallon bucket in the fume hood. This should be enough base solution to neutralize a batch of 20 1-Liter bottles.

3. Carefully, without losing any of the sediment in the bottles, add the 1-5% supernate Hydrofluoric Acid/Nitric Acid (1-5% HF-HNO₃) solution to the designated bucket. Do this very slowly. There will be a reaction - so keep the hood sash as low as is reasonable as you pour.

4. If a reaction ceases to occur, the basic solution may be spent and the solution in the bucket. In order to check, lower pH tape into the bucket using plastic tongs and read the pH. If the pH is low, add NaOH slowly (in 50 ml portions) until the solution is neutral.
5. Neutral solutions may be poured down the sink. Be careful to avoid too-full buckets that are heavy. Aim to empty the bucket when it is only half full. Be careful to avoid splashing of the solution. It all should be pH neutral at this point, but it can still leave white stains wherever it lands.

6. If you add too much base (NaOH) to the bucket, you can add some waste acids to get the solution back to neutral conditions. Do not add unused acid.

**Strong/Concentrated-Acid Waste Disposal**

1. Stronger acids ( > 5%) may NOT be neutralized to pH neutral conditions (pH>7) in the hood. They will be picked up by Penn’s hazardous waste personnel.

2. Find the appropriately labeled acid/base waste container near the window of Hayden Hall 166 and carefully carry it (closed) to the hood.

3. Wipe off the bottom with a damp paper towel before placing it in the hood to avoid contamination from the other room.

4. In the hood, open the waste container and use a funnel to transfer the solution to the waste receptacle.

**Phosphoric Acid Boiling**

*Samples are boiled in Ortho-phosphoric acid to dissolve a whole host of minerals in many rock types.*

- Check the glass beakers thoroughly for cracks.
- Clearly label your beakers using a Black Sharpie Marker.
- Be very careful of cross contamination if you are boiling more than 1 sample.

1. Weigh up to 80 g. of non-magnetic sample into 1000 ml beakers. Weigh the sample directly into the beaker in the fume hood both to avoid both inhaling dust and contaminating the lab with dust.

2. While in the fume hood, add some DI-H2O to each beaker (to keep the dust down). Then, at the sink rinse them thoroughly with DI-H2O to wash off the fines. (You don’t need to use MilliQ-H2O for this.)

3. In the fume hood, add 400 ml of concentrated (85%) O-phosphoric acid to each beaker and cover the beakers with a watch glass. Set the hotplate to about 325°C and monitor the hotplate temperature using a surface thermometer. Bring the samples to a boil. The
boiling can be very vigorous at first, so you must stay in the lab until it has reached a steady rolling boil. Make sure the vigorous boiling isn’t causing the beakers to “walk” off the hotplate. After about 1 hour the boiling will become gentle. Boil for 1 – 2 hours longer (or until the volume reaches about 300 ml). After a while, usually a total of about 2-3 hours, the rolling boil subsides and the surface can become quite flat. This is a good time to take off the samples.

**CAUTION:** Sometimes when the sample has boiled too long the acid will become very thick and jelly-like. (It seems it happens more w/ samples that have a lot of fines and organics, such as lichen from the surface of the rocks – another reason to rinse well.) To reduce the amount of sample lost in this thick gel, pour it off before stirring the sample up and suspending it in this dense liquid. If the samples boil for too long, a dense gel can form which can be difficult to remove without losing a lot of sample. If this should happen, read about “What to do if your sample gel’s” below.

4. Remove the beakers from the hotplates and place them on heat resistant tiles. You can remove the watch glasses so they cool faster, but then rinse them with DI-H2O into a container in the hood. Do not squirt water into the hot acid! Let the samples cool for about an hour. The acid may form a gel around the sample and on the side of the beaker (this film of supersaturated silica solution), which will dissolve during the sodium hydroxide cleaning.

5. Once the beakers are cool (lukewarm is ok), pour off the acid into the Phosphoric Acid waste container. In the hood squirt down the sides of the beakers with ~200 ml MQ-H2O and stir the samples with a clean metallic micro-spoon spatula. Allow the samples to settle and decant the water off into the waste container. Then add another 500 ml of DI-H2O. You can now take the samples over to the sink without risk of inhaling acid fumes. Rinse them 3 or more times with DI-H2O in the sink.

6. Add 300 ml DI-H2O to each beaker. In the fume hood, add 100 ml 50% NaOH (sodium hydroxide) to each beaker. The NaOH will dissolve the silicate coating around the quartz grains left by the phosphoric acid leach. Cover the beakers with the watch glasses and boil for ten minutes. (Use the same watch glass for the same sample as before, otherwise thoroughly rinse off any sample grains so as to avoid cross contamination of your samples.)

**DO NOT LEAVE THE SAMPLES! At this step the boiling is usually very vigorous and beakers can “walk” off the hotplate!** If the boiling is too vigorous, reduce the heat. After 10 minutes, place the beakers on the heat resistant tiles and allow them to cool (about 30 minutes). You can remove the watch glasses immediately, rinsing the lids directly into the beaker. Once cool, pour off the solution into the NaOH waste container. Rinse w/ ~100 ml DI-H2O and pour off into the waste container and then rinse three times with DI-H2O water and in the sink.

7. Either proceed directly to the HF/HNO3 leaching step or dry the sample in the oven overnight. If you are drying the samples, transfer them to small beakers, combining the
same sample into one beaker. Once the sample is dry let it cool, weigh it and record the weight in the notebook. Cover the sample with parafilm. If you are going directly to the HF step, combine 2 beakers of the sample into each bottle for the leaching step on the shaker table.

**BEAKER CLEANING:**
Scrub the beakers in the sink using a brush or sponge if necessary and rinse thoroughly so that no samples grains remain in the beakers. If they are really filthy, you can soak them in a soapy solution. Use MQ-H2O for the final rinse. Dry beakers on the drying rack.
**Hydrofluoric/Nitric Acid Leach**

Samples are leached in a dilute hydrofluoric/nitric acid solution in order to dissolve minerals other than quartz and to remove meteoritic 10Be. Samples are generally leached twice in 1000 ml of a 5% HF/HNO₃ solution and placed on the shaker table, each time for 1 day, and once in a 1% HF/HNO₃ solution in a heated ultrasonic bath for 24 hours. Some samples require additional leaching steps before they are sufficiently clean.

**ROLLER TABLE**

You can put ~100 g. of sample in a 1 Liter HDPE bottle, though this will vary by sample. Most samples dissolve a lot after the first leaching step, but you might want to adjust the amount of sample for sample types that don’t dissolve as much at this step.

1. If you use the narrow mouth bottles, use a funnel. Always use a clean funnel to put the acid into the bottles, but when moving the funnel between bottles containing different samples, make sure you are not transferring sample grains between bottles.

2. For a 5% HF + 5% HNO₃ solution – Add 850 ml MilliQ-H₂O. Then, working in the fume hood, add 100 ml concentrated (49%) HF and 50 ml concentrated (79%) HNO₃. (Use certified A.C.S. grade. Not superpure grade! ($$$))

   **NOTE:** ALWAYS ADD WATER FIRST! NEVER ADD WATER TO ACID!

   Email me: erosion@sas.upenn.edu

3. Place the bottles on the roller table overnight. Make sure there are no drips of acid on the sides of the bottles. The samples do not need to be on for a full 24 hours but can be. If you put them on in the afternoon, it is ok to change them the next morning. For a 5% HF + 2% HNO₃ solution, use 875 ml MilliQ-H₂O, 100 ml HF and 25 ml HNO₃.

**RINSING**

4. In the hood, pour the acid solution into a properly labeled waste container being careful not to pour out your sample. Use a funnel to reduce dripping.

5. While working in the fume hood, add water to each bottle. Shake them vigorously, and then decant the water into the sink, again being careful not to spill any sample. (It is dilute enough that you can work outside of the hood.) Rinse the samples two more times filling the bottles about a third of the way and shaking them vigorously each time. (The vigorous shaking breaks up weaker feldspar grains.)

6. Repeat this roller table leach step for a total of 2 leaches. Neutralize acid afterward.

**ULTRASONIC LEACH in 1% HF 1% HNO₃**
1. Transfer the samples directly from the 1000 ml bottles into labeled 2000 ml bottles. We generally put in about 50g per bottle. (You can approximate the amount. It’s not worth drying them first.)

2. Fill the bottle with 1800 ml MQ-H₂O

3. In the hood, add 40 ml HF and 30 ml HNO₃. Put the lids on tight when putting into the ultrasonic bath. Fill the bath to the brim with DI-H₂O.

5. Turn on both the sonicator and the heat. You will need to check the level of the water from time to time. Even without the heat on the water will evaporate. Keep it almost full.

**RINSING**

6. Remove the bottles from the bath and allow them to cool for about 30 minutes.

7. Decant the acid into a waste container or neutralize the acid.

8. Under the hood, fill the bottles 1/2-way with MilliQ-H₂O to rinse. You do not need to pour this rinse into a waste container. This is already sufficiently dilute for the sink (do the math, a few ml 1% HF and HNO₃ diluted to 2000 ml).

9. As with the small bottles, shake these up vigorously, decant into the sink and repeat for a total of 3-4 rinses.

10. Transfer sample into a very clean and labeled beaker for storage and cover with Parafilm™. Do not put the Parafilm™ on a hot beaker or it will melt!

**BOTTLE WASHING (Make sure you remove all sample grains from the bottles)**

Rinse the bottles thoroughly using the water straight from the DI line. You can turn the bottle upside down and forcefully clean off any grains that may be stuck to the bottom and sides. Give the final rinse with MilliQ-H₂O. Once your bottles are cleaned, remove all labels and put them away. Only bottles without labels are assumed to be clean!
SAMPLE DECOMPOSITION AND $^{10}\text{Be}$ & $^{26}\text{Al}$ SEPARATION

PURITY CONTROL (ICP-OES)

1. Take ca. 200 mg of each sample in 7 ml Savillex beakers

2. Weigh the amount of sample

3. Add 3 ml 28M HF, and heat overnight with closed lid; and evaporate afterwards until the HF is almost completely evaporated.

4. Add 1 ml 15M HNO$_3$, and heat 1 hour with closed lid; and evaporate

5. Check if all material is dissolved. If not, add Aqua Regia (2 ml 6M HCL and 1 ml 15M HNO$_3$) and evaporate

6. Add 1 ml 0.3 M HNO$_3$ to beaker, make sure all sample dissolves

7. Dilute to convenient concentration, Shake

8. Measure concentrations on ICP-OES, for Al-procedure sample should have <100 ppm Al, for Be-procedure <1000 mg Al. Ask David Vann for help with ICP-OES questions.

Final Quartz Leach

1. Take weight of 90 ml or 240 ml Savillex beaker including lid (max 50g Qtz in 90ml Savillex beaker, max ca. 150 g in 240 ml beaker)
   Add 7M HF so that sample is just all covered with HF plus 5 mm excess liquid height
   (28M HF: Milli-Q H$_2$O = 1:3)
   Heat 1 hour maximum 120°C with lid
   Cool down
   Wash with Milli-Q H$_2$O

2. Add Aq. Re.so that sample is just all covered with acid plus 5 mm excess liquid height (15M HNO$_3$ : 6M HCl = 1:3)
   Cool without lid until gas gone (~30 min)
   Minimum 1 hour hot (120°C) with lid
   Wash, rinse, shake thoroughly (4-5x) with Milli-Q H$_2$O
   Dry on hotplate in Savillex Beaker
   Take precise weight
SAMPLE DISSOLUTION, CARRIER ADDITION

1. Add carrier amount depending on AMS requirements, take precise weight of ~0.2 mg Be
   Alternative: add carrier after dissolution (between steps 2b and 3a).
   This comes handy if natural Be content has to be determined.

2. HF Addition - Principles
   Stochiometric reaction: SiO$_2$ + 4 HF -> SiF$_4$ + 2 H$_2$O
   Need 116 ml 28M HF for 50 g Quartz - ONLY use HF in TEFLOON beakers!! No GLASS!!

2a. Add 28M (~49%) HF so that sample is fully covered with acid plus 5 mm excess liquid height.
   1$^{st}$ and 2$^{nd}$ additions: strong exothermic reaction; do not heat; add HF in increments!
   Heat (120°C) without lid, evaporate to dryness
   3$^{rd}$ addition: add HF 2x that of Qtz volume, put open beaker on hot plate and evaporate. Repeat if not all Qtz is dissolved.
   Dry down. Don't loose any sample flakes! Do not touch open beaker with gloves!

2b. Alternative: Single Step dissolution method
   Take 240 ml Savillex beaker
   Add 2x stochiometric amount of HF. CAREFUL!
   Place closed beakers into cold water bath, wait minimum 2 hours (better overnight)
   Close beaker and heat until all Qtz is dissolved
   Evaporate

   Alternative Carrier: - Take aliquot of dissolved sample from HF to determine natural Be content (only if no carrier has been added so far)
   - Add carrier, proceed with sample conversion

3a. Sample conversion
   Add ~20 ml Aq. Reg. (7 ml 15M HNO$_3$ and 14 ml 6M HCl)
   Heat until all residue dissolved and evaporate gently
   Add 10 ml 6M HCl
   Transfer into cleaned 10 ml centrifuge tubes
   Centrifuge 5 min, 3000 rpm
   Check Purity by ICP-OES

3b. Optional BeF$_2$-Leaching (only when NO Al-chemistry is done; carrier must have been added prior to dissolution)
   Do not add Aq. Reg. to sample
   Add 1 ml HF and evaporate to dryness, if the cake does not dissolve add 1ml more
   Add 1 ml HF and evaporate to dryness, if the cake does not dissolve add 1ml more
   Add 10 ml H$_2$O to fluoride cake
   Heat gently for a minimum of 1 hour
Transfer the cake and the supernate into a labeled centrifuge tube. Centrifuge at 3500 rpm for 5 minutes. Transfer the 10 ml supernate (containing water-soluble BeF$_2$, TiF$_4$, Fe(II)F$_2$ but no AlF$_3$) into Savillex beaker. Evaporate supernate. Add 1 ml 6M HCl. Transfer into cleaned 10 ml centrifuge tubes. Add another 1-2 ml of 6M HCl to centrifuge 5 min, 3000 rpm.

4. **Al-chemistry**
   Label 15 ml cleaned centrifuge tubes for Al-TSS, place empty tube on balance, zero balance. Label cleaned 60 ml bottle for Al- aliquot, place on second (less precise) balance, take bottle weight, then zero balance. Transfer sample solution into small tube, leave undissolved residue behind, take weight of TSS (total sample solution). Take 250 µl aliquot, transfer into 60 ml bottle, take weight of Al aliquot. Add 5 ml 3M HNO$_3$ to Al aliquot (storage in strong acid to prevent adsorption of Al). Before OES measurement: dilute to 0.3M HNO$_3$ by addition of 45 ml Milli-Q H$_2$O.

**SEPARATION OF $^{10}$Be & $^{26}$Al**

1. **Column Fe**
   2 ml Biorad 1x8 100-200 mesh in 15 ml Eichrom column stored in H$_2$O. Sample is in 10 ml 6M HCl.

   Open column and let H$_2$O drop out.
   5 + 5 ml 0.3M HCl clean resin
   2 + 2 + 2 ml 6M HCl condition resin
   Load sample collect Be (+Al)
   2 + 2 + 2 ml 6M HCl collect Be (+Al)
   5 + 5 ml 0.3M HCl clean resin

   Seal and store column in Milli-Q H$_2$O.

   Evaporate sample.
   For next step, add 2 ml (20 ml for dirty Qtz) 0.4M Oxalic Acid on sample.
   Warm to 60° with lid for ~2 hours.
   Cool down, wait for 30 min, transfer to 10 ml centrifuge tube.
   Centrifuge 5 min, 3000 rpm to remove any potential particulates.
   Load supernate only to Be column.

2a. **Small column Be** (clean samples: total cation load <1 meq)
   1 ml Biorad AG50-X8 (200-400 mesh) in 7.5 ml RKBN104704 column stored in H$_2$O.
   Sample in 2 ml 0.4M Oxalic Acid (amount can be adapted if sample is not completely dissolved).
Open column and let H₂O drop out

2 + 3 ml 5M HNO₃ clean resin
2 + 3 ml Milli-Q H₂O remove HNO₃ from resin
2 + 3 ml 0.4M Oxalic Acid condition resin

Load sample
1 ml 0.4M Oxalic Acid collect Al
1 ml 0.4M Oxalic Acid collect Al
5 + 5 ml 0.4M Oxalic Acid collect Al (elute Fe, Al, Ti)
1 + 2 ml Milli-Q H₂O remove Oxalic Acid from Column
2 + 2+ 4 ml 0.5M HNO₃ elute Na

3 + 3 +5 ml 1M HNO₃ **collect Be**
5 + 5 ml 5M HNO₃ clean resin
5 ml H₂O remove 5M HNO₃

Seal & store column in Milli-Q H₂O
Go to Be precipitation directly

2b. Large column Be (dirty samples: total cation load >1 meq; max 5 meq)
5 ml Biorad AG50-X8 (200-400 mesh) in 15 ml Eichrom column stored in H₂O
Sample in 20 ml 0.4M Oxalic Acid (amount can be adapted if sample is not completely dissolved)

Open column and let H₂O drop out

5 + 5 ml 5M HNO₃ clean resin
5 + 5 ml Milli-Q H₂O remove HCl from resin
5 + 10 ml 0.4M Oxalic Acid condition resin

Load sample
5 ml 0.4M Oxalic Acid collect Al
5 ml 0.4M Oxalic Acid collect Al
25 + 25 ml 0.4M Oxalic Acid collect Al (elute Fe, Al, Ti)
5 + 10 ml Milli-Q H₂O remove Oxalic Acid from Column
15 + 25 ml 0.5M HNO₃ elute Na
10 ml 1M HNO₃ wash

20 + 15 ml 1M HNO₃ **collect Be**
20 + 20 ml 5M HNO₃ clean resin
5+5 ml H₂O remove 5M HNO₃

Seal & store column in Milli-Q H₂O
Dry down, take up in 11 ml 1M HNO₃, and go to Be precipitation

3. Column Al
1 ml Biorad AG1-X8 (100-200 mesh) in 7.5 ml RKBN104704 column stored in H₂O
Sample in 0.4M Oxalic Acid from Be-column
Open column and let H₂O drop out
(Mixture of 0.05M Oxalic Acid and 0.5M HCl is prepared by mixing equal amounts of 0.1M Oxalic Acid and 1M HCl)
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<tr>
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<td>H₂O</td>
<td>remove HCl</td>
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<tr>
<td>2 + 2 + 2 ml</td>
<td>0.4M Oxalic Acid</td>
<td>condition resin</td>
</tr>
<tr>
<td>Load sample</td>
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<td>save effluent in case Al elutes early</td>
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<tr>
<td>4 + 2 ml</td>
<td>0.05M Ox/0.5M HCl</td>
<td>wash, save effluent in case Al elutes early</td>
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<td>collect Al</td>
</tr>
<tr>
<td>5 + 5 ml</td>
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<td>elute Ti</td>
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Seal and store column in Milli-Q H₂O

Dry down sample in Savillex beaker
Add 2 ml Aq. Reg. (15M HNO₃: 6M HCl = 1:1)
Evaporate to dryness
Repeat once
Add 1 ml 15M HNO₃ and 1 ml H₂O₂
Evaporate to dryness
Repeat 2x

4a. Be Precipitation (Aim: leave remaining 1+ and 2+ cations in solution)
Sample is in 2 tubes of 11 ml 1M HNO₃ after Be column
Dry down one tube of 11 ml 1M HNO₃ in the Teflon vessel at ~100 deg C.
Add the second tube of 11 ml 1M HNO₃ and transfer back to one of the tubes
Dilute suprapure NH₄OH conc : Milli-Q H₂O = 1 : 1
Add diluted NH₄OH to sample, ca. 0.3 ml Ammonia to 1 ml 1M HNO₃ until pH » 10
Shake when NH₄OH is added.
Centrifuge at ~3500 rpm for ~5 minutes
Decant supernate and Wash precipitate in 5 ml Milli-Q H₂O
Centrifuge at ~3500 rpm for ~5 minutes
Decant supernate and Wash precipitate in 3 Milli-Q H₂O
Centrifuge and Decant supernate
PREPARATION OF SAMPLES FOR AMS MEASUREMENT

1. Silver addition (for ETH-AMS only)
   Silver solution: Prepare fresh solution for each batch
   157 mg AgNO₃ into 10 ml 5M HNO₃, shake
   ⁴⁰Be: add 0.3 ml Ag solution
   (Aim: Ag : Be = 20 : 1 => for 0.15 mg Carrier, take less for samples where some Be was lost)
   ²⁶Al: add 0.5 ml Ag solution
   (Aim: Ag : Al = 5 : 1 => for 1 mg “Al Carrier”)

   Transfer to Quartz crucible
   Dry samples on hotplate in holder at ~150°C

2. Oxidize over Bunsen burner (>1000°C) (for all AMS facilities)
   15 sec drying sample outside of flame
   1 min in blue part of flame
   Use Pt-coated tongs.
   Wear dusk mask

3. Target (for ETH-AMS only)
   Work with dust mask or in fume hood!
   Clean targets 1 min in 1M HCl, rinse with Aceton
   Clean all instruments with Aceton
   Scratch down sample with spatula
   Load sample from rear in cleaned target with spatula, use cleaned steel plate coated with Al foil
   Hammer often but slightly, press down target
   Add sample, then fill hole from rear with excess Cu (63µm; p.a. quality)
   Label target on the front face with sample number

3. Target (for PRIME Lab)
   Work with dust mask and in glove box!
   Add 1:3 BeO:Niobium powder to quartz vial - check website for updates to this
   Add 1:3 Al:Ag powder to quartz vial - check website for updates to this
   Scratch down sample with spatula
   Tip into the (already cleaned by PRIME Lab) cathode
   Press with tamping rod and tap gently with a hammer to pack powder down.

GAMMA RAY DETECTOR

Safety information: You must get Penn radiation safety training and be added to the radiation license before working with the detector and before touching the detector.
ALWAYS WEAR safety goggles, gloves, long pants and closed shoes. Never cut or deface the standard bottles. Never open the unopenable bottles. Put the (always closed) standards back into the lead safety cabinet when not calibrating the detector.

If something happens with the detector or the standards, tell Jane Willenbring immediately (cell 612-270-6591). If I am not available, contact David Vann

Procedure
1. Fill the detector with liquid nitrogen from the dewar using the pouring technique from the training session. Make sure the overflow bubble hose is submerged in the water bath. Never touch liquid nitrogen without the insulated safety gloves and make sure it is handled carefully and in the proper way per safety training.

2. Calibrate the detector using the 7503 standard according to the software instructions.

3. Calibrate your sample’s case geometry using the point $^{210}$Pb (1µCi) standard.

4. Insert only sealed samples into the detector space and never allow any standard or sample to spill. This should be impossible because ALL samples that go in the detector should be completely sealed and cleaned on the outside.

5. Report in the lab notebook the sample name, the time that the detector started and which sample case you used and which output files were produced as well as your initials

6. When you leave after the detection is finished, make sure all the standards are in their lead shielded storage box. Remove any sample from the detector and make sure that the liquid nitrogen dewar and storage tank is full. If your sample will take days to count, check the liquid nitrogen level each day and add liquid nitrogen if the level is below 1/3 full.
### Appendix C. Sample input for the erosion rate calculation.

| A  | B    | C  | D    | E    | F    | G    | H    | I    | J    | K    | L    | M    | N    | O    | P    | Q    | R    | S    | T    | U    | V    |
|----|------|----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|    |      |    |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1  | **Sample input for the erosion rate calculation.** |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 3  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 4  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 5  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 6  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 7  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 8  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 9  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 10 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 11 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 12 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 13 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 14 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 15 |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |

*Note: The table contains numerical data for erosion rate calculations.*
Appendix D. Field photos, sketches, PSDA and FeO/FeD plots from the (top to bottom) Cox (Qt3, hanging wall), AF2 (Qt4a, hanging wall), BB1 (Qt4b, hanging wall), and Site D (Qt5, footwall)
**Appendix E.** The raw data used in the heavy mineral analysis. From left to right, the columns are visual descriptions, elemental percentages, mineral name and percentage of the sample.

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</table>
Vita

Matthew McGavick was born in Stamford, Connecticut, on February 17, 1993, and soon after moved to Sudbury, Massachusetts where spent the rest of his childhood. After graduating from Lincoln-Sudbury Regional Highschool in 2011, he attended Union College (NY). Starting in 2011 he studied environmental geology and received a B.S. degree in 2015. He then enrolled in the graduate earth and environmental sciences program at Lehigh University in the summer of 2015.