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A SOIL CHRONOSEQUENCE STUDY ON TERRACES OF THE CATAWBA RIVER NEAR CHARLOTTE, NC: INSIGHTS INTO THE LONG-TERM EVOLUTION OF A MAJOR ATLANTIC PIEDMONT DRAINAGE BASIN

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ABSTRACT

Relatively few soil chronosequence or long-term landscape evolution studies exist for the Piedmont of the southeastern United States. Here, we present a chronosequence of soils on five well-expressed, unpaired alluvial terraces from the Catawba River near Charlotte, NC. Ten soil profiles were excavated and described on the terrace sequence. Soil pits were sampled by horizon and the <2 mm fraction analyzed for particle size and extractable iron. Ages are assigned to the terrace units through comparison with regional surface age/elevation curves (Mills, 2000). The elevations (and calculated ages) of the terraces above the modern channel are: 3 m (4±0.5 ka), 10 m (50±6 ka), 14 m (128±16 ka), 28 m (610±75 ka), 42 m (1,470±180 ka).

Color hue, pedogenic iron (Fe_d) and clay content (%) recorded positive trends with increasing terrace age. Specifically, these variables increased from 10YR to 2.5YR, 3.6% to 6.4%, and 21.9% to 62.6% respectively, from the lowest (~4 ka) to the highest (~1,470 ka) terrace. These results are consistent with regional chronosequence studies developed in different physiographic provinces and parent materials. This consistency implies that the relatively rapid oxidation of iron bearing minerals and development of pedogenic clays overshadows the effect of differences in parent material and regional climate. The rate of development of these soil properties plateaus after ~128 ka. Fe_o/Fe_d ratios and clay contents record a break in soil development between ~128 and 50 ka, which is ascribed to the inheritance of reworked, previously weathered material. These results indicate a unique, dramatic change in the sediment provenance of the Catawba River from the erosion of relatively unweathered bedrock to relatively well developed soils, stripped from basin hillslopes during this time period. This switch represents a major change in landscape evolution likely driven by the colder climatic conditions of the Late Pleistocene. Sedimentological changes from cobble gravel facies to sand facies indicates that terrace formation was coupled with a change in fluvial transport capacity prior to ~128 ka. These data represent some of the first insights into the long-term soil and landscape evolution of a major drainage in this region of the Piedmont.

INTRODUCTION

Despite their value in Quaternary geologic studies, relatively few soil chronosequences exist for the southeastern United States (Fig. 1). Soils develop under the influence of several environmental factors including climate, organisms, relief, parent material and time (Jenny, 1994). A soil chronosequence is defined as a series of soils for which weathering characteristics vary as a function of time. Using this paradigm, soil development can be employed as a tool for mapping, correlating and assigning ages to Quaternary deposits (e.g. Leigh, 1996; Mills, 2005), for understanding landscape dynamics in the context of climate change or tectonics (e.g. Eppes et al., 2002, 2008), or for evaluating ecosystem variability (e.g. McAuliffe et al., 2007). Previous chronosequence studies on fluvial terraces in the southeastern

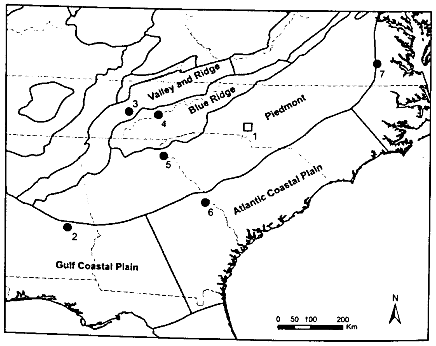

Fig.1. Map of select physiographic provinces in the southeastern United States. Figure shows approximate location of study area and published regional chronosequence studies as follows: 1) Study location; 2) Shaw et al. (2003); 3) Delcourt (1980); 4) Leigh (1996); 5) Foss et al. (1981); 6) Pavich et al. (1981); 7) Howard et al. (1993).

United States have been conducted in the physiographic provinces of the Valley and Ridge (e.g. Delcourt, 1980), Blue Ridge Mountains (e.g. Leigh, 1996), Piedmont (e.g. Foss et al., 1981) and Coastal Plain (e.g. Markewich et al., 1989; Howard et al., 1993; Shaw et al., 2003) (Fig. 1). More comprehensive chronosequences exist for the Coastal Plain due to terrace continuity and the availability of paleontologically dated marine units (Mills, 2005). Chronosequence studies on other deposits in this region, such as pediments, alluvial fans and debris flows, have typically focused on the Blue Ridge Mountains (e.g. Mills, 1983; Mills and Allison, 1995; Liebens and Schaetzl, 1997). The dearth of chronosequence studies in the Piedmont physiographic province is likely due to a number of factors including the overall maturity of the landscape and consequent perceived homogeneity of "red clay" soils, and the lack of exposure of a suitable stratigraphy of landforms. Nevertheless, such studies still stand to provide valuable insights into the landscape evolution of this understudied region.

The major drainages of the southeastern United States have also received little study in the Piedmont. Long-term fluvial evolution research in the eastern United States has tended to focus on more northern drainages or other physiographic provinces. For example, several studies have investigated terraces of the Susquehanna River to interpret the interaction of fluvial processes with base level fluctuations (isostatic and eustatic) and changes in climate (e.g. Pazzaglia and Gardener, 1993; Engel et al., 1996; Reusser et al., 2006). Research conducted on the alluvial deposits of the New River in the Valley and Ridge province of Virginia has documented late Cenozoic channel migration (e.g. Bartholomew and Mills, 1991), as well as the timing and rates of Quaternary incision and aggradation events (e.g. Granger et al., 1997; Ward et al., 2005). More recently, Leigh (2008), utilizing fluvial deposits in the Atlantic Coastal Plain, documented the fluvial response of river channels to Late Quaternary climate change. The depositional and incisional history of drainages in the southeastern Piedmont however is effectively unexplored despite the fact that the evolution of these major drainages could provide insight into ongoing landscape scale response to climate and land use change.

In this study, we aim to improve understanding of the soil geomorphology and landscape evolution of the Piedmont physiographic province in the southeastern United States through the study of fluvial terraces located in the Cowan's Ford Wildlife Preserve, NC. In this locality, an unusually large meander bend of the Catawba River has resulted in the preservation of a suite of terraces that have been relatively undisturbed by modern development. We describe the stratigraphy, sedimentology and soils of these terraces and in doing so provide insight into the long-term fluvial history of a major east coast drainage basin.

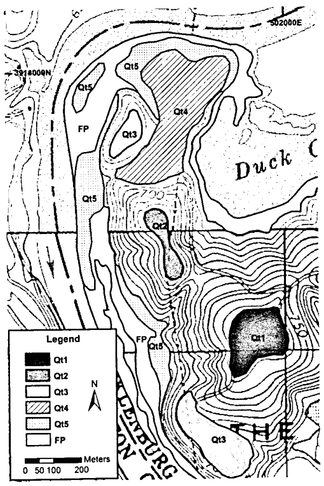

Fig.2. Surficial geologic map of study area showing terrace tread(Qt1-5) and floodplain (FP) surfaces. Base map includes USGS 7.5' Quadrangles Mountain Island Lake and Lake Norman South. Contour interval is 10 feet.

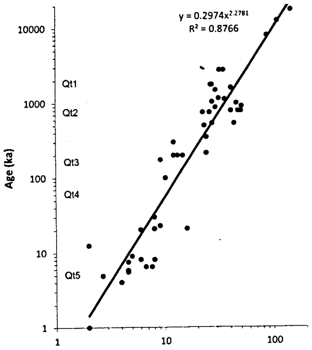

Fig.3. Log-log plot of surface age vs. elevation above modern stream level (modified from Mills, 2000). We estimate error on calculated ages for terrace units to be within 13% based on the unexplained variance.

GEOLOGY AND SETTING

The study area is located along the Catawba River in the Cowen's Ford Wildlife Refuge, near Charlotte, in the Piedmont of North Carolina (Figs. 1 and 2). The Catawba River is approximately 350 km long and flows from the Blue Ridge Mountains to its confluence with the Wateree River in South Carolina. The Catawba River watershed drains approximately 9,000 km^2 of Western North Carolina. The modern channel is heavily impounded by seven reservoirs designed for hydroelectric power generation. The study area is located at the uppermost end of Mountain Island Lake, where the river is sometimes still free flowing. Soils in the area are mapped as Typic Hapludults (Cecil, Georgeville, and Pacolet Series), Rhodic Peludults (Davidson Series), and Fluvaquentic Eutrochrepts (Monacan Series). The study area lies within the Charlotte Belt, which consists of intrusive plutonic suites, ranging from gabbro to granitic rock, as well as metamorphosed diorite and biotite gneiss. Bedrock in the field area consists of metagranodiorite, comprised mainly of plagioclase, quartz, potassium feldspar, and biotite. The modern climate is characterized by hot, humid summers and moderate,

Table 1. Representative soil properties described from soil pits on terrace units.

Unit	Horizon	Depth (cm)	Color Moist	Color Dry	Gravel (%)	Texture	Structure	Consistence Wet	Consistence Moist	Clay Films	Boundary	Roots	Pores
Qt1	Ap	0-21	5YR 3/4	5YR 4/6	<10	CL	3 m sbk	ss-s p	fi	3 p cobr	a s	2m 3f 3vf	1c 1m 1f 2vf
	Bt1	21-64	2.5YR 3/6	2.5YR 4/6	<10	L	3 m sbk	s p	fi	3 p cobr	d s	2m 1f 1vf	1m 3vf
	Bt2	64-105	2.5YR 3/6	2.5YR 4/6	<10	L	3 c sbk	s p	fi	3 p cobr	---	1m	3vf
Qt2	Ap	0-20	7.5YR 4/6	7.5YR 4/6	<10	SL	2 f sbk	so po	fr	---	c s	1m 3f 3vf	2f 3vf
	Bt1	20-73	2.5YR 4/8	2.5 YR 5/8	<10	C	3 f sbk	s p	fi	3 d pf	d s	3f 3vf	2f 3vf
	Bt2	73-128	2.5YR 3/8	2.5YR 5/8	<10	C	3 f sbk	s p	fi	3 p cobr	---	1m 2f 2vf	---
Qt3	Ap	0-10	7.5YR 2.5/3	7.5YR 3/3	<10	L	2 f sbk	ss p	fr	---	a s	2c 2m 2f 3vf	1c 3m 3vf
	Bt	10-25	5YR 3/3	5YR 4/3	<10	L	3 f abk	s p	fi	3 d cobr	c s	2c 2m 2f 2vf	2m 1f 3vf
	Btc1	25-45	5YR 4/4	5YR 4/4	<10	CL	3 f abk	s p	fi	3 p cobr	c s	1f 2vf	2m 3vf
	Btc2	45-102	2.5YR 4/6	2.5YR 4/6	<10	C	3 f abk	s p	fi-vfi	3 p cobr	---	1f 1vf	3vf
Qt4	Ap	0-20	7.5YR 5/6	7.5YR 5/6	<10	L	2 f sbk	ss p	fi	---	a s	1c 1m 2f 3vf	1c 1m 2f 3vf
	Bt1	20-52	5YR 5/8	5YR 5/6	<10	C	2 m sbk	s p	fi	3 p cobr	g s	1f 1vf	1f 3vf
	Bt2	52-77	5YR 5/8	5YR 5/6	<10	C	2 f sbk	s p	vfi	3 p cobr	---	---	1vf
Qt5	A	0-10	10YR 3/3	10YR 5/2	<10	SIL	3 f sbk	ss ps	fr	---	a s	1c 2m 2f 2vf	3m 2f 3vf
	Bc	10-21	10YR 3/6	10YR 5/4	<10	L	2 m sbk	s p	fr	---	a s	2c 2m 3f 3vf	1m 2f 3vf
	Btc1	21-39	10YR 5/6	10YR 6/4	<10	L	2 m sbk	s p	fr	2 d pf	g s	1f 1vf	1m 2f 3vf
	Btc2	39-55	10YR 5/8	10YR 6/6	<10	L	2 c sbk	s p	fi	2 d pf	c s	1m 1vf	1f 2vf
	Btc3	55-82	10YR 5/6	10YR 6/6	<10	L	2 m sbk	s p	fi	2 d pf	---	---	2vf

Subordinate horizons: c = manganese concretions, p = ploughed, t = clay accumulation
Texture: C = clay, CL = clay loam, SL = sandy loam, L = loam, SIL = silty loam.
Structure: Grade: 1 = few, 2 = common, 3 = many; Size: f = fine, m = medium, c = coarse; Type: abk = angular blocks, sbk = sub-angular blocks.
Consistence: so = non-sticky, po = non-plastic, ss = slightly sticky, ps = slightly plastic, s = sticky, p = plastic; fr = friable, fi = firm, vfi = very firm.
Clay films: 1 = few, 2 = common, 3 = many; d = distinct, p = prominent; pf = ped faces, co = coats, br = bridges.
Boundary: a = abrupt, c = clear, g = gradual, d = diffuse; s = smooth.
Roots and pores: Grade: 1 = few, 2 = common, 3 = many; Size: vf = very fine, f = fine, m = medium, c = coarse.

short winters. Annual precipitation averages approximately 106 cm, while average temperatures range from 5 °C in January to 25 °C in July (NOAA, 1981-2010). Vegetation consists primarily of mixed hardwood and pine-hardwood forests and grasslands.

METHODOLOGY

Terraces were mapped in the field utilizing topographic maps (United States Geological Survey Mountain Island Lake and Lake Norman South 7.5' Quadrangles). Terrace units were distinguished based on 1) terrace tread elevation, 2) soil development, 3) stratigraphy and 4) sedimentology. Numerical dating of older (e.g. Pleistocene) alluvial landforms in the Eastern United States has until recently been largely unobtainable (Mills, 2005). Cosmogenic isotope dating has been successfully employed in some studies (e.g. Mills and Granger, 2002) but remains prohibitively expensive. In this study, we assign numerical ages to terrace units by comparing the elevation of mapped terraces above the modern river channel to regional surface age/elevation curves published by Mills (2000; Fig. 3). Mills utilized data from research conducted throughout the southeastern and eastern United States and obtained a strong correlation between surface age and elevation above the modern stream channel (R^2 value of 0.877).

A total of ten soil profiles, two per terrace unit, were described according to Soil Survey Staff (1993) and Birkeland (1999). Soil pits were both hand excavated (5 total) and exhumed via auger boring (5 total). All profiles were located on relatively flat tread surfaces, away from terrace scarps in order to minimize the effects of erosional and colluvial processes. Analysis of soil morphology from soil pits (Table 1) included descriptions of horizon thickness and boundaries, color, structure, gravel content, consistence, roots and pores, texture, clay films, as well as sedimentary descriptions (grain size, rounding, sorting). Select properties were described from auger borings to account for spatial variability. Pits were sampled by horizon with multiple samples being collected where horizons were greater than 25 cm in thickness. All samples were sieved in the field and the <2 mm fraction analyzed for particle size (pipette method). Iron content was measured through both oxalate (McKeague and Day, 1966) and dithionite-citrate (Mehra and Jackson, 1960) methods for samples from horizons with the greatest evidence of weathering (B or Bt horizons).

RESULTS

Five distinct, unpaired terrace treads (Qt1-Qt5) were distinguished in the field area ranging from 3 to 42 m in elevation above the modern channel (Fig. 2). Soil morphological data described from soil pits for each terrace unit is provided in Table 1. The Qt1 terrace is the highest in the sequence standing approximately 42 m above the modern stream channel. The calculated age for the unit based on this elevation is 1,470±180 ka (Fig. 3). The unit is characterized by alluvial sediments, comprising pebble and cobble gravel, with moderately to poorly sorted, sub-rounded to rounded quartzite clasts. These clasts, varying in size from 4-60 mm, were distributed throughout the profile, with a clast supported facies beginning at a depth of 2.1 m below the tread surface. Qt1 soils exhibit Ap/Bt horizonation and are characterized by dark reddish brown to red colors (5YR 3/4 to 2.5YR 4/6) and sticky to plastic consistence. Soil texture consists of clay, which grades upward to clay loam. Soil structure is well developed with distinct sub-angular, blocky peds between 10-20 mm in diameter. Clay content in the soil varies from 31.9% in the A horizon to 61.9% in the B horizon (Fig. 4) with many, prominent clay films forming coats and bridges. Extractable iron content in the B horizon was determined to be 6.37% (Fe_d) and 0.61% (Fe_o) with an iron activity ratio (Fe_o/Fe_d) of 0.10 (Fig. 5).

The Qt2 terrace tread is approximately 28 m in elevation above the modern channel of the Catawba River and was assigned an age of 610±75 ka (Fig. 3). Several quartzite clasts, ranging in size from 2 to 50 mm, were distributed throughout the soil profile, suspended in a fine-grained matrix. Clast supported gravel and

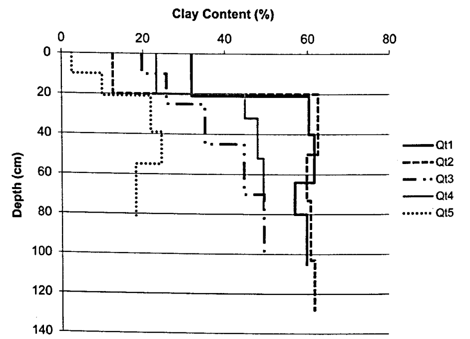

Fig. 4. Depth profile plot of clay content (%) for representative soil profiles on terrace units. Analytical error is <1% for clay content.

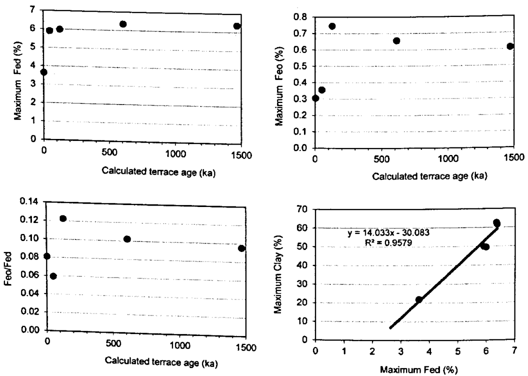

Fig.5. Chronofunctions of extractable iron for representative terrace soils. Plots show maximum extractable iron values (both Fe_d and Fe_o) from the B horizon, iron activity ratios (Fe_o/Fe_d) and the relationship between Fe_d and clay content (%). Analytical errors are <0.2% for Fe_d and Fe_o. Estimated ages for terrace units are: 4 ka (Qt5), 50 ka (Qt4), 128 ka (Qt3), 610 ka (Qt2), and 1,470 ka (Qt1).

cobble facies were found 1.3 m below the tread surface. Soil development is characterized by Ap/Bt horizonation with strong brown to red coloration (7.5YR 4/6 to 2.5YR 5/8), strongly developed structures with sub-angular blocky peds, between 5-10 mm in diameter, and sticky to plastic consistence. Soil texture consists of clay, which grades upward to silt loam. Qt2 soils have the highest observed clay content, which ranges between 59.8% and 62.6% in the B horizon (Fig. 4), and have many distinct to prominent clay films covering ped faces and forming bridges between peds. Iron contents were similar to Qt1 soils with values of 6.35% (Fe_d), 0.66% (Fe_o) and a Fe_o/Fe_d ratio of 0.10 (Fig. 5).

The Qt3 unit stands at a relative elevation of 14 m above the river and has a calculated age of 128±16 ka (Fig. 3). The alluvial parent material consists of moderately to well sorted gravelly sand, with approximately 10% quartzite pebble and cobble gravels, ranging from 5-20 mm in diameter. No gravel and cobble facies were found in this unit; rather an unweathered, well-sorted compacted sand layer was discovered at 2.4 m depth. Qt3 soils have A/Bt horizonation with manganese concretions in the B horizon, approximately 5 mm in size, below 25 cm in depth. Soil color ranges from dark brown (7.5YR 2.5/3) in the A horizon to red (2.5YR 4/6) in the B horizon. Soil consistence is sticky and plastic. Soils have clay textures, which grade upward to clay loams and loams, as well as strongly developed structures with angular blocky peds between 5 and 10 mm in diameter. Clay films are prominent in the B horizon forming coats and bridges; however measured clay content is less than that of Qt1 and Qt2 units ranging from 25.7% to 49.5% in the B horizon (Fig. 4). Qt3 soils recorded the highest Fe_o values of 0.75%. Fe_d values were 5.98%, which yielded the highest Fe_o/Fe_d ratio of 0.12 (Fig. 5).

Qt4 deposits stand approximately 10 m in elevation above the modern river channel. The calculated age for the unit based on this elevation is 50±6 ka (Fig. 3). The alluvial parent material is composed of well-sorted silty sand with less than 5% fine quartzite pebble gravel. Soil development is characterized by A/Bt horizonation with colors ranging between strong brown and yellowish red (7.5YR 5/6 – 5YR 5/8). A typical Qt4 soil has a sticky and plastic consistence, clay texture which grades upward to loam, and a moderately developed structure, with sub-angular peds primarily between 5 and 10 mm in diameter. The range of clay content in the B horizon, between 44.9% and 49.4% (Fig. 4), was typically higher than in Qt3 deposits, although the maximum measured clay content was similar. Peds were covered with prominent clay coatings, which formed coats and bridges. Extractable iron content was determined to be 5.90% (Fe_d) and 0.36% (Fe_o), which yielded the lowest Fe_o/Fe_d ratio of 0.06 (Fig. 5).

The lowest terrace unit (Qt5) sits 3 m above the modern channel and has a similar alluvial parent material composition to Qt3 and Qt4 deposits. The determined age for the unit based on this elevation is 4±0.5 ka (Fig. 3). Soil development is weakest in this unit typified by A/B/Bt horizonation, 10YR color hues (10YR 3/6 - 10YR 6/6), loam textures and relatively low clay contents (10.0% to 24.5% in the B horizon) (Table 1; Fig. 4). Qt5 soils also had the lowest extractable iron content. Fe_d was measured at 3.63%, Fe_o 0.31%, and Fe_o/Fe_d 0.08 (Fig. 5). Soil consistence was similar to other units (sticky and plastic) while structure was moderately developed with sub-angular peds between 10 and 20 mm. Manganese nodules between 2 and 8 mm in diameter were noted in all B horizons.

DISCUSSION

Soil Chronosequence

Soil morphological properties, including color hue and clay content, show positive trends with deposit age in a similar fashion to chronosequences found in other regional physiographic provinces despite differences in climate and parent materials. Maximum color hue increased from 10YR on Qt5 (~4 ka) to 2.5YR on Qt1-3 (~1,470-128 ka) (Table 1; Fig. 6). This trend of progressive reddening has been shown in other regional chronosequence studies (e.g.

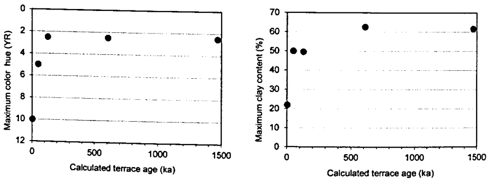

Fig. 6. Chronofunctions of color hue and clay content for representative terrace soils. Plots show maximum values obtained from the B horizon. Estimated ages for terrace units are: 4 ka (Qt5), 50 ka (Qt4), 128 ka (Qt3), 610 ka (Qt2), and 1,470 ka (Qt1).

Foss et al., 1981; Leigh, 1996) and is explained by the progressive accumulation of pedogenic iron oxides in the soil (see below). Color hue was found to plateau at 2.5YR on Qt3 deposits, which are calculated to be ~128 ka in age. Foss et al. (1981) found that hues of 2.5YR typically occurred in colluvial and alluvial Piedmont soils believed to be older than 100,000 years.

In addition to color hue, clay content has typically been found to increase as a function of soil age in a variety of settings throughout the southeastern and eastern United States (e.g. Howard et al., 1993; Leigh, 1996; Engel et al., 1996) regardless of changes in climate and parent material. In our field area, maximum clay content of the B horizon increased from ~25% in Qt5 soils to ~62% in Qt1 soils (Fig. 6). Observed clay contents are similar to those published in other regional chronosequences for soils of similar ages. For example, Engel et al. (1996) reported clay contents of ~53% in soils of Early Pleistocene age (~770-970 ka) from the Piedmont of Pennsylvania, which developed in diamictic alluvium. Maximum measured clay content appears to reach an asymptote at approximately 60% for terrace units Qt2 (~610 ka) and Qt1. This trend in clay content likely represents an internal threshold, such that the high clay content either prevents further illuviation (Howard et al., 1993) or promotes runoff and surface degradation. There is a break in slope, however, in the clay content chronofunction at ~50 ka (Fig. 6) with an unexpectedly higher proportion of clay for the Qt4 deposit (see also Fig. 4). A likely explanation for this high clay content in Qt4 soils relative to older Qt3 (~128 ka) soils is that the clay in Qt4 was derived from inheritance of an older, previously weathered clay-rich soil, presumably eroding off of drainage basin hillslopes.

Dithionate extractable iron (Fe_d) was found to increase progressively with age from 3.63% on Qt5 to 6.37% on Qt1 (Fig. 5). Regional studies have found similar increases in Fe_d with age despite differences in parent material, e.g. soils developed in alluvial and eolian deposits in the Valley and Ridge and Piedmont of Pennsylvania (Engel et al., 1996). The rate of Fe_d formation has been shown to initially increase rapidly but then decline with time due to a progressive reduction in the availability of fresh mineral surfaces to weather (McFadden and Hendricks, 1985; Birkeland, 1999). Our results echo this trend with Fe_d reaching a penultimate level of ~6.3% on Qt2 deposits. A close relationship has been shown to exist between Fe_d and clay content in soils (e.g. McFadden and Hendricks, 1985) because both are weathering products that progressively accumulate in a soil profile through time. Our results support this relationship, showing a strong positive correlation between these variables (R^2 value of 0.958) (Fig. 5).

Changes in iron content related to pedogenesis are commonly expressed through the iron activity ratio (Fe_o/Fe_d) rather than in absolute amounts. This ratio negates the difference in the initial Fe_o content of the parent material and emphasizes the formation of crystalline iron oxides due to weathering processes. Generally, this ratio decreases with time as amorphous iron oxides (Fe_o), which are the initial precipitate, convert to more stable, crystalline oxides (Fe_d) over time (e.g. McFadden and Hendricks, 1985; Birkeland, 1999). This declining trend has been documented in other chronosequence studies under a variety of climates (e.g. McFadden and Hendricks, 1985; Shaw et al., 2003; Eppes et al., 2008). In the Catawba River terrace soils, we observe a decline in Fe_o/Fe_d with deposit age between Qt4 and Qt5 time (~50-4 ka) and between Qt1, Qt2 and Qt3 time (~1,470-128 ka; Fig 5). Maximum Fe_o/Fe_d values, indicating relatively low degrees of iron crystallinity due to weathering processes, were found in Qt3 deposits. Data also indicate that the youngest deposits (Qt4 and Qt5) have the lowest ratios of amorphous to crystalline iron oxides. The observed drop in Fe_o/Fe_d ratios between Qt3 and Qt4 time can be attributed to change in sediment provenance of the Catawba River. It is likely that the low Fe_o/Fe_d ratios, which indicate high proportions crystalline iron oxides relative to amorphous iron oxides, in Qt4 and Qt5 deposits result from the presence of reworked, previously weathered material. As such, the Fe_o/Fe_d ratios in these two terraces are the product of inheritance rather than in situ soil development. It is possible that Qt3 and older soils were eroded in portions of the landscape and that stripped material was deposited during Qt4 time. These data therefore have implications for regional landscape evolution (see below).

In our study, other soil morphological characteristics such as structure, complexity of horizonation, solum thickness and Bt horizon thickness were not found to be useful indicators of relative age as they have been in other studies (e.g. Foss et al., 1981; Markewich and Pavich, 1991; Engel et al., 1996). Soil structure increased in grade from moderate to strong with terrace age (Table 1) however no quantifiable trend was identified. The weak trend in structure is likely due to the high clay content in all terrace soils, which is an important factor in the formation of blocky structure (e.g. Birkeland, 1999). The lack of any trend in horizon complexity is attributed to the relatively rapid formation of Bt horizons in the study area. Clay films are present in all terrace units although they are less prominent in the lowest terrace soils (Qt5). Our data suggests that Bt horizons form in Piedmont soils in as little as 4,000 years. However, this rapid rate of formation may be a function of the clay contributions from previously weathered, reworked material that we discuss above. Most soil pits could not be dug deep enough to expose unweathered parent material (C horizon) and therefore solum and Bt horizon thickness could not be accurately determined.

Landscape Evolution

The apparent increase in soil development around Qt4 time reflected in the chronofunctions of both clay content and Fe_o/Fe_d ratios could conceivably result from an increase in weathering rates due to wetter or hotter climatic conditions. There is no paleoclimatic data, however, which indicates that overall time period was particularly warmer or wetter than any other warm-wet period in the past. Instead, we conclude that sediment deposited at that time was largely derived from erosion of previously weathered materials in the Catawba River basin (Figs. 5 & 6). We suggest that between Qt3 & Qt4 time (128-50 ka), the primary sediment source for the Catawba River switched from relatively unweathered bedrock, likely derived from incision into channel bottoms, to relatively well developed soils stripped from hillslopes and/or eroded by lateral migration of the river channel into older terraces in valley bottoms. Such a switch represents a major change in the overall landscape evolution of the Catawba basin at that time. Studies have shown that the character of alluvial deposits reflects the erosional history of the source area as well as the dynamics of the river transporting sediment (e.g. Schumm, 1981). The lack of coarse quartzite gravels in Qt4 deposits suggests that the Catawba River also experienced a decrease in stream power during this time period, which resulted in the crossing of a threshold, such that the river could no longer transport coarse cobble gravel clasts (e.g. Bull, 1979; Schumm, 1979). This overall decrease in competency was likely ongoing from Qt3 time when the percentage of coarse gravels significantly decreased from previous terrace deposition episodes. Furthermore, it is possible that finer sediments, which previously would have been transported downstream to the coastal plain, began to be deposited at higher reaches in the Piedmont as discharges decreased.

The implication from these data is that the observed change from a cobble gravel regime to a sand regime and the change in sediment source between 128-50 ka was driven by a significant forcing event such as climate change or base level change. It is unlikely that Piedmont terraces were formed by eustatic changes in base level, however, since the upstream range of Quaternary eustatic influences is thought to be limited and only in the Coastal Plain (e.g. Leigh and Feeney, 1995). Lack of absolute dating of our studied terraces as well as of good paleoclimate data for this region of the Southeast preclude drawing strong conclusions regarding climate forcing, however, some general connections can be made.

Climatic fluctuations often alter the relationship between sediment supply and discharge in alluvial systems through changes in precipitation, vegetation cover and runoff patterns (e.g. Bull, 1991). Leigh (2008) summarizes the findings of limited studies that document the existence of riverine dunes and braid deposits between 70-30 ka in southeastern Coastal Plain rivers, whose basins extend into the Piedmont. These types of deposits are consistent with the high sediment supply that we infer for the Catawba River during the middle of this time interval. The period around 50 ka sits within the MIS 4 cold period, and it has been suggested that much of this period in the Southeast was characterized by cool climatic conditions (e.g. Leigh, 2008). Cold climatic regimes are typically thought to increase sediment supply by increasing physical weathering processes and removing vegetation cover from hillslopes, which promotes the mass movement of sediment to the valley floor. Eaton et al. (2003) present a model of landscape evolution for the central Blue Ridge which indicates enhanced debris flow activity and debris fan progradation during colder Late Pleistocene climates. It is therefore probable that Qt4 alluvium was deposited around 50 ka due to increases in sediment supply, delivered from basin hillslopes, and decreased discharge resulting from cold climates. Calculated ages for all other terrace units, however, correlate with warm, interglacial time periods. For example, the age of the Qt3 unit (~128 ka) corresponds with the peak interglacial high stand during MIS 5e. A possible reconciliation of the observed terrace formation during these different climatic regimes is that the Qt4 terrace is a fill terrace, whereas older terraces are strath terraces. If correct, the Qt5 unit may be a fill-cut terrace formed in the Qt4 alluvium. Unfortunately, the lack of outcrops in the study area precludes drawing firm conclusions regarding the nature of terraces.

CONCLUSIONS

Soils in the Piedmont appear to vary predictably over time in terms of the development of certain soil properties. In particular, color hue, pedogenic iron (Fe_d) and clay content appear to be the most useful indicators of relative soil development for these Piedmont soils. Results, highlighting the development of these properties over time, are analogous to other studies (e.g. Engel et al., 1996; Leigh, 1996; Shaw et al., 2003) outside of the Piedmont and developed in other parent materials implying a regional consistency as a function of age. These soil characteristics progressively increase with age up to approximately 128,000 years after which the rate of development plateaus indicating the attainment of a developmental threshold. Howard et al. (1993) found that after an early, rapid phase of soil formation, soils in the fall zone of Virginia had attained a more or less steady state by about 100,000 years. Our results imply that steady state conditions in Piedmont soils occur around the same time or perhaps slightly later. This pattern of development indicates that while these soil properties show positive trends with increasing age they are less useful for correlating and establishing relative ages of older soils (i.e. older than 128,000 years) as their development is approaching or has attained a form of equilibrium. The trend in clay content specifically, represents a threshold where the high clay content of the soil prevents further illuviation as found in other studies (e.g. Howard et al., 1993). Fe_o/Fe_d results indicate a break in soil development between Qt3 and Qt4 time (~128-50 ka), which is attributed to the erosion of relatively well developed soils from local hillslopes and/or valley bottoms. Evidence derived from soil development, fluvial landforms and sedimentological changes allow us to make tentative assertions concerning the geomorphic history of the Catawba River. This history can be summarized as one of overall incision, coupled with a lowering of peak discharges over time, punctuated by periods of aggradation that may be driven by increases in sediment supply during cold climatic conditions, at least in the latter history of the river.

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