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ARTICLE

Terminal Pleistocene through Holocene Evolution of Whiteoak Bottoms, a Southern Blue Ridge Mountains Peatland

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Abstract Our primary objective was to develop an understanding of the geomorphic evolution of Whiteoak Bottoms (WOB), a peatland along the Nantahala River in the Southern Blue Ridge Mountains (SBRM) of western North Carolina. Radiocarbon dates directly above basal fluvial sediments returned ages of 14,000 to 15,000 cal yr BP. These ages indicate WOB is the oldest dated peatland in the SBRM and that such wetlands have persisted throughout the Holocene. Below the relatively flat surface of the wetland, paleochannels, similar to those of the modern channel, were found; suggesting a persistence of similar channel morphology since the terminal Pleistocene. The wetland's stratigraphy reveals a consistent pattern with basal fluvial cobbles being overlain by sandy channel-fill grading up into peat. Two different distinct inorganic deposits separate the lower organic deposits from the sapric peat deposits at the surface. Interestingly, we estimate more than 56% of the organic matter preserved by the wetland accumulated during the first 6,000 years of development. Overall, WOB has accumulated approximately 424 Mg/ha of carbon during the past 15,000 years. Maintenance of this wetland initially depended on the Nantahala River; however, today it is ground water and beavers that allows for the persistence of this rare landscape.

Keywords Allostratigraphy · Carbon Sequestration · Geomorphology · Paleochannels · Wetland Evolution

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Introduction

Peat-forming wetlands are rare, endangered and poorly studied landforms in the Southern Blue Ridge Mountains. Peatlands are rare in the southern Appalachian Mountains due to the steep, well-drained nature of the landscape (Weakley and Schafale 1994). Many of the settings where these wetlands occurred have been historically drained for agriculture (Gaddy 1981). Weakley and Schafale (1994) estimated that up to 83% of prehistoric wetlands in North Carolina were drained and destroyed during the past 200 years due to anthropogenic land cover change. Conservation and restoration of these rare landforms is extremely important because of the multitude of rare and endangered plants and animals that often exist only in these wetlands (Murdock 1994). The majority of previous research on southern Appalachian wetlands has focused primarily on classifying and inventorying the rare biotic communities of these endangered landscapes with little emphasis on why, or where, these wetlands occur (Gaddy 1981; Schafale and Weakley 1990; Murdock 1994; Weakley and Schafale 1994). Schafale and Weakley's (1990) classification of the natural communities in North Carolina admits that the classification of mountain wetlands is still somewhat tentative due to a lack of knowledge of the factors responsible for the initiation and maintenance of these unique landforms.

The objective of this project was to develop an understanding of the hydrologic and geomorphic conditions that led to the formation and persistence of Whiteoak Bottoms (WOB), a peatland in the Southern Blue Ridge Mountains of western North Carolina. This was done by determining the depth, extent, and stratigraphic context of organic soil (Histosols) development. A secondary goal was to establish a timeframe and rate of organic soil accumulation to determine if WOB is a remnant of the last glacial period or if it is a relatively young landform created by anthropogenic disturbance. Our results will help to understand the ability of these wetlands to accumulate and store carbon, for potentially long periods of time, will facilitate future management and restoration of wetland in the southern Appalachians, and provide an insight into the poorly studied paleoenvironmental history of the region.

Previous research suggests that geomorphic disturbances (alluvial or colluvial), humans (deforestation and fire), or beavers may be important factors determining the occurrence and persistence of Southern Blue Ridge wetlands (Gaddy 1981; Shafer 1988; Weakley and Schafale 1994; Moorhead et al. 2000). Moorhead et al. (2000) studied the soil characteristics of four southern Appalachian wetlands in North Carolina, but do not discuss the factors responsible for initiation or maintenance of these wetlands. However, from the description of their landscape positions, it can be inferred that all but one of the wetlands are developing within depressions likely created by the adjacent rivers or streams. Shafer (1986, 1988) studied the paleoenvironmental history of Flat Laurel Gap, a Southern Appalachian Bog on Pisgah Ridge near the Blue Ridge Parkway. Flat Laurel Gap was interpreted to have started forming 12,000 to 10,000 years ago when periglacial conditions caused a landslide, creating habitat favorable for ericaceous shrubs to grow. The occurrence of disjunct northern species in the Flat Laurel Gap profile as well as the modern day plant assemblage suggests Flat Laurel Gap (and Southern Appalachian wetlands with similar disjunct species) has persisted since the terminal Pleistocene, serving as a refuge for these northern species. However, there is no direct evidence of a Southern Appalachian wetland persisting back into the terminal Pleistocene (Shafer 1986; Pittillo 1994; Weakley and Schafale 1994). The timing of wetland genesis at Flat Laurel Gap was inferred from thermoluminescence dating of a solifluction deposit (12,500 to 10,000 year BP), and not from wetland sediments (8605±360 cal yr BP) (Shafer 1988). Further analysis of Flat Laurel Gap has suggested that organics may have only accumulated during the past 1,000 years in swales created by the differential erodibility of the underlying saprolite and subsequent inundation by ground water (Lizee et al. 1998).

Conversely, it has also been suggested that some of these landscapes could be quite young (e.g. Panthertown Valley bogs and Tulula bog), formed as a result of logging and catastrophic fire followed by colonization by beavers (Weakley and Schafale 1994; Warren et al. 2004). Although, once again, the age of these wetlands is only conjecture and based solely on the fact that no disjunct northern species are found within them. Recently, an in-depth analysis of wetland sediments at Panthertown Valley determined that organic matter began to accumulate by 7,900 cal yr BP; thousands of years earlier than had been inferred from biotic communities and landscape position (Tanner et al. 2010). The uncertainty involved in the understanding of these unique landforms shows a need for a hydrogeomorphic analysis within a chronological framework to determine the factors necessary for peat-forming wetland initiation and persistence. Understanding the genesis and evolution of WOB will help provide such a framework to better understand, conserve, and restore similar peatlands within the Southern Blue Ridge Mountains.

Study Area

Whiteoak Bottoms (35°04′44″N, 83°31′50″W) is located at approximately 1030 m above sea level in the Nantahala River valley, Macon County, North Carolina (Fig. 1). The study area was chosen because it is located on public land (Nantahala National Forest) with easy access, is not in danger of being drained or modified, and is the largest wetland in the Nantahala River valley. Initial interest in the study area began in the Fall of 2008 when two radiocarbon ages (UGAMS #03503 and #03528 (Table 1)), resulting from preliminary field work of David Leigh and Ed Schwartzman (North Carolina Natural Heritage Program), revealed that the basal age of organic sediment at WOB was around 14,000 cal yr BP. These ages not only made WOB the oldest dated peatland in the Southern Blue Ridge Mountains, but also suggested that the wetland could harbor a uniquely complete record of Holocene environmental history.

Whiteoak Bottoms is located along the Nantahala River, between the hillslope and floodplain, on the backlevee and floodbasin portion of the first terrace (T1) (Fig. 2A). The wetland is classified as a Southern Appalachian bog with wet organic or mucky mineral soils that are very acidic, not subject to flooding, and fed by seepage water (Schafale and Weakley 1990). Although classified as a bog, a small watershed of approximately 19 ha drains directly into WOB through a number of hillslope seeps and manmade culverts (Fig. 2A). In order to prevent confusion as to whether WOB is a bog or fen and because pH was not measured, WOB will be generically referred to as a wetland from here on. The 19 ha watershed consists of forested hillslopes underlain by biotite gneiss with scattered pockets of amphibolite (Robinson et al. 1992). According to U. S. Forest Service personnel, the hydrology of WOB, historically, was affected by a failed attempt to drain and convert the wetland into agriculturally productive land. During this attempt, ditches were dug along the western side of the wetland. These ditches do not currently affect the hydrology of the wetland, having become mostly filled with sediments.

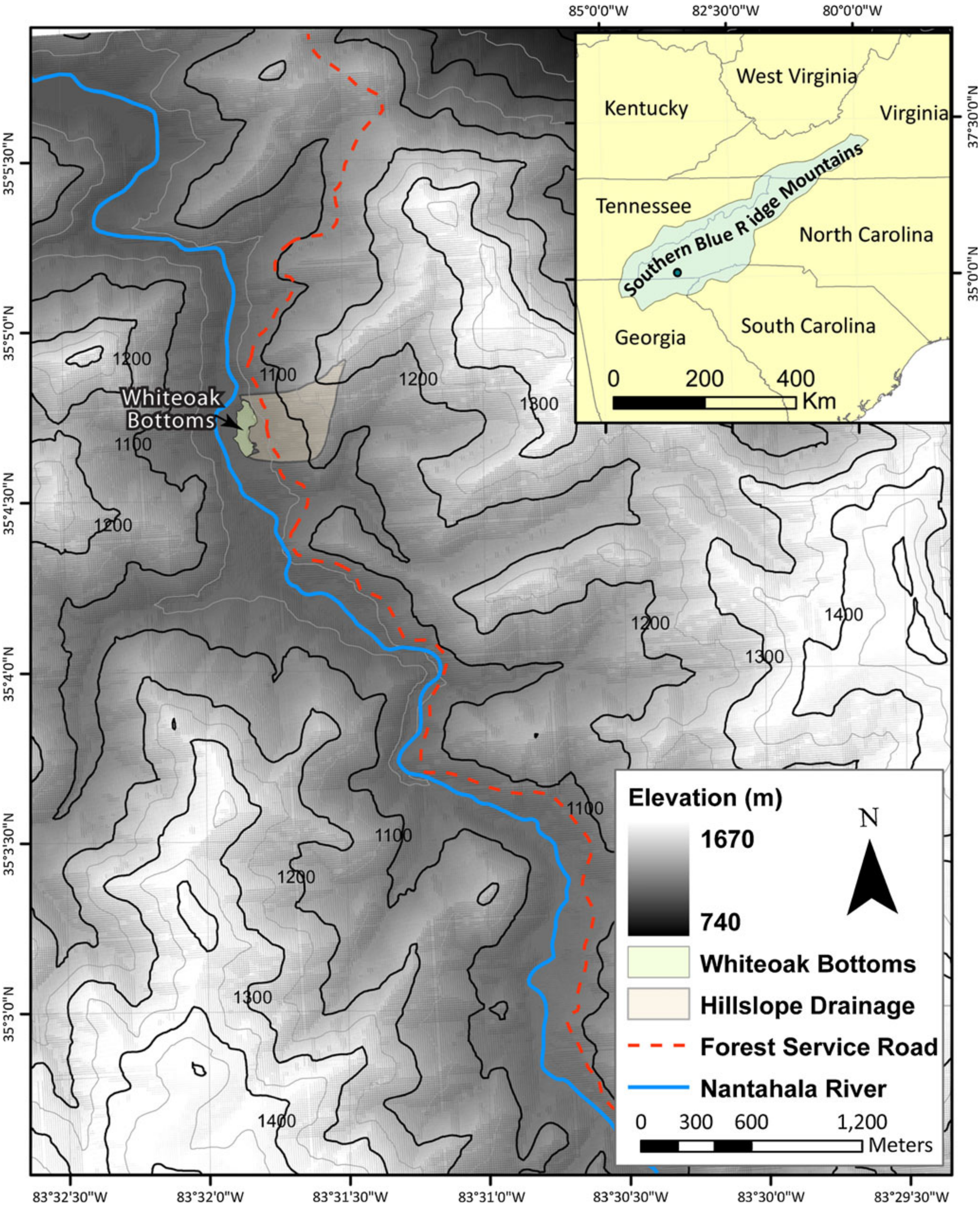

Fig. 1 The location of Whiteoak Bottoms (WOB) within the Nantahala River valley of western North Carolina. The Nantahala River flows from south to north to the west of the wetland. An area of approximately 19 ha drains into Whiteoak Bottoms. Inset map shows the location of WOB within the Southern Blue Ridge Mountains

Table 1 Radiocarbon ages

Lab number	Depth (cm)	Material	$\delta^{13}C$ (‰)	$\delta^{13}C$ corrected age (^{14}C yr BP)	Calibrated 2-σ range (cal yr BP)	Calibrated intercepts (cal yr BP)
Northern Core						
UGAMS 6586	50–55	Uncarb. Wood	−28.9	Modern (142.42%mC)	na	na
UGAMS 6406	65–70	Uncarb. Wood	−26.9	11450±40	13200–13426	13315±55
UGAMS 6407	105–110	Seeds	−27.3	12250±40	13920–14523	14150±169
UGAMS 3503	185–190	Peat	−27.9	12190±30	13892–14185	14042±88
UGAMS 3528	190–195	Seeds	−27.0	11940±70	13600–13995	13794±95
Southern Core						
UGAMS 6585	45–50	Wood Charcoal	−21.1	8160±35	9011–9253	9105±64
UGAMS 6408	99–103	Uncarb. Wood	−28.1	11850±40	13485–13838	13696±82
UGAMS 6409	155–160	Uncarb. Wood	−29.9	12400±40	14115–14935	14477±225

OxCal 4.1 used to determine calibrated 2-σ range and calibrated intercepts (cal yr BP)

Currently, the northern edge of WOB is completely underwater because of a beaver dam. Many of the deeper, natural pools have been connected by beaver excavations creating canals that snake through the wetland.

The vegetation of WOB is a mosaic of shrub thickets and herb dominated openings composed of northern bog and acid-tolerant coastal plain vegetation, underlain by *Sphagnum* mats (Gaddy 1981; Schafale and Weakley 1990; Schwartzman 2010). Three vegetational zones were identified: 1) a northern zone dominated by herbaceous openings; 2) a central zone dominated by shrubs; and 3) a southern zone which is a mixture of herbaceous openings and shrubs (Schwartzman 2010). The annual temperature at the nearest climate station, the low elevation (685 m) Coweeta Hydrologic Laboratory (12/1/1942 to 12/31/2007) to the east of Whiteoak Bottoms, is 12.72°C, with an average January temperature of 3°C and average July temperature of 22°C SERCC ((12/1/1942 to 12/31/2007)). The average annual precipitation estimated by the PRISM climate group for WOB is 2187 mm (PRISM Climate Group 1895–2009). The majority of rainfall is delivered from late fall to early spring with a maximum occurring in January and minimums occurring during July and October (PRISM Climate Group 1971–2000).

Methods

Field Methods

Field measurements were conducted in two stages, including: (1) a topographic and stratigraphic survey of the wetland to determine the depth and extent of Histosols; and (2) an in-depth allostratigraphic (Autin 1992; North American Commission on Stratigraphic Nomenclature 2005) analysis of both the wetland and the surrounding landscape to determine the context of histic soil development. Seven benchmarks were placed within WOB using a Trimble GeoXH sub-meter global positioning system to provide georeferenced (UTM, NAD83) locations and elevations for subsequent surveying. Approximately 900 points were surveyed using a Topcon 211-D electronic total station to create a topographic surface and subsurface of the wetland. At each survey location, a 1 cm diameter tile probe was driven down through the histic and/or fine clastic sediment until gravel or cobble was penetrated. A high-resolution (close-interval spacing of 1 m) survey of wetland basal topography was conducted along three transects to better understand the underlying topography and to locate sites suitable for vibracoring. Thirty-four cores were taken to understand the stratigraphy of the wetland and floodplain, including 17 using a Russian corer (organic soils) and 17 using a hand-driven bucket auger (clastic soils). Cores were described using standard National Resource Conservation Service (NRCS) terminology (Soil Survey Division Staff 1993). At two locations known to have the greatest accumulation of Histosols, a vibracore, utilizing three-inch diameter aluminum pipes, was used to obtain relatively undisturbed cores for laboratory analysis. Grab samples of sediment were retrieved from two hillslope seeps located on the edges of the northern and southern transects, and from two additional locations within the Nantahala River channel at locations south of the southern transect and on the middle transect to determine source areas and provenance of wetland sediments.

Laboratory Methods

The aluminum pipes holding the cores were cut longitudinally, photographed, and then described using standard NRCS terminology. Bulk density was measured on one half of the core using 3 cm diameter circular plugs at 5 cm

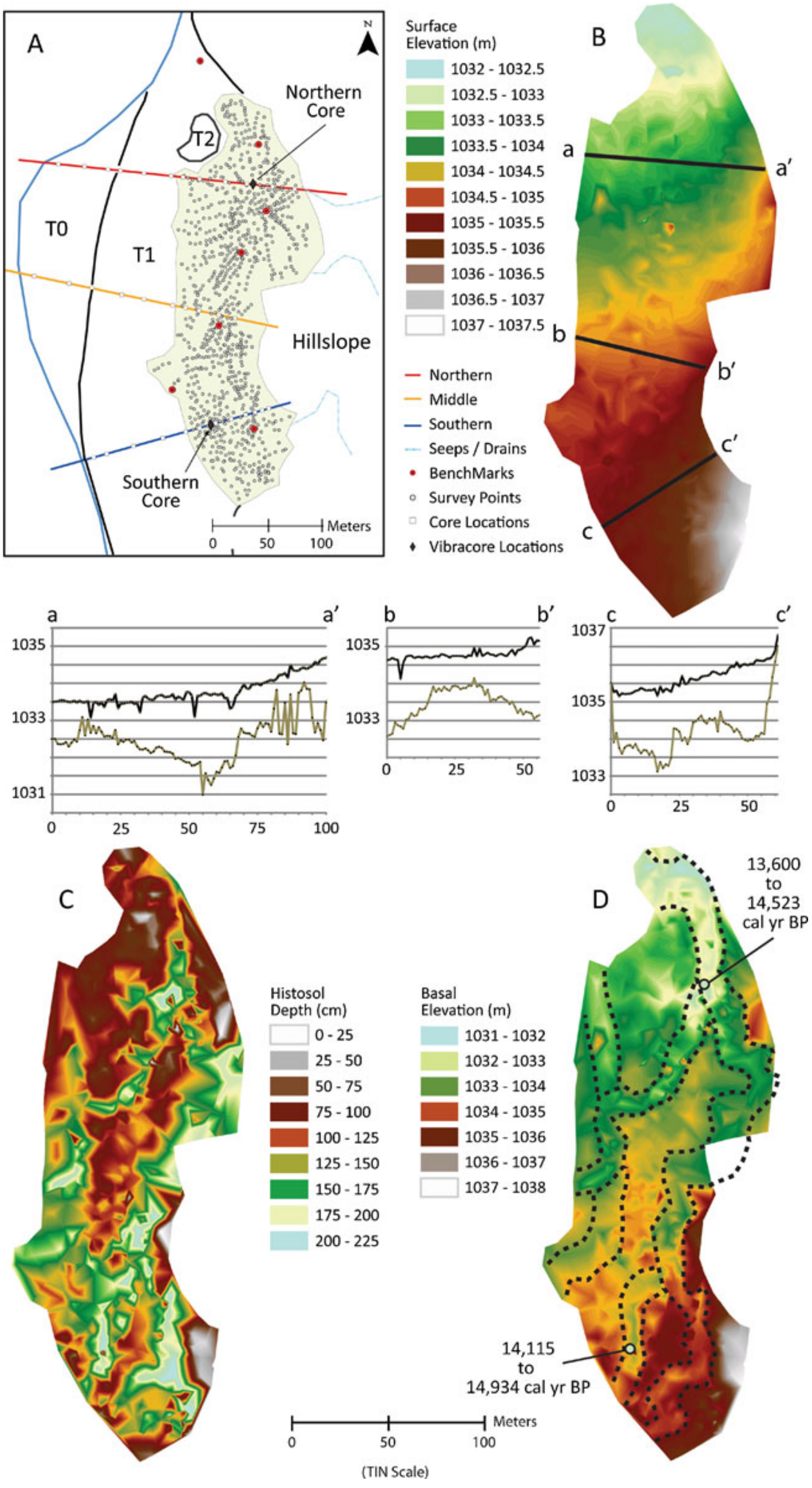

Fig. 2 **A** Geomorphic map of the Nantahala River valley at Whiteoak Bottoms showing topographic survey points and core hole locations. T0, T1, and T2 correspond to the floodplain, first terrace, and second terrace (respectively) of the Nantahala River. **B** Surface topography TIN; **C** Depth of Histosols TIN; and **D** Basal topography TIN with dotted lines showing the approximate left and right banks of interpreted paleochannels. Circles indicate basal radiocarbon date locations. The graphs are the results of the close interval (1 m) topographic survey

intervals or at smaller intervals to bracket major stratigraphic boundaries. Bulk density measurements were adjusted for the compression observed in the cores by applying a correction factor, 0.83 (north) and 0.78 (south), to the measurements. The other half of the core was cut into 25 cm segments for x-radiography. These segments were x-rayed using a Torrex 120 (small animal x-ray machine) at 5 mA and 50 W for 50 s. X-rays easily penetrate organic matter, exposing the film, while clastics block the x-rays and show up as shades of light grey to white on the developed film.

Organic content was determined by loss on ignition (LOI). The LOI samples were placed in a muffle furnace for 4 h at 550°C in order to insure complete combustion of organics (Heiri et al. 2001). Carbon content was determined by comparing 20 subsamples (10 from each core) that were measured for both LOI and total carbon content by micro-Dumas combustion at the University of Georgia's Odum School of Ecology's Analytical Chemistry Laboratory. The resulting correlation between of the LOI and total C percentages was used to estimate total carbon from LOI (C=0.51 LOI-0.0083, R^2=0.99 in northern core, and C=0.58 LOI−0.0141, R^2=0.97 in southern core). The inorganic residue from the LOI analyses was placed into a 1 N HCl bath for 24 h to dissolve ash residue. Samples were then thoroughly washed to remove dissolved solids before particle size analysis was performed. Particle size was determined using the pipette and sieve method described in Gee and Bauder (1986) to measure <2 μ clay and >63 μ sand on the <2 mm fraction (>2 mm fraction being sieved out prior to pipetting). A roundness analysis of the 4 to 16 mm portion of the >2 mm fraction was done by separating 30 to 100 randomly selected particles into categories based on sphericity and angularity (Powers 1953). Radiocarbon ages were determined on seeds, twigs, and charcoal by the University of Georgia Center for Applied Isotope Studies using an accelerator mass spectrometer following an acid-alkali-acid pretreatment of the samples and graphite target preparation.

The data obtained from the topographic surveys were compiled in Microsoft Excel^{TM}. Basal topography was determined by subtracting the tile probe depth from the surface topography. The data were then imported to ArcMap 9.3^{TM} and triangulated irregular networks (TIN) were created to interpolate between data points and allow for easier analysis of surface topography, basal topography, and accumulation of Histosols. From these interpolated surfaces, the volume of Histosols and the amount of carbon that had accumulated were calculated based on the stratigraphic and laboratory analyses.

Results

Topography and Hydrology

The surface topography (Fig. 2B) exhibits a general decrease in elevation from south to north, in accord with the slope of the alluvial Nantahala River valley. A slight downward slope from the eastern hillslope towards the river in the west also is apparent. Latitudinally, the hummock and pool topography create fluctuations in elevation of up to 60 cm. The largest pools are present on the north and middle transects; while the size of the hummocks (10 to 20 cm higher than surrounding lawns) is relatively similar across all three transects. Histosols are thickest along the eastern border as well as areas that meander through the middle of the wetland that are not in accord with the surface topography. The greatest accumulation of Histosols was determined to be at 55 m on the northern transect (a–a') and at 17 m on the southern transect (c–c', Fig. 2C). It was on these thickest sections that the vibracores were taken (Fig. 2A). Histosols were measured over an area of 1.99 ha with an average depth of 1.2 m. From these measurements, we estimate at least 23,300 m^3 of sediment have accumulated in the wetland above the basal gravels within the surveyed bounds of the wetland.

The TIN of basal topography shows the same general pattern as the Histosols thickness TIN with a number of low-lying depressions meandering through the middle and eastern side of the wetland (Fig. 2D). These low-lying meandering patterns show up on all of the transects as relatively deep (1.5 to 2.0 m) depressions (Fig. 2). These depressions are approximately 10 to 15 m wide, are longitudinally continuous, and have a slope ranging from 0.005 to 0.006, and thus appear to be paleochannels. For comparison, the modern Nantahala River is approximately 15 to 20 m wide, has a slope of approximately 0.005 to 0.007, and its banks are 1.5 to 2.0 m high.

The wetland's water table is at or within 10 to 15 cm of the surface during the summer and less than 10 cm during the winter. A seasonally fluctuating water table was inferred from the presence of redoximorphic features (mottles and gleying) in the clastic sediments of T1 and T0 (Fig. 3). Although the deepest depressions beneath WOB are at approximately the same elevation as the bed of the current river channel, the absence of a redoximorphic surface sloping towards the wetland suggests little if any influence from the river on the hydrology of the wetland. The slope of the water table, as indicated by the slope of the redoximorphic features, clearly indicates a hillslope source of ground water to the wetland (Fig. 3).

Stratigraphy

Whiteoak Bottoms is situated on the first prominent terrace (T1) of the Nantahala River (Fig. 3). The facies within T1 can be divided into the following units: T1a-Basal T1 cobbles and gravels; T1b-Lower T1 sandy facies; T1c-Upper T1 silty facies; T1d-Lower T1 sand and gravel facies; T1e-Lower T1 peat facies; T1f-Middle T1 mucky silt facies; T1g-Middle T1 angular gravel facies; and T1h-Upper T1 mucky peat facies (Fig. 3). T1 abuts the hillslope in the east and is separated from the river by the floodplain

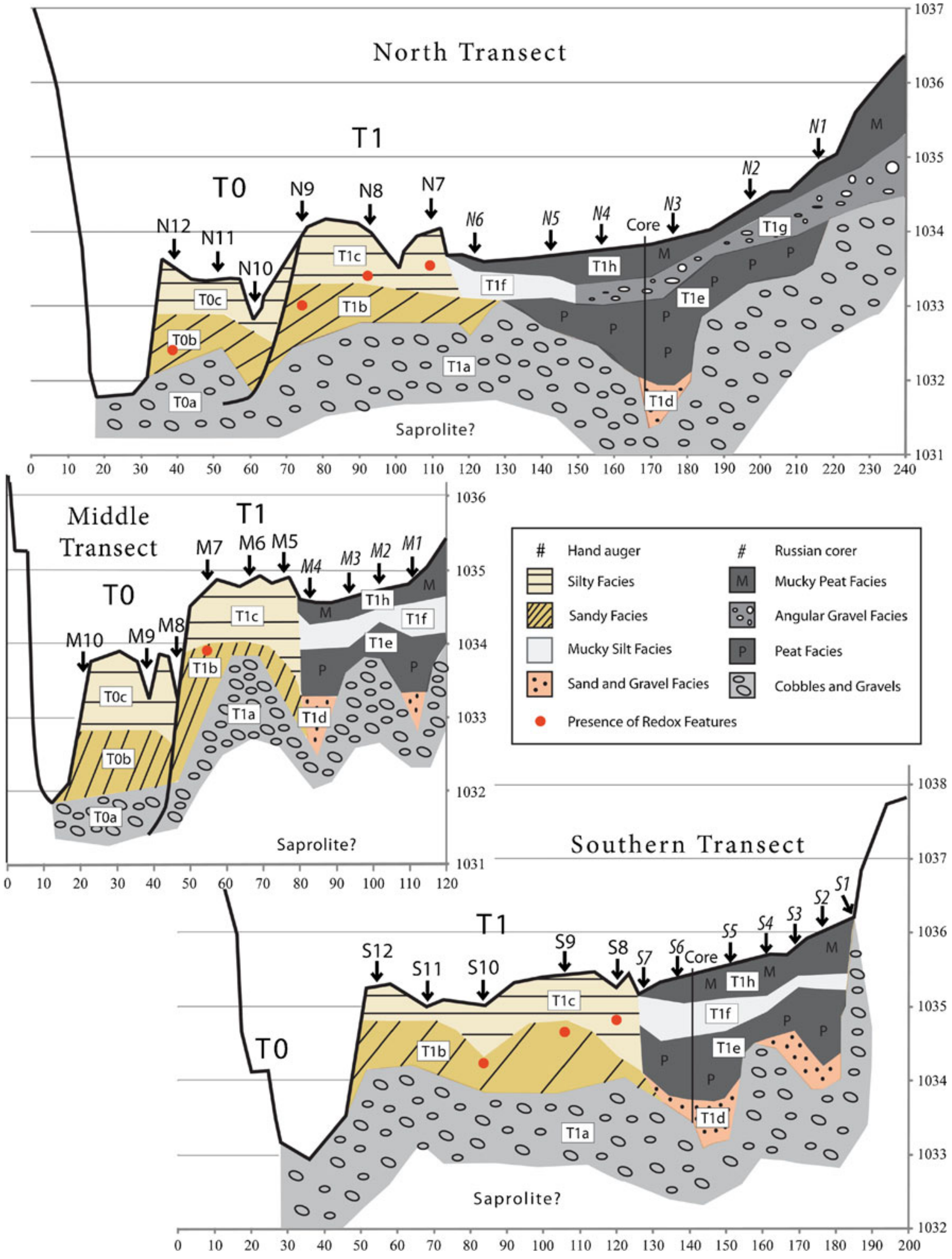

Fig. 3 Allostratigraphy of Whiteoak Bottoms and associated floodplain. The facies within T1 include: T1a-Basal T1 gravels and cobbles; T1b-Lower T1 sandy facies; T1c-Upper T1 silty facies; T1d-Lower T1 sand and gravel facies; T1e-Lower T1 peat facies; T1f-Middle T1 mucky silt facies; T1g-Middle T1 angular gravel facies; and T1h-Upper T1 mucky peat facies. The facies within T0 include: T0a- Basal T0 gravels and cobbles; T0b-Lower T0 sandy facies; and T0c-Upper T0 silty facies. Red dots indicate redoximorphic features

(T0) on the western sides of the north and middle transects; T1 extends to the river on the southern transect. The active floodplain of the Nantahala River (T0) also is underlain by coarse facies of gravels and cobbles, designated T0a. T0a is overlain by two units: T0b-Lower T0 sandy facies; and T0c-Upper T0 silty facies. The facies were separated based on readily discernable erosional or depositional boundaries.

T1a-Basal T1 Cobbles and Gravels

The basal unit of T1 is composed of well-rounded gravels and cobbles and is designated T1a. T1a underlies all of T1 and ends abruptly at the hillslope. The thickness and lower boundary of T1a are unknown, although T1a likely overlies the weathered saprolite that typically blankets the landscape. There are abrupt unconformable upper boundaries with T1b and T1e.

T1b-Lower T1 Sandy Facies

Unconformably overlying T1a, to the west of the wetland, is a massive sandy unit (T1b). The color of this unit ranges from dark yellowish brown (10YR 3/4) to olive yellow (2.5Y 6/6). The color of T1b also shows evidence of being totally submerged beneath the water table all year (gleyed) or seasonally (mottling) (Fig. 3). The distinguishing characteristic of T1b is the texture, which is mostly sandy loam with loamy sand occurring in some cores directly overlying T1a. T1b was designated 2C or 2Cg in the majority of the cores. T1b varies in thickness from 0.25 to 1.0 m.

T1c-Upper T1 Silty Facies

A massive silty unit (T1c) overlies T1b. The color of this unit ranges from black (10YR 2/1) at the surface to dark yellowish brown (10YR 3/6) at its base. A, B, and C horizons make up this unit. Much better developed B (Bw) horizons are present in the cores nearest the bog and decrease in thickness and pedogenic development towards the river. The texture of this unit is mostly silt loam, although loamy silt and loam textures are found within this unit. T1c is thickest on the northern transect (avg. 1 m) and thinnest on the southern transect (0.25 m).

T1d-Lower T1 Sand and Gravel Facies

Overlying T1a in the deepest parts of the wetland is a massive sand and gravel unit (T1d). Gravel from this unit has a moderate degree of sphericity, are sub-angular to angular, and range in size from 2 to 15 mm. The gravels from T1d have many of the characteristics of both the hillslope and the river gravels. Unlike the hillslope gravels, there are a lot of sub-rounded to rounded gravels in the T1d grains; and unlike the river gravels, a significant proportion of the grains are angular (40% in the 8 to 16 mm fraction and 38% in the 4 to 6 mm fraction). From the bottom of the unit the color tends to get darker (5Y 3/2 to 10YR 3/1) with height. Texture of this unit is sandy ranging from gravelly sand to sandy loam with a fining-upward trend. T1d is laterally discontinuous, only occurring in the deep depressions that meander through the wetland. The unit varies from 0.25 m to 1 m thick. An unconformable boundary separates T1d from T1a (below) and T1e (above).

T1e-Lower T1 Peat Facies

Unconformably overlying T1d is an organic unit (T1e) that is composed of alternating beds of woody and mossy peat that range in thickness from 15 to 50 cm. The soil horizons in this unit were designated Oe (mossy peat) or Oi (woody peat). The histic soil horizons within this unit are very dark brown (10YR 2/2) to black (10YR 2/1). This unit is very organic with LOI ranging from 11% (at the bottom) up to 78%. There is thin inorganic bedding within the organic matrix that is readily visible in the x-ray images (Fig. 4). This inorganic bedding thins away from the river as revealed in the Russian cores along the 1 m interval transects. An abrupt unconformity separates T1e from overlying units T1f and T1g.

Radiocarbon dating of seeds, uncarbonized wood, and bulk peat (Table 1) indicate organic sedimentation began sometime between 15,000 to 14,000 cal yr BP. The basal ages from the northern core come from a pilot core retrieved in 2008 by David Leigh with a Russian corer. At the bottom of the inorganically bedded portion of T1e from the southern core (99 to 103 cm) an age of 13,800 to 13,600 cal yr BP was returned. An age from the top of T1e in the northern core (65 to 70 cm) is 13,400 to 13,200 cal yr BP at the abrupt unconformable boundary with T1g. To summarize, T1e appears to have been deposited between 15,000 and 13,200 cal yr BP, indicating relatively rapid accumulation of peat during the time immediately prior to the Younger Dryas global cooling phase (circa 12,900–11,500 cal yr BP).

T1f-Middle T1 Mucky Silt Facies

Unconformably overlying T1e on the southern and middle transects and on the western side of the northern transect is a mucky silt unit (T1f). The color of this unit ranges from very dark gray (10YR 3/1) to dark gray (10YR 4/1). The texture of this unit is loam fining upwards into silt loam. The upper limit of T1f is found at an average depth of 35 cm, and it slopes up toward the hillside to the east. This unit is an average of 20 cm thick with its maximum thicknesses occurring on the eastern and western edges of the wetland, thinning away from the river as well as sloping up towards the hillslope in the east. T1f is bounded by an abrupt unconformable boundary on its western side by T1c.

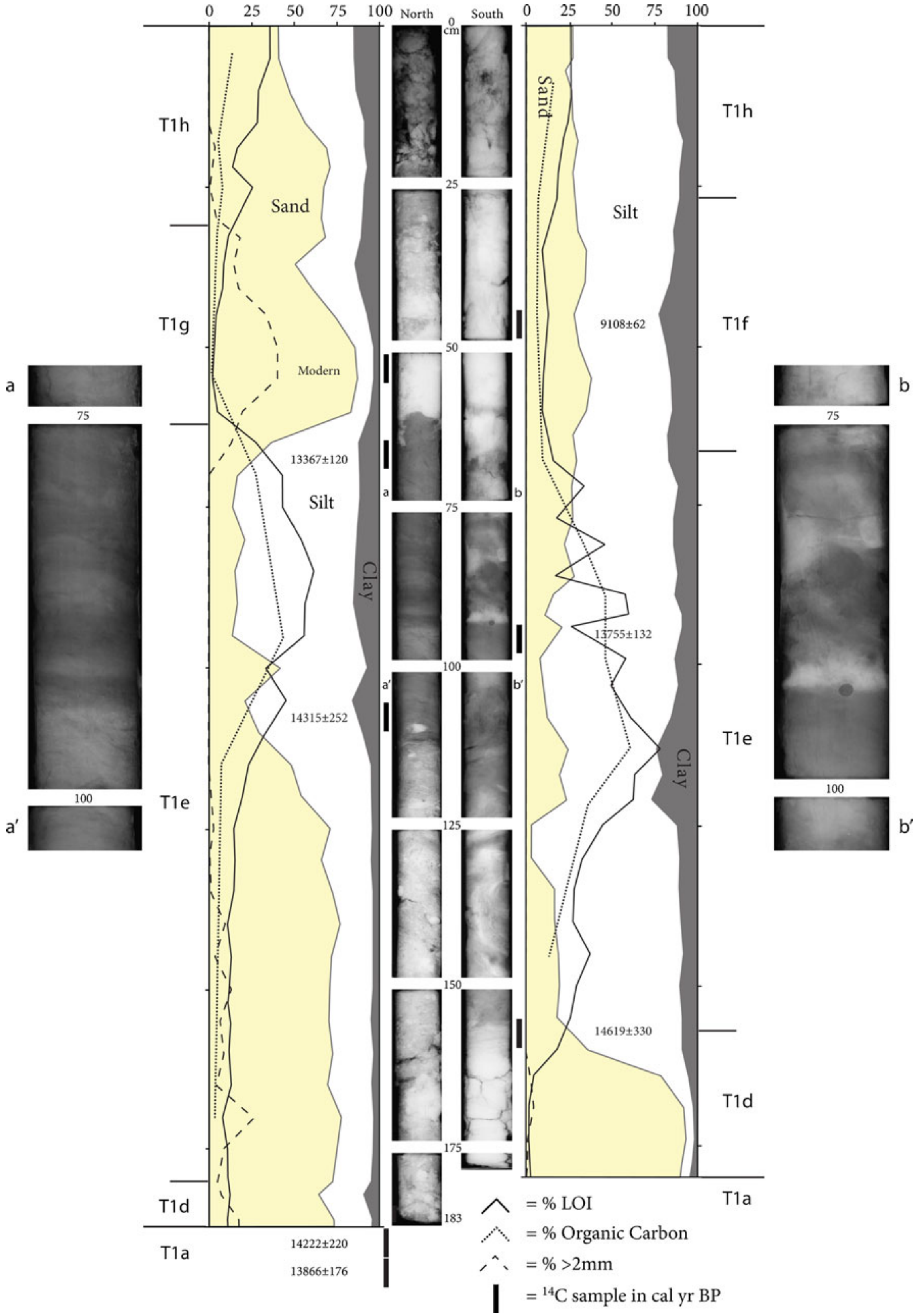

Fig. 4 The results of the PSA, LOI, x-radiography, organic carbon analysis, and radiocarbon dating. Stratigraphic units are also listed to provide easier interpretation. A zoomed in view of the inorganically bedded portion of T1e is shown to the left and right of the cores. Depths (cm) given between the two cores are those of the compressed core

On the middle and southern transects, T1f is abruptly and unconformably bounded by the hillslope to the east. On the northern transect, the eastern side of T1f is abruptly and unconformably bounded by T1g. Radiocarbon dating of wood charcoal from the middle of this facie from the southern core (45 to 50 cm) returned an age of 9,144 to 9,011 cal yr BP (Table 1).

T1g-Middle T1 Angular Gravel Facies

Overlying T1e to the east of T1f is an angular gravel unit (T1g). This unit was found on the eastern side of the northern transect and grades from gravelly loamy sand in the east to gravelly muck in the west. Gravels from this unit range in size from 2 to 12 mm and tend to have very low sphericity and be angular to very angular. The T1g gravels have many of the same characteristics as the hillslope gravels. The diversity of shapes observed in the river gravels are not found in the T1g gravels. Color ranges from very dark grayish brown (10YR 3/2) to dark gray (10YR 4/1). T1g is found at a depth of 35 to 60 cm and averages approximately 30 to 40 cm thick. The thickness of the unit increases with proximity to the hillslope. An abrupt unconformity separates T1g from T1e (below). Radiocarbon dating of uncarbonized wood from the middle of T1g (50–55 cm) returned a modern, post bomb-spike age (Table 1).

T1h-Upper T1 Mucky Peat Facies

The upper-most unit within the wetland is a highly humified mucky peat unit (T1h) that overlies T1f and T1g. These soils were designated Oa horizons. The color of this unit is black (10YR 2/1) to very dark grayish brown (10YR 3/2). Texture fines-upward with sandy loam or loam at its lower boundary and loam or silt loam at the surface. The top of this unit is composed of partially decomposed organic matter with the degree of decomposition tending to increase with depth. The average thickness of this unit is approximately 40 cm.

T0a-Basal T0 Gravels and Cobbles

The basal unit of T0 is composed of gravels and cobbles and is designated T0a. T0a underlies all of T0 and is bounded to the east by an unconformable boundary with T1a. The highest elevation of T0a is about 1 m below the highest occurrence of T1a. The deepest portions of T1a are at about the same elevation as T0a. The vertical extent and lower boundary of T0a are unknown although it likely overlies weathered saprolite. T0a abruptly and unconformably underlies T0b.

T0b-Lower T0 Sandy Facies

Overlying T0a is a massive sandy unit (T0b). The soils in T0b grade from loamy sand to sandy loam up and away from the river. The color of this unit tends to be dark yellowish brown (10YR 3/4). T0b also shows evidence of being affected by ground water exhibiting gleying or mottling (Fig. 3). This unit tends to occur at a depth of 35 to 40 cm and averages 70 cm thick. T0b is found between T1 and the river and is characterized by C or 2 C soil horizons. Abrupt, unconformable boundaries separate T0b from T0a (below) and T1b (east).

T0c-Upper Silty Facies

Overlying T0b is a massive silt unit (T0c). Color tends to lighten with depth, being very dark brown (10YR 2/2) at the surface, lightening to dark brown (10YR 3/3) at depth. The soils in T0c have over-thickened cumulic A-horizons that thin away from the river. No B-horizons were found on the middle transect but there were thin, weakly expressed, B-horizons on the northern transect. The soils formed in T0c are consistently less well developed than those in the similar facies of unit T1c, which is consistent with a younger age of T0 relative to T1. Textures in T0c are silt loam and tend to have many fine roots in the upper 10 to 15 cm. T0c is approximately 35 cm thick and is laterally continuous from its contact with T1 in the east to the river in the west.

Vibracore Analysis

Each core was described and analyzed using the measured depths from the slightly compressed cores, unless stated otherwise. A total of 76 bulk density samples (38 from each core) and 81 LOI and PSA samples (40 from the north core and 41 from the south core) were analyzed. The northern core refused on cobbles and gravels at a true depth of 226 cm (187 cm compressed) and the southern core refused at a true depth of 229 cm (178 cm compressed). Both cores exhibit the same general lithology of highly clastic sediments at the bottom of the core overlain by highly organic horizons, which are overlain by clastic sediments that grade up into organic sediments at the surface (Fig. 4). The major differences between the two vibracores are: (1) the bottom third of the northern core (110 to 183 cm) is much sandier than the southern core; (2) the southern core becomes abruptly organic (160 cm) while the northern core becomes organic much more gradually; and (3) overlying T1e in the northern core is a gravelly, extremely inorganic unit (T1g), whereas in the southern core, a mucky silt unit (T1f) overlies T1e.

Northern Vibracore

The bottom of the northern core is sandy loam to gravelly loamy sand (165 to 182 cm) (T1d). The color of this section is a very dark gray (10YR 3/1). LOI results for this portion of the core are around 10%. The bottom gravelly unit grades up into an increasingly organic unit (110 to 165 cm) (lower portion of T1e). This section, although still sandy loam and loamy sand, is black (10YR 2/1) and has partially identifiable woody plant materials that are not present in T1d. LOI begins low (12%) but rises up to 23% at 110 cm. Above the sandy lower portion of T1e, is a black (10YR 2/1) mossy peat section (75 to 110 cm) that grades up into very dark brown (10YR 2/2) woody peat (60 to 75 cm). Within this largely homogenous zone, faint and thin (15 to 20 mm thick) bedding is visible in the x-rays (Fig. 4). The complex spatial arrangement (thinning away from river as well as sloping up towards the hillslope to the west) and the physical and mineralogical composition of these sands indicate they are alluvial and/or colluvial in origin. These bands correspond to relatively large fluctuations in percent sand from 20% at 105 cm up to 42% at 100 cm, then down to 13% at 95 cm. The effects of this influx of sand shows up in the LOI record, with 46 percent at 105 cm down to 32% at 100 cm and then back up to 55% at 95 cm.

Abruptly overlying the peat facies is an angular gravel and sand unit (30 to 60 cm) (T1g). This section is very dark grayish brown (10YR 3/2) at its base and black (10YR 2/1) at the top. The lowest LOI results are from this section of the core with a minimum of 2% at 55 cm. The >2 mm fraction peaks in this unit, reaching a maximum of 40% at 45 to 50 cm. Overlying T1g is a black (10YR 2/1) highly humified mucky peat unit (T1h) (0 to 30 cm). This highly humified unit becomes progressively more organic reaching 36% at the top of the core. There is a deviation from the general increasingly organic trend at 22 cm where in a very dark grayish brown (10YR 3/2) portion, LOI drops down to 13% before starting to increase again. There is a corresponding increase in percent sand from 67% at 25 cm up to 70%t at 22 cm. Textures in this section are sandy (sandy loam) but grade up into loam.

Southern Vibracore

From its base (178 cm), the southern core starts out at about 1 to 2% organic but then increases up to 18% at 160 cm. This lower inorganic unit (T1d) is dark olive gray (5Y 3/2) sand at the bottom that fines upwards, becoming very dark brown (10YR 2/2) loamy sand. Abruptly overlying the lower inorganic unit is a black (10YR 2/1) mossy and woody peat unit (64 to 160 cm) (T1e). The LOI results for this unit range from 18% at the bottom, up to 78% at 113 cm, and then decreases to 16% at 64 cm. There are a series of increases in percent sand with corresponding decreases in percent LOI at 72 to 77 cm, 81 to 86 cm, and 92 to 94 cm. These sandy layers are visible in the x-rays showing up as 2 to 4.5 cm thick, lighter (clastic) bands within the dark (organic) matrix (Fig. 4). Overlying the peaty lower unit is a mucky silt unit (T1f) (27 to 64 cm). This unit is gray (10YR 5/1) to dark gray (10YR 4/1) at its base and very dark gray (10YR 3/1) at the top. Textures of this unit are loamy grading up into silt loam. LOI ranged from 10 up to 13%. The top of the core is a black (10YR 2/1) highly humified mucky peat unit (T1h) (0 to 27 cm). This unit becomes increasingly more organic (18 to 26%) and progressively less sandy with height.

Carbon Accumulation

Carbon accumulation within the wetland sediments of WOB went through three distinct stages: (1) initial infilling and deposition of extremely organic peat layers (T1d and T1e); (2) deposition of a relatively inorganic clastic rich drape upon T1e (T1f); and (3) re-initiation of organic accumulation on top of the middle inorganic layers (T1f and T1g) represented by T1h. The total volume of sediment found within the wetland (23,300 m^3) was divided into these three groups so that the total amount of carbon accumulated could be determined.

The first stage of wetland development, occurring between 15,000 and 9,000 cal yr BP, deposited approximately 12,000 m^3 of sediment. This deposit, which includes T1d and T1e, averages 0.624 m in thickness and 0.04 g/cm^3 of carbon; which equals approximately 480 Mg (241 Mg/ha) or 0.04 Mg/ha/yr of carbon accumulation for the first 6,000 years of wetland development. The second stage, occurring after 9,000 cal yr BP and before the deposition of unit T1h, deposited approximately 5,500 m^3 of sediment. The amount of carbon per cubic centimeter (0.03 g/cm^3) was determined by multiplying the bulk density and percent carbon values from only the southern core, because T1f apparently was eroded from the northern core by the deposition of T1g. The total amount of carbon sequestered in this middle layer is approximately 172 Mg (86 Mg/ha). The third and most recent stage of carbon accumulation deposited approximately 5,800 m^3 of sediment. This layer had an average of 0.033 g/cm^3 of carbon and was assumed to be 0.3 m thick. The top increasingly organic layer holds approximately 192 Mg of carbon (96 Mg/ha). Combining the second and third periods together (9,000 years), approximately 363 Mg of carbon have been sequestered in WOB (182 Mg/ha). During the past 15,000 cal yr BP, WOB has sequestered approximately 424 Mg/ha of carbon, with >56% being accumulated during the first 6,000 years of development.

Discussion

Topography and Paleochannels

The undulating land surface and the high-resolution transect surveys show the highly complex hummock-pool topography of a normal bog/fen system (Fig. 2). This topography is likely the result of the differential decay of the various wetland species found in the wetland as well as the beaver activity that helps add complexity to the surface of the wetland (Naiman et al. 1988; Johnson and Damman 1991). The beaver influence is especially easy to see on the northern transect (14, 53, 65 m) and the mid-south transect (6 m) where they have accentuated pools connecting trenches in the wetland (Fig. 2).

The depressions that meander through the middle of the wetland and along the eastern border are interpreted as paleochannels because: (1) they are apparent on the basal topographic surface of the cobbles and gravel, (2) they are longitudinally continuous; (3) their dimensions are very similar to the modern channel (width and depth); and (4) they have a similar slope to that of the modern river channel. Although multiple channels are visible, the different ages returned from the base of the vibracores, 15,000 to 14,100 cal yr BP for the southern core and 14,500 to 13,600 cal yr BP for the northern core, indicate that single-thread meandering river systems were active during the terminal Pleistocene. This observation is at odds with the assertion that streams in the eastern United States were stable, multi-channel, anabranching systems prior to historic settlement and disturbance (Walter and Merritts 2008). Instead, the late Pleistocene paleochannels of the Nantahala River were rather similar to the modern channel; suggesting meandering rivers are quite natural and existed in the region as early as the terminal Pleistocene.

Interestingly, neither the modern vegetation nor the surface topography of the wetland reflects the geomorphic history of this landscape. A number of studies have suggested that within a fluvial system, species occurrence is highly correlated to the fluvial landform (Osterkamp and Hupp 1984; Hupp and Osterkamp 1996; Bendix and Hupp 2000). The three identified vegetation zones within the wetland (northern, middle, and southern) are, instead, a reflection of the uneven distribution of hillslope seep and road runoff contributions to the wetland, coupled with the presence of beaver terraces that create wet herbaceous areas in the north and south and relatively dry shrubby areas in the middle. A study of the modern-day vegetation composition would not provide any indication that the wetland initiated in paleochannels of the Nantahala River, although the wetland's landscape position scalloped into the hillslope would suggest a fluvial history.

Landscape Evolution

Eight samples of seeds, carbonized and uncarbonized wood, and bulk peat from Whiteoak Bottoms resulted in radiocarbon ages ranging from 15,000 cal yr BP to approximately 1970 CE (Table 1). The ages indicate that WOB is the oldest dated wetland in the Southern Blue Ridge Mountains. The wetland sediments contain the first record of the terminal Pleistocene to Holocene transition in the Southern Blue Ridge Mountains; while the clastic sediments from T1 and T0 provide insight into the depositional behavior of the Nantahala River over the past 15,000 years.

The stratigraphy and radiocarbon ages indicate that during the terminal Pleistocene, between 15,000 and 13,600 cal yr BP, the paleo-Nantahala River flowed through the wetland depositing T1a. At 15,000 to 14,100 cal yr BP, the Nantahala River avulsed away from the southern paleochannels and began to occupy the paleochannels on the western side of the wetland (Fig. 2D). The Nantahala River occupied the northern core's paleochannel until 14,500 to 13,600 cal yr BP. The river then likely migrated to the west (Fig. 2D) still providing sandy sediments and sub-rounded gravels to the site of the northern core (T1d). The large percentage of angular to sub-angular gravels in T1d also suggests a hillslope influence on the early sedimentation within the wetland. While the paleochannels were active, the eastern portion of T1b (lateral accretion sediments) and T1c (vertical accretion sediments) probably were being deposited along the western margin of the wetland, slowly impounding the low-lying paleochannels that ultimately became the peatland. At some point between 15,000 to 14,000 cal yr BP, avulsion and channel migration to the western side of the valley stranded the WOB area from the direct effects of the Nantahala River, allowing the wetland to develop and Histosols to begin to accumulate.

Between 15,000 and 9,000 cal yr BP, the peat of T1e accumulated; likely beginning in the paleochannels then spreading across the area that is now WOB. Peat accumulation may have been initiated by beaver damming of the lower end of the paleochannels or by damming of the paleochannels caused by rapid sedimentation near the active channel zone. The peat, in both vibracores, begins woody but abruptly transitions to mossy peat around 14,500 to 14,000 cal yr BP, suggesting WOB was becoming increasingly wet (Vitt and Wieder 2009). This increased wetness is interpreted as an increase in the height of the water table caused either by an increase in effective precipitation (which would increase groundwater discharge), by the downstream damming of the paleochannels, or by a combination of these factors.

Based on the limited paleoenvironmental data for the region, studies of the Southern Blue Ridge Mountains do not confidently indicate an increase in precipitation during late Pleistocene and early Holocene (Delcourt and Delcourt 1984; Kneller and Peteet 1999). However, Leigh (2006, 2008) found that bankfull floods on rivers of the Coastal Plain were much larger during the terminal Pleistocene to middle Holocene than during the late Holocene. Leigh

(2008) also found that effective precipitation (runoff) was maximized during the terminal Pleistocene and first half of the Holocene. During this time period, there is also evidence of an increase in hillslope failures in the Blue Ridge Mountains, providing an excess amount of sediment, which if connected to the fluvial system would cause stream aggradation (Shafer 1988; Eaton et al. 2003; Delcourt and Delcourt 2004; Leigh and Webb 2006). Delcourt and Delcourt (2004) studied the stratigraphy of the Little Tennessee River, into which the Nantahala River ultimately flows, and they observed rapid aggradation of the valley bottom between 17,000 to 7,000 years BP. This agrees with the interpretation that T1a was likely aggrading at this time and possibly damming the lower ends of the WOB paleochannels, assuming synchronous behavior of tributaries with the main stem. Indeed, early and middle Holocene aggradation of tributaries to the Little Tennessee River was recognized at Ravens Fork (Leigh and Webb 2006) and synchronous aggradation of tributaries with main stems of the Little Tennessee River has been observed for historical timeframes (Leigh and Webb 2006; Leigh 2010).

As T1 continued to aggrade to the west of the wetland, around 13,800 to 13,600 cal yr BP, thin sandy beds began to be laid down within the otherwise extremely organic T1e (Fig. 4). These thin beds are interpreted as overbank flood drapes because they thin away from the river, being thicker in the more proximal southern core than the distal northern core. Inorganic sedimentation continues to increase between 13,400 and 9,000 cal yr BP as T1e is replaced with T1f (Figs. 3 and 4). The replacement of T1e with T1f is interpreted as either (1) evidence of a pronounced increase in the magnitude of flood events during this time period or (2) increased contributions from hillslope sources of clastic sediment. In either case, T1f is interpreted as clastic sedimentation that outpaced the accumulation of organic matter. Other studies in the southeastern USA also have found evidence of higher magnitude flood events, as well as increased hillslope sedimentation, during the early Holocene (Goman and Leigh 2004; Leigh and Webb 2006; Leigh 2008; Liang 2008; LaMoreaux et al. 2009). Although these studies are all from somewhat larger watersheds, USGS gaging records show that large and small basins in the Blue Ridge Mountain respond in a similar fashion during flood events.

Leigh and Webb (2006) studied the alluvial and colluvial stratigraphy of Raven Fork, a stream north of the Nantahala River, within the Southern Blue Ridge Mountains of North Carolina. They found more rapid hillslope sedimentation during the early Holocene, which they attribute to a greater magnitude and perhaps greater frequency of extreme rain events. From their study of a peat core along the Little River on the upper Coastal Plain of North Carolina, Goman and Leigh (2004) also determined that extreme events were more prevalent during the early to middle Holocene (9,000 to 6,100 cal yr BP); with overbank flood events being five times more frequent during the early Holocene compared to the late Holocene. At some point after 9,000 cal yr BP, the Nantahala River incised to the level of the modern river channel and began depositing T0a. This incision event could be related to the reduction of extreme precipitation events during the middle to late Holocene as suggested by Goman and Leigh (2004) and Leigh and Webb (2006), but an age from the beginning of T0b deposition and a terminal age for T1f accumulation is needed to know for sure.

The modern age returned for T1g is somewhat unusual and could be the result of a tree fall that had penetrated the wetland and embedded a branch into T1g. The other interpretation is that T1g is modern and the angular gravel unit is a consequence of historic anthropogenic disturbance of the eastern hillslope. Moorhead et al. (2000) found a gravel layer at a depth of 30 to 50 cm at Deep Gap Fen that could be analogous to T1g. They did not go any deeper because they assumed this to be the extent of wetland sedimentation. Deep Gap Fen is located in close proximity to the Blue Ridge Parkway and State Highway 421 creating the possibility that this wetland could also have been affected by anthropogenic disturbance.

Wetland Hydrology

The only sources of water to WOB are from hillslope seeps, groundwater seepage, and precipitation, proven by the lack of a redoximorphic surface sloping towards the wetland and the water table sloping from the hillslope through the wetland and down toward the river (Fig. 3). The majority of the organic matter sequestered in WOB was deposited during a time when the Nantahala River probably had a much greater influence on the hydrology of the wetland. The stratigraphy of T1 to the west of the wetland, suggests the highly organic peat deposits represented by T1e were deposited during a time that allowed the locally high water table, caused by river bed aggradation and/or increases in groundwater discharge as a result of more effective precipitation, to engulf any dead plant material in the wetland, inhibiting decomposition.

Currently, we do not know whether organic matter had accumulated during the middle Holocene and then subsequently was oxidized or eroded. T1h could be the result of historic drainage attempts, which would have created a greatly accelerated rate of decomposition in any organic matter that had accumulated subsequent to the initial phase of peat accumulation. T1h could also be a natural response to the significant drop in water table that occurred as the Nantahala River incised to its current elevation. It is important to note that whatever the cause of the reduction in carbon accumulation, WOB is still active and groundwater levels have been sufficient throughout the entire

Holocene to preserve what had been accumulated between 15,000 and 9,000 cal yr BP.

Carbon Sequestration

Carbon was sequestered at a rate of 0.04 Mg/ha per year during the early phase of wetland development (15,000 to 9,000 year BP). The early rate of carbon accumulation is more than an order of magnitude less than observed carbon sequestration rates in forested plots (Clark et al. 2004; Liu et al. 2006; Weishampel et al. 2009). Liu et al. (2006) estimated the carbon sink strength of Appalachian forests to be around 1.8 Mg/ha of carbon per year, approximately 45 times that of WOB's sink strength. Although forests can sequester carbon much faster than wetlands, the total amount of carbon storage per hectare is maximized in peatlands because of the loss of soil organic carbon by microbial respiration in forested soils (Weishampel et al. 2009; Miller et al. 2004). Weishampel et al. (2009) compared the amount of carbon sequestered in forested upland compared to peatlands in northern Minnesota. In their study area, the forested uplands sequestered 150 to 200 Mg of carbon per ha compared to 1,200 Mg/ha in peatlands. Forest soils in the southern Blue Ridge have been found to contain between 96 and 120 Mg/ha of carbon (Miller et al. 2004; Liu et al. 2006). The amount of carbon sequestered in WOB (424 Mg/ha) is considerably less than the amount stored in the peatlands studied by Weishampel et al. (2009) but still shows that wetlands can sequester more carbon per hectare than forests. These studies show the importance of wetland conservation because significant disruption of the factors that maintain them (climatic, geologic, or biologic) can turn these large sinks into significant sources.

Conclusion

Whiteoak Bottoms is the oldest dated wetland in the Southern Blue Ridge Mountains. Initiation of peat deposition began circa 14,000 to 15,000 cal yr BP in the paleochannels of the Nantahala River. The presence of paleochannels beneath the surface of the relatively flat wetland highlights the fact that the subsurface of these landforms can be highly variable and the depth and extent of Histosols cannot be assumed uniform. The peat deposit transitions from woody to mossy peat indicating a steadily rising water table possibly linked to river aggradation and or more effective precipitation that would have caused increased groundwater discharge. WOB was cut off from the influence of the Nantahala River until 13,000 cal yr BP when sedimentation within the wetland became increasingly inorganic. We suggest that the increase in inorganic bedding in the stratigraphy of the wetland is evidence of an increased frequency of overbank flood events and/or hillslope contributions of sediment during the terminal Pleistocene and earliest Holocene. The past 9,000 years have seen a drastic reduction in the amount of organic matter being sequestered in the wetland. We believe that it was the incision of the Nantahala River to its current elevation that caused this drastic change in wetland dynamics, although better chronologic control is needed to be sure. Presently, hillslope seeps, groundwater seepage, and beaver activity are the most important mechanisms maintaining the persistence of the wetland at Whiteoak Bottoms. This study illustrates the importance that landscape position and hydrology have had on the evolution of this wetland. Currently and for the past 15,000 years, the hydrology has been such that approximately 424 Mg/ha of carbon have been sequestered in the wetland.

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