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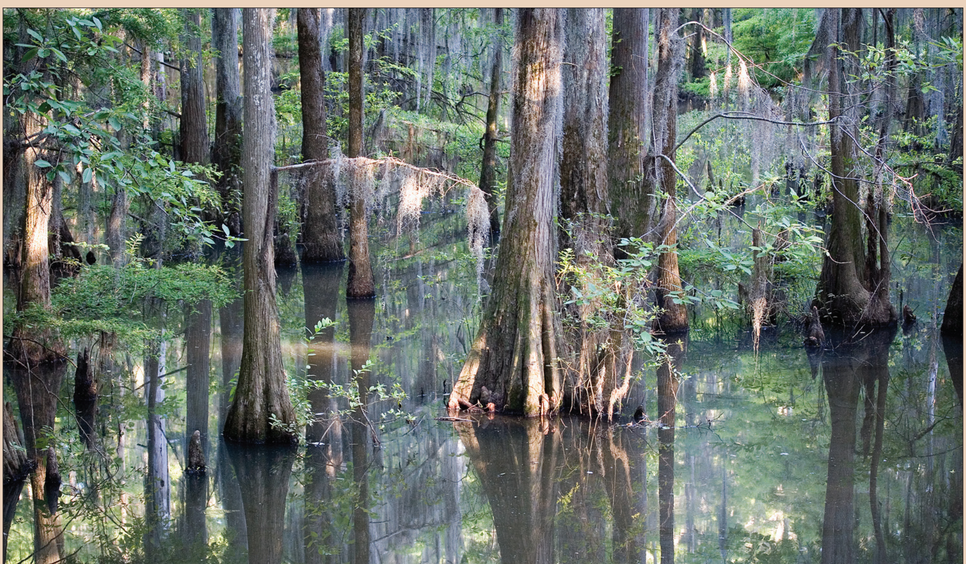

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Cover photograph: Bald Cypress (*Taxodium distichum*) from the Cahaba River floodplain. Photo by Jay Y. S. Hodgson.

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The Development of an Oxbow Lake in Alabama, USA, Inferred from Diatom Microfossils and Sedimentation

Jay Y. S. Hodgson[1*] and Amelia K. Ward[2]

Abstract - We reconstructed the development of an oxbow lake in the southeastern United States coastal plain using a combination of diatom microfossils and bulk sediments retrieved from a sediment core. Sediment ages were established from ^{14}C measurements of bulk fractions. A previous analysis of the lake using vegetational succession estimated the main channel cutoff to be >500 YBP. Our results refine the chronology, with early meandering bend abandonment beginning approximately 2000 YBP. During that time, sedimentation rates and sedimentary organic content increased, indicative of increased flooding during early main channel migration away from the oxbow. Concomitantly, diatoms transitioned from predominantly lotic species assemblages before this time to lentic and planktonic organisms after it. After 1600 YBP, sedimentation rates decreased consistent with final channel cutoff and decreased flood connectivity. Organic matter and diatom indicators of nutrient enrichment increased considerably in the most recent 800 years as human activity became more established in the surrounding watershed. In contrast to reports elsewhere, we found no conclusive evidence in the sediment core to corroborate the presence of a mid-Holocene hydrogeological maximum, but future studies in the area may help resolve this question.

Introduction

The southeastern United States (USA) coastal plain possesses a unique combination of ancient, Mesozoic river systems and younger, Holocene oxbow lakes, floodplain marshes, and ponds (Gaiser et al. 2001, Ward et al. 2005). Parts of this region are known for having high species richness resulting from the lack of glaciation and other factors (Ward et al. 2005). Although the current river systems are considered hotspots for studying biodiversity and evolutionary biology (Lydeard and Mayden 1995), comparatively less is known about the Holocene paleohydrogeology of this coastal plain compared to other regions in North America (Gaiser et al. 2001, 2004). For example, in a recent meta-analysis of 93 paleohydrologic records encompassing North and Central America, including reconstructions from caves, lakes, ponds, and bogs, only 1 was from the southeastern USA, and it was from a cave in Florida (Shuman et al. 2018). Much of this paucity is from the lack of glacially formed lakes, which are robust repositories of paleo-indicators of Holocene environmental changes (Cohen 2003). Moreover, frequent cycles of flooding, scouring, and desiccation have severely degraded many sedimentary archives from coastal plains, making reconstructing environmental change difficult (Gaiser et al. 2001).

Much of the current paleohydrogeology information about the southeastern USA is of regional resolution and has come from geologic, pollen, and archeological records. Geologic formations and bathymetry indicate that sea levels have fluctuated since the Paleozoic era, with repeated cycles of transgression and recession within the coastal plain; however, sea level changes during the Holocene have been smaller than other epochs (Mancini et al. 1993, Pashin 1993, Ward et al. 2005). Pollen records showed that coastal plain vegetation communities throughout the Holocene were transient. Specifically, long-standing forests of Oak (*Quercus* spp.) and Hickory (*Carya* spp.) were replaced by Pine (*Pinus* spp.) and swamp vegetation during the mid-Holocene as a result of increased

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moisture and warmer temperatures from glacial retreat and climate amelioration (Barron 1992; Frey 1953; Gaiser et al. 2001; Whitehead 1953, 1972, 1981). Brooks et al. (1996) used archeological evidence of human settlements coupled with paleobathymetry data to infer historical water levels and pond distribution in the coastal plain of South Carolina, USA. They concluded that the middle Holocene was wetter than present day with deeper and more permanent water depressions.

Paleohydrogeological research in the southeastern USA is progressing, as suitable study sites have been identified and the science of proxy interpretation has matured. Gaiser et al. (2001, 2004) revisited a pond in the South Carolina coastal plain previously studied by Brooks et al. (1996). Using diatom (Bacilliarophyceae) microfossils, they were able to reconstruct a high-resolution estimation of historical water level changes in the region. Specifically, they demonstrated a substantive transition in the hydrogeology between 6000–3000 YBP. They concluded that standing waters were at the highest levels between 4600–3800 YBP. These trends were inferred from characteristic changes in diatom taxa indicative of rising and falling water tables. From those data sets, Gaiser et al. (2001, 2004) hypothesized there was a mid-Holocene hydrogeological threshold in the coastal plain that was crossed due to the combination of glacial retreat, increased precipitation, rising water tables, and eustatic sea level rise. During this hydrogeological maximum, they proposed the predominantly fluvial coastal plain was inundated with water, subsequently filling in many low-lying depressions with standing water. This ultimately created many of the marshes, ponds, and other lentic environments that are present today. After 3800 YBP, precipitation and water tables decreased, and some ponds desiccated, which marked the end of the hydrogeologic maximum.

Despite this high-resolution data, paleoecological and paleohydrogeological records from the coastal plain remain patchy. However, the coastal plain contains a multitude of oxbow lakes (Joo 1990, Joo and Ward 1990, Ward et al. 2005), which could be valuable sedimentary archives to track paleohydrogeological patterns in the region. Oxbow lakes have been used elsewhere to infer flooding regimes from analyzing sedimentation rates (Gasiorowski and Hercman 2005), isotopic composition of sediments (Lobo et al. 2001, Wolfe et al. 2006), and changes in diatom microfossil assemblages (Wolfe et al. 2005). Sokal et al. (2008) created a high-resolution meta-analysis of diatom records from 41 shallow lakes, including oxbows, in a river system in Canada to show net water flow in the floodplain system. Geographically closer to this study, Wren et al. (2008) used sedimentation rates to establish the cutoff date of an oxbow lake in the Mississippi alluvial floodplain. Therefore, investigations of oxbow lake diatom assemblages and sedimentary properties in the southeastern coastal plain should help resolve the paleohydrogeology of the region.

Our overall objectives were to investigate an oxbow lake in the southeastern coastal plain, establish its chronology and development, and improve our understanding of the paleohydrogeology of the region. In this study, we revisited Touson Lake, an oxbow in the Black Warrior River basin (Alabama, USA) previously analyzed by Joo and Ward (1990). They characterized its morphometry and used vegetational succession in the floodplain to estimate the cutoff date of the oxbow from the main river channel. That technique was first proposed by Harper (1912) and had been tested by others, notably Shankman (1991), who analyzed coastal plain oxbows. However, one major limitation of this method is that it can only establish a minimum age of channel abandonment. We wanted to improve the resolution of the estimated cutoff date of Touson Lake by using diatom microfossils and sedimentary content collected in a sediment core. Here, we estimated early meandering bend abandonment to have begun approximately 1500 years earlier, and permanent channel cutoff to have stabilized around 1100 years prior, than the calculation of Joo (1990), and Joo and Ward (1990), respectively.

Additionally, we sought evidence for the mid-Holocene hydrogeological maximum proposed by Gaiser et al. (2001, 2004), but did not elucidate corroborating data.

Geological Setting

Touson Lake (N 33° 00' 15.7", W 87° 39' 51.1") is an oxbow lake (surface area = 7.5 ha, maximum depth = 6.3 m) located in the floodplain of the Black Warrior River 2.5 km west of Moundville, Alabama, and 300 km north of the Gulf of Mexico (Fig. 1). The Black Warrior River is a sixth-order river with a floodplain between 6–7 km wide in the area around Touson Lake (Joo and Ward 1990). Using vegetational succession, Joo and Ward (1990) estimated a minimum date of channel cutoff at >500 YBP. The lake is privately owned and experiences minimal direct anthropogenic perturbations (e.g., fishing, watercrafts, and point-source pollution). However, agriculture is prevalent within the lake basin, which likely contributes some nutrient addition. Physiochemical characteristics and patterns of primary production have been previously studied in Touson Lake (Joo 1990; Joo and Ward 1990, 1991). A series of locks and dams were installed along the Black Warrior River beginning around the year 1910. According to Joo (1990) and Joo and Ward (1990), the lake maintains overland, hydrogeologic connectivity during occasional periods of flooding with the Black Warrior River, although the channel has been cut off, and the river is now partially regulated by dams. The mean annual air temperature of Moundville is 17.1º C, with a mean January temperature of 7.2º C and a mean July temperature of 27.6º C. The mean annual precipitation is 136.9 cm.

Materials and Methods

Sediment core

In November 2004, we retrieved a continuous 701 mm sediment core from the deepest portion of the lake by using a 6.5 cm wide core barrel attached to a modified Glew gravity corer (Glew 1989). Upon retrieval, the core was stored at a constant temperature of 4º C

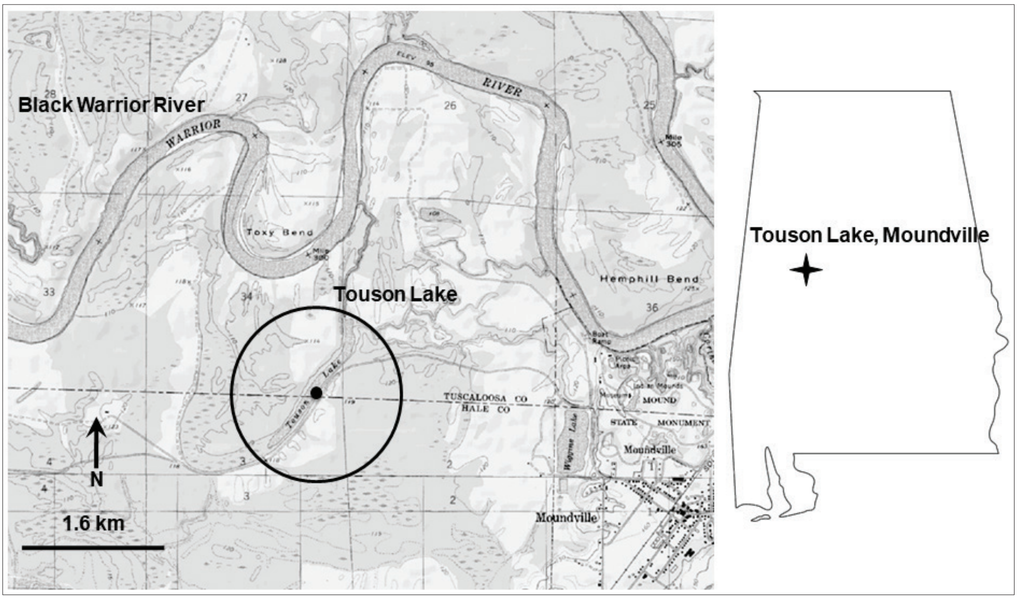

Figure 1. Location map of the study site, Touson Lake, Alabama. The black dot inside the lake shows where the sediment core was retrieved. The topographic map is a USGS quadrangle in the public domain and is free to reproduce with acknowledgement.

until removed for analyses. Within the laboratory, the core was extruded and sectioned into 141 discrete 5 mm subsamples. Approximately 1 g wet mass was taken from each 5 mm subsample for diatom analyses. The remaining portion of each subsample was dried at 50º C until a constant mass was obtained. Once obtained, the subsamples were finely ground with a mortar and pestle. Approximately 1 g dry mass from each 5 mm subsample was combusted at 550º C for 24 hours to determine organic content from loss on ignition (LOI). After combustion, samples were weighed, rehydrated with deionized water, dried, and weighed again to account for any loss of water of hydration.

Additionally, 7 subsamples in the sedimentary sequence were carbon dated using reservoir-corrected ^{14}C (present day = year 1950; calibration data from INTCAL 98 [Stuvier et al. 1998]). We sampled from the core depths of 0 mm (top of core), 56 mm, 201 mm, 301 mm, 411 mm, 591 mm, and 701 mm. These depths were chosen because they were potential transitional horizons as inferred from color and/or compositional changes. Terrestrial macrofossils were rare in the core and were absent at these important zones of transition in the core, so we were obligated to use bulk organic sediments for aging. Walker et al. (2007) and Wren et al. (2008) demonstrated that bulk organics were suitable for dating sediment cores when macrofossils are unavailable. A main risk of using bulk organics is overestimating older ages due to reservoir and hard water effects of ancient carbon, especially limestone (Wren et al. 2008). To test for this, we dated the top of the core and found no confounding bias or issues (it accurately represented the calibrated 0 YBP, year 1950). We interpolated sediment ages between each actual ^{14}C date by fitting a best-fit cubic spline regression of the ^{14}C dates. All dates hereafter are reported as YBP (year 1950 = 0 YBP).

We estimated rates of sedimentation from dividing the depths between each of our 7 carbon dated samples by the age ranges in between actual carbon dates; we did not use any interpolated dates generated by the cubic spline regression for this method.

Diatom enumeration

We digested the 1 g wet mass of lake sediments from each 5 mm subsample designated for diatom analyses following the methods of Battarbee (1986) and Hodgson et al. (2013). Wet samples were first washed with 10% HCl and rinsed with deionized water to remove any carbonates. Then, they were digested with 30% H_2O_2 and heat to remove organic matter and given a final rinse with deionized water. At this point, only silicates remained suspended in water. To avoid damaging any frustules, all suspended samples were allowed to settle via gravity for 24 hours after each washing and rinsing sequence in lieu of centrifuging. No sieving was necessary because the sediments were devoid of coarse-grained (>0.5 mm) organic and inorganic debris. Finally, washed samples were allowed to evaporate on glass cover slips before permanently mounted on glass slides with Naphrax (refractive index = 1.65).

Diatom species were identified by use of 1000X phase-contrast microscopy (Zeiss Axioskop) following the taxonomy of Patrick and Reimer (1966, 1975), Round et al. (1990), Wehr and Sheath (2003), and Williams and Round (1987). All species taxonomy and names were updated and verified with the Integrated Taxonomic Information System database (ITIS) and the North American Diatom Ecological database. When possible, at least 300 frustules per 5 mm sample were counted to determine the relative abundance of each species. When it was not possible to enumerate 300 frustules per sample due to diatom paucity, 4 slide transects encompassing 50 fields of view were counted. Also, broken frustules were ignored unless the broken valves had enough material (usually >50% of the valve remaining) to allow proper species identification with the dichotomous key. In total, 40,608 frustules encompassing 62 species from 31 genera were identified and enumerated.

Statistical analyses

We analyzed the diatom relative abundance data following the methods of Hodgson et al. (2013). Before analyzing, any diatom species that composed <0.5% of the relative abundance of any depth profile was removed from the database. This reduced the original 62 species to 61 species used for further analyses. The relative abundance matrix was normalized using the arcsine-square root transformation (Gotelli and Ellison 2004). To reduce the dimensionality of the diatom assemblage and to identify important individual species, we performed principal components analysis (PCA) on the variance-covariance matrix of the normalized diatom relative abundance data over the 141 sub-samples. PCA is appropriate for the multicollinearity often found in time series and relative abundance data (Gotelli and Ellison 2004). Each principal component (PC) point along a PCA axis is a factored representation of the entire diatom assemblage at that specific point. The major species loadings on each PCA axis indicate the ecological characteristics of the assemblage at each step. We then applied correlation analyses between sedimentation rate, organic content, and diatom PC1 at $\alpha = 0.05$.

Results

Sediment core characteristics

The chronosequence of the Touson Lake core was established from seven ^{14}C analyses (Fig. 2). The top sample of the core was ^{14}C dated as post-present day (year 1950; 0 YBP ± 50 years), and the bottom of the core (sample from 701 mm) dated to 4600 YBP ± 35 years. The cubic spline regression used to interpolate YBP dates from ^{14}C data was robust and significant ($r^2 = 0.972$, $F = 34.6$, $p < 0.008$). The sedimentation rate of Touson Lake was variable (Fig. 3), ranging from a low of 0.08 mm per year between depths 416–591 mm (2000–4140 YBP) to a high of 0.55 mm per year between depths 306–411 mm (1850–2000 YBP). Sedimentation was nearly as high at 0.50 mm per year between depths 206–301 mm (1600–1800 YBP) before falling considerably to 0.13 mm per year between depths 61–201 mm (450–1600 YBP) and remaining nearly constant at 0.15 mm per year between depths 0–56 mm (0–370 YBP). Additionally, sedimentation was moderately high at the bottom of the core at 0.23 mm per year between depths 596–701 mm (4140–4600 YBP).

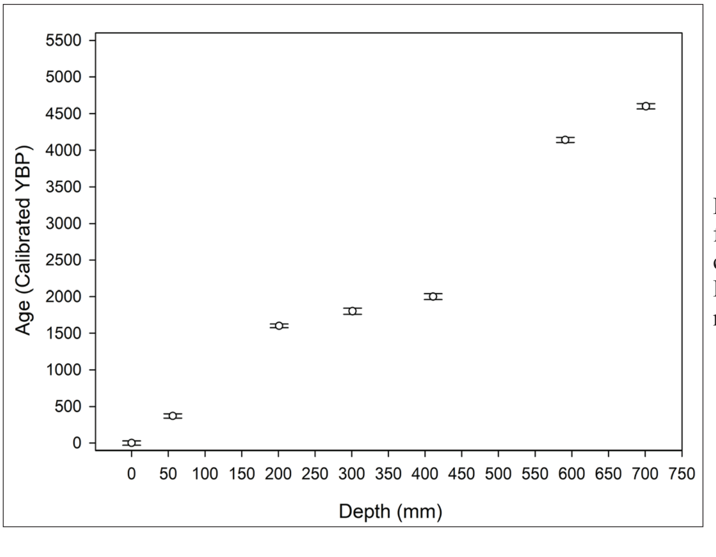

Figure 2. Age-depth profile for the Touson Lake sediment core based on ^{14}C analysis. Error bars are fraction of modern ^{14}C error.

The Touson Lake core was dominated by a nearly homogenous mixture of gyttja at all depths from the surface to the bottom. The bulk organic content of the core was generally low and highly variable throughout the core (Fig. 4), ranging from a low of 7.6% (LOI) near the bottom of the core to a high of 15.9% near the top of the core. There was an intermittent increase in organic content between depths 296–316 mm (1800–1900 YBP) that coincided with the highest sedimentation rates between depths 306–411 mm. However, organic content was not correlated with sedimentation rate ($r = 0.074$, $p = 0.400$).

Diatoms

The diatom assemblage varied throughout the Touson Lake core and contained 62 species from 31 genera. PCA extracted 1 useful axis (PC1) for further analyses, which accounted for 30.9% of the total assemblage variance (Fig. 5). Diatom PC2 and PC3 accounted for 8.9% and 5.9% of the variance, respectively, and were omitted from further analyses. Eight diatom species were strongly associated with PC1 (Table 1, Fig. 6); these species were the most statistically relevant in creating the PC1 variable (PCA loadings and communalities) and were also the most commonly occurring diatoms throughout the core. Species with the most positive loadings along PC1 included *Aulacoseira distans*, *A. granulata*, *Gomphonema gracile*, and *Pinnularia acuminata*. Ecologically, these species prefer lentic habitats (Patrick and Reimer 1966, 1975; Round et al. 1990; Wehr and Sheath 2003). Additionally, the meroplanktonic genus *Aulacoseira* is a common indicator of turbid water columns (Licursi et al. 2006; Patrick and Reimer 1966, 1975; Sherman et al. 1998).

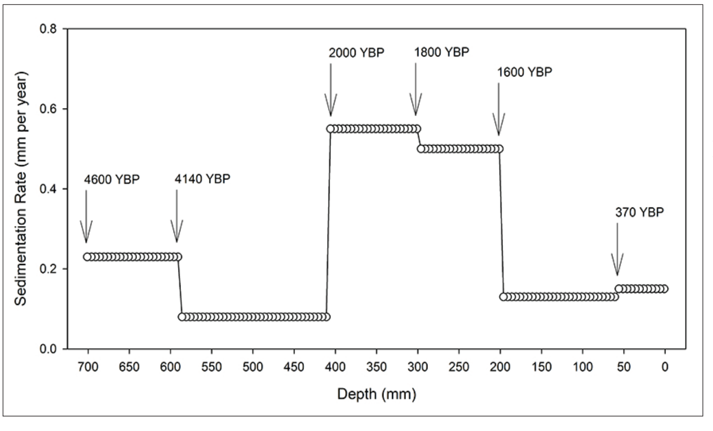

Figure 3. Sedimentation rate-depth profile for the Touson Lake sediment core inferred from ^{14}C analysis of the seven samples found in Fig. 2.

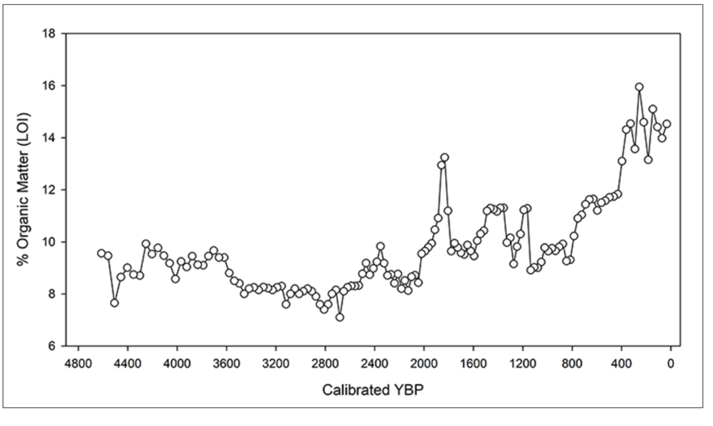

Figure 4. Organic content-depth profile for the Touson Lake core determined by loss on ignition (LOI).

Conversely, PC1 was negatively loaded by *Epithemia argus*, *G. dichotomum*, *Hantzschia amphioxys* and *P. abaujensis*. *Epithemia argus* contains endosymbiotic cyanobacteria capable of nitrogen fixation and the genus is frequently epiphytic in lotic ecosystems with low nitrogen content (Round et al. 1990, Wehr and Sheath 2003). *Gomphonema dichotomum* is commonly found in lotic habitats (Patrick and Reimer 1966, 1975; Wehr and Sheath 2003). *Hantzschia amphioxys* is an aerophilic species that often indicates mesic conditions and is nearly ubiquitous in terrestrial soils and epiphytic on bryophytes (Gaiser et al. 2001; Patrick and Reimer 1966, 1975; Round et al. 1990; Wehr and Sheath 2003). *Pinnularia abaujensis* has a wide habitat tolerance and can be found in both lentic and lotic habitats (Patrick and Reimer 1966, 1975).

Collectively, the 8 most common diatoms with the largest PCA loadings and communalities were variable throughout the core and had shifts in relative abundances that coincided with changes in PC1, sedimentation rate, and organic content. *Aulacoseria distans* (planktonic and lentic) was rare below depths 416 mm (2000 YBP) before rapidly emerging, after which it was the most common diatom in the core with relative abundances up to 31%. Similarly, *P. acuminata* (lentic) was rare below depths 201 mm (1600 YBP) before increasing in abundance. In contrast, *G. dichotomum* (lotic) was common below depths 306 mm (1800 YBP), and was the second most common diatom with relative abundances up to 25%, before becoming completely extirpated above that depth. Likewise, *H. amphioxys* (aerophilic) was common below depth 411 mm (2000 YBP) but then became increasingly rare above.

As PC1 scores became more positive, the relative abundances of *A. distans*, *A. granulata*, *G. gracile*, and *P. acuminata* increased, which show the local environment had lentic characteristics or areas of standing water; likewise, their decline is indicative of waters becoming

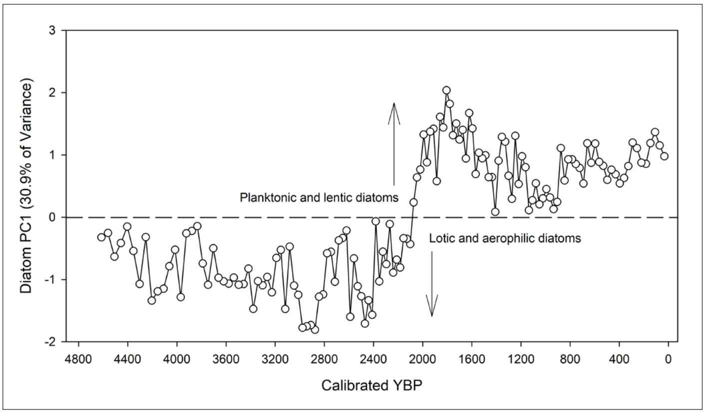

Figure 5. Diatom PC1-depth profile for the Touson Lake core.

Table 1. The 8 diatom species with the strongest PCA loadings and communalities from the Touson Lake core. These species also had the highest relative abundances.

Taxon	PC1 loading	Communality
Aulacoseira distans	0.928	0.861
Aulacoseira granulata	0.515	0.539
Gomphonema gracile	0.617	0.410
Pinnularia acuminata	0.677	0.479
Pinnularia abaujensis	-0.770	0.742
Epithemia argus	-0.526	0.407
Gomphonema dichotomum	-0.926	0.882
Hantzschia amphioxys	-0.724	0.550

less lentic and more transient in nature (PC1 scores become more negative). As the PC1 scores became more negative, the relative abundances of *E. argus*, *G. dichotomum*, *H. amphioxys* and *P. abaujensis* increased, which demonstrate the local environment became more lotic; likewise their decline is indicative of increased moisture and/or lentic habitats (as PC1 scores become more positive). Ultimately, it appears that PC1, as a whole, is capturing diatom assemblage variance associated with changes in water levels and whether the water is predominantly lentic or lotic. Diatom PC1 transitioned from negative values (lotic diatom dominated) to positive scores (lentic diatom dominated) at core depth 351 mm (2000 YBP), which coincided with peak sedimentation rates and an intermittent increase in organic content. Furthermore, diatom PC1 was significantly correlated with sedimentary organic matter ($r = 0.663$, $p < 0.000001$) and modestly correlated with sedimentation rate ($r = 0.349$, $p < 0.000001$).

Discussion

Touson Lake is currently an oxbow lake that was formerly part of the main channel of the Black Warrior River. As a result, it had declining connectivity with the main channel through time as the meandering neck was eroded. Oxbow lake ontogeny is often estimated from changes in basin morphometry and vegetational succession, especially Water Tupelo (*Nyssa aquatica*) and Bald Cypress (*Taxodium distichum*) (Harper 1912, Joo 1990, Joo and Ward 1990, Melack 1984). Additionally, changes in sedimentation rate and primary productivity can often be used to determine the chronology of oxbow lake formation (Gasiorowski and Hercman 2005, Joo and Ward 1991, Lobo et al. 2001, Wren et al. 2008). Therefore, it was possible to infer the paleohydrogeology of the Touson Lake basin using a combination of sediment and diatom proxies. This is further supported by the significant correlations between diatom PC1, organic content, and sedimentation rate. Decreases in organic matter and/or sedimentation rate often signify reductions in

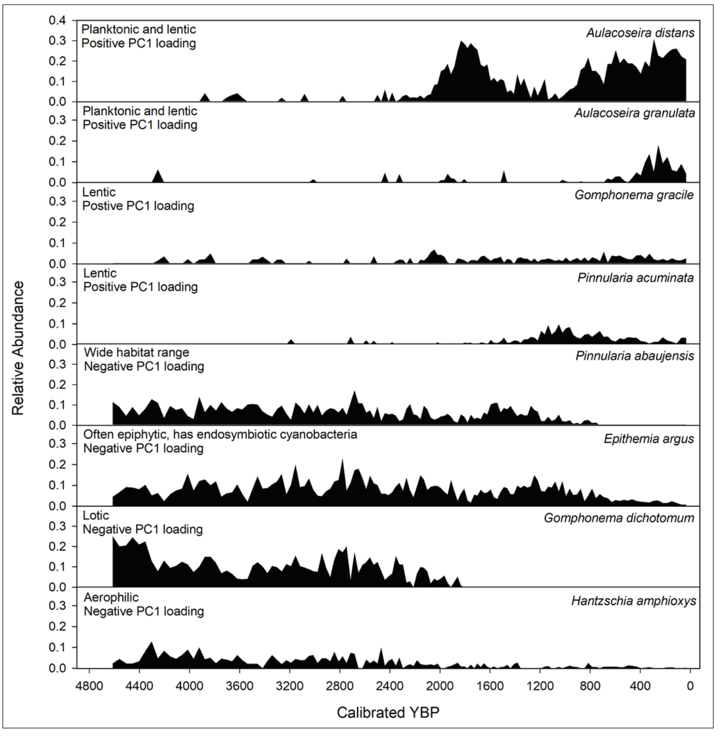

Figure 6. Relative abundance-depth profiles for the eight species of diatoms with the most predominant loadings from PCA within the Touson Lake core. These eight species were also the most common throughout the core.

productivity over time, and vice versa. Likewise, diatom species are often preferentially lentic or lotic species; assessing changes in assemblage characteristics can infer changes in the aquatic environment. The sediment and diatom profiles of Touson Lake showed changes through time, and these shifts were likely caused by changes in aquatic habitat type and availability.

We divided the chronology of the sediment core into 3 zones (Table 2). Preliminarily, we identified 6 potential zones based on differences in color and physical appearance and we carbon dated those transitional horizons. Analyses of sedimentation and diatom assemblage characteristics confirmed 3 of these 6 were likely deposited under different hydrogeological conditions. We combined depths 416–701 mm (2000–4600 YBP) into zone 1, depths 206–301 mm (1600–1800 YBP) and 306–411 mm (1800–2000 YBP) into zone 2, and depths 0–56 mm (0–370 YBP) and 61–201 mm (370–1600 YBP) into zone 3. We interpret these 3 zones below. Collectively, we interpret the river channel transitioning from a meandering bend to a cutoff oxbow lake beginning approximately 2000 YBP, which predates the previous analysis by Joo and Ward (1990) by 1500 years. After this period, flooding and inundation likely decreased as the oxbow became increasingly isolated from the main channel while human development spread through the region.

Zone 1: 2000–4600 YBP

The oldest section of the core (depths 416–701 mm), as a whole, represents a lotic environment before the meandering bend was abandoned. Zone 1 showed several characteristics of an active river channel, most notably sedimentation rate, organic content, and diatom indicator species. The sedimentation rate in this zone was generally low, with the lowest of the entire core between depths 416–591 mm, as would be expected from scour and erosion of running waters coupled with floodplain deposition (Allan and Castillo 2007, Callaway et al. 1996, Junk et al. 1989). Additionally, organic content was the lowest in this zone consistent with predictions of rivers typically being less productive than marshes, wetlands, and lakes (Allan and Castillo 2007, Søballe and Kimmel 1987, Wetzel 2001, Woodwell et al. 1978). Moreover, fluvial sediments typically have lower organic content than lentic sediments (Lobo et al. 2001).

Diatoms in this zone were predominantly lotic indicator species. *Gomphonema dichotomum* was very common in zone 1 before becoming permanently extirpated in zones 2 and 3. Likewise, *E. argus*, which is often epiphytic, was more common in the bottom zone before decreasing in abundance in the top two. Interestingly, *E. argus* houses endosymbiotic cyanobacteria capable of nitrogen fixation, which gives them an advantage over other algal species in lower nutrient environments (Round et al. 1990, Wehr and Sheath 2003), which rivers often are compared to marshes and lakes (Allan and Castillo 2007, Søballe and Kimmel 1987, Wetzel 2001, Woodwell et al. 1978). In contrast, *E. argus* had its lowest abundance between 0–600 YBP, which was when human impacts likely enriched the water (in zone 3 discussed below). Coupled with *H. amphioxys*, which is also aerophilic,

Table 2. Three zones in the Touson Lake sediment core differentiated by carbon dates, rates of sedimentation, and diatom assemblage characteristics. Each zone was segregated by actual carbon dates and not by any interpolated dates from the cubic spline regression.

Zone	Depths	Ages	Sedimentation	Diatoms
3	0-201 mm	0-1600 YBP	0.13-0.15 mm per year	Planktonic and lentic
2	206-411 mm	1600-2000 YBP	0.50-0.55 mm per year	Planktonic and lentic
1	416-701 mm	2000-4600 YBP	0.08-0.23 mm per year	Lotic and aerophilic

epiphytic, and frequently found attached to bryophytes, these diatoms likely indicate the establishment of vegetation along a defined riverbank. Diatom PC1 scores were negative, further demonstrating this region was one of overall lotic characteristics.

We also investigated the possibility of the mid-Holocene hydrogeological maximum during this period that was reported by Gaiser et al. (2001, 2004). They reconstructed the paleohydrogeology of a South Carolina coastal plain pond and indicated that water levels were at their highest between 3800–4600 YBP. This maximum was believed to be caused by a combination of retreating glaciers, increased precipitation, rising water tables, and eustatic sea rise. During this period, the predominantly fluvial coastal plain was inundated with water, subsequently filling in many low-lying depressions with standing water, including marshes, ponds, and river channels. After 3800 YBP, precipitation and water tables decreased, and some ponds desiccated, which marked the end of the hydrogeological maximum.

In our core, the only evidence we could use to corroborate the mid-Holocene hydrogeological maximum was the higher sedimentation rate (0.23 mm per year) between depths 596–701 mm (4140–4600 YBP) than the rate (0.08 mm per year) between depths 416–591 mm (2000–4140 YBP). These data indicate the river environment may have been more depositional and/or productive at the bottom of zone 1 than at the top of the zone, possibly caused by increased flooding or higher water levels that would establish a moving littoral zone, as proposed by Junk et al. (1989). Nonetheless, this is a weak connection and inconclusive; we cannot establish the presence of a mid-Holocene hydrogeological maximum from the information retrieved from the Touson Lake core. Our lack of this signal may simply be from differences in riverine and pond sediments. However, evidence from other regions in the southeastern USA is sparse, although there is some suggestion of large-scale expansion of wetlands after 6500 YBP. Specifically, extensive flooding caused the formation of the Okefenokee Swamp in Georgia (Cohen 1973). Likewise, the Florida Everglades may have been formed during the same period by similar flooding and precipitation patterns (Dovell 1947, Gleason and Stone 1994). Questions will remain because these landscape formations were traditionally thought to be isolated events that were unique combinations of flooding, plant decay, anaerobic metabolism, and peat formation (Cohen 1973). Future research on additional oxbows and ponds in the area could resolve this uncertainty.

Zone 2: 1600–2000 YBP

This zone (206–411 mm) represents a period of transition and early oxbow formation characterized by the greatest sedimentation rates and some of the highest organic content found in the sediment core. Specifically, the sedimentation rate in zone 2 was between two and six-fold greater than zone 1 and approximately four-fold larger than zone 3. While studying the Mississippi alluvial floodplain, Wren et al. (2008) noted that increases in sedimentation rates indicated frequent flooding during early oxbow abandonment from the main channel. During early oxbow formation, sedimentation rates are often the highest compared to the rest of its ontogeny because planktonic autochthonous production from within the newly forming lake is combined with an abundance of allochthonous deposition from the main channel (Gasiorowski and Hercman 2005). We also found an increase in organic content during the middle of this period, with levels rivaling some of the high values in zone 3, further demonstrating this time likely experienced frequent flooding and deposition. Abrupt changes in organic content facies are strong indicators of lotic to lentic transitions (Lobo et al. 2001). Also, the flood pulse concept (Junk et al. 1989) describes how flooding establishes a dynamic edge effect and a moving littoral zone flush with nutrients along the banks of the river, resulting in productivity higher than permanent waterbodies. Moreover, confined channels and lakes are typically less productive and depositional on a per area unit basis than expansive floodplains (Junk et al. 1989, Wetzel 2001, Woodwell et al. 1978).

Concomitant with the increased sedimentation and organic content in Touson Lake, we found lentic diatom species began to emerge in this zone after being rare in zone 1. Most notable, *A. distans*, which is a meroplanktonic genus and is particularly known for identifying standing, turbid, and nutrient rich waters, such as this coastal plain lake (Licursi et al. 2006; Patrick and Reimer 1966, 1975; Sherman et al. 1998), had a peak abundance during this period, further indicating turbid and nutrient-rich waters consistent with flooding. After flooding likely subsided near the top of zone 2, *A. distans* temporarily decreased before emerging again in zone 3 (discussed below). Gaiser et al. (2001) used *Aulacoseria* as an indicator organism of rising and standing water levels in the South Carolina coastal plain. Furthermore, lotic species of diatoms, which had been common in zone 1, became increasingly rare or absent in zone 2, implying water conditions were transitioning from a lotic river channel to a lentic oxbow environment. Diatom PC1 transitioned from negative to positive loadings during this zone, demonstrating that the entire diatom assemblage shifted in response to environmental changes. Overall, this period was likely one of channel abandonment coupled with flooding.

Zone 3: 0–1600 YBP

The stratigraphy in the top section of the core (0–201 mm) demonstrates the oxbow lake was likely fully abandoned from the main channel by 1600 YBP. At 1600 YBP, sedimentation rate decreased by nearly four-fold compared to the previous zone 2, which shows a reduction in flooding and oxbow connection while the main channel migrates away (Wren et al. 2008). As the main channel migrates from the oxbow, down cutting and deposition along the meandering neck forms earthen dams that lowers allochthonous sediment transport during flooding (Gasiorowski and Hercman 2005, Hupp 2000). It has also been shown that vegetation rapidly colonizes these earthen dams between the main channel and a new oxbow (Hupp and Osterkamp 1996, Joo and Ward 1990, Melack 1984), which would likely intercept overland sediment transport during flooding events. Joo and Ward (1990) previously used vegetation succession to estimate the cutoff date of Touson Lake at >500 YBP, and we found a pattern of increased sedimentary organic content originating around 800 YBP, with a sharp increase beginning at 400 YBP, corroborating their findings of increased productivity in the basin during this period. This trend was expected, since lakes are often more productive than rivers, and older oxbows are more productive than younger ones (Joo and Ward 1991, Wetzel 2001).

Diatom indicator species found in this zone were predominantly planktonic and lentic; diatom PC1 scores were positive during this period. While *A. distans* had another peak in abundance in zone 2 (discussed above), it began to show a steady rise between 1200–1600 YBP, which continued to present day, further showing the development and nutrient enrichment of this waterbody. Furthermore, *A. granulata* experienced its largest abundance during this period. Additionally, *P. acuminata*, which was essentially absent for most of the sediment core, emerged as a common species at 1600 YBP. Coupled with the presence of these planktonic and lentic diatoms is the notable lack of lotic and aerophilic species, providing additional evidence that this period was one of standing waters with limited interaction with the main channel, either via flooding or direct connection. Matsumoto et al. (2016) used a collection of diatoms in sediments, including the aerophilic *H. amphioxys*, to show the spatial scale of erosion and sedimentation associated with flooding. They determined that flooding washed this terrestrial diatom from the land into the path of flowing water. We can infer a decrease, or complete lack of, *H. amphioxys* in the top section of our core compared to the bottom sections as a metric for a reduction or absence of flooding. Moreover, *H. amphioxys* was essentially absent from the core after a series of flood control locks and dams were constructed along the Black Warrior River over the last 100 years.

Increases in organic matter and turbidity-tolerant diatoms in the most recent 800 YBP may also reflect human activity in the area. Touson Lake is located adjacent to one of the major political and religious centers of the Native American Mississippian culture (Moundville, Alabama) that was occupied from 500–1100 YBP and reached its peak between 600–800 YBP (Jenkins and Krause 1986, Knight 2004, Ward et al. 2005). A signature characteristic of this society was its cultivation of corn and other crops in the nutrient-rich soils of the Black Warrior River floodplain. Even without the use of modern synthetic fertilizers and other farming aids, such agrarian practices may have had long-term impacts on nutrient and sedimentation regimes in Touson Lake. For example, continuing high total adsorbed phosphorus concentrations in soils in an area in France were attributed to a 200-year period of Roman agriculture that occurred 2000 YBP (Dupouey et al. 2002). Therefore, it is likely that Mississippian culture farming practices may have begun a period of increased productivity in Touson Lake that continued into modern times. The most recent increase in organic matter in Touson Lake sediments, as indicated from samples in the period from around 400 YBP to the present, may have been enhanced by new settlers in the area beginning 300 YBP. After the collapse of the Mississippian culture 500 YBP, European immigrants from the eastern USA brought their own row crops, livestock, and deforestation to the coastal plain region (Ward et al. 2005).

Conclusions

Paleolimnological studies yield valuable insights into ecosystem responses to changes in climate and landscape use over time. These patterns of change provide further information on how rapidly lake productivity and biotic composition react to alterations in surrounding terrain. Paleolimnological studies have typically been performed in lakes formed by glacial, tectonic or volcanic processes (e.g., summaries in Haworth and Lund 1984, Moss 1988, Wetzel 2001), although focus on floodplain lakes, as cited in this study, has begun to emerge. Because oxbow lakes originate from river channels and maintain close association with floodplain environments, paleolimnological studies of oxbow lakes add to our understanding of riverine/hydrologic impacts on lakes. They are especially useful in testing whether typical paleolimnological proxies, e.g., diatom taxa, can capture the chronology of transitions from flowing water to more lentic conditions that oxbow lakes experience as part of their trajectory of development.

We demonstrated in this study that diatom microfossils in sediments of an oxbow lake were especially effective in delineating these transitions that we organized into 3 time periods beginning about 4000 YBP, a timeframe before the meandering bend in the river that would become the oxbow lake basin had separated from the main river channel. Changes in taxa of diatom microfossils closely tracked sequences of change through subsequent millennia, including progression toward a lentic environment about 2000 YBP and eventual effects of human activities in the proximate floodplain in more recent years. Ultimately, individual paleolimnological studies such as this one contribute to a broader, synthetic understanding of floodplain lakes as conclusions from multiple investigations across geographical regions are compiled.

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