Late Pleistocene baldcypress (*Taxodium distichum*) forest deposit on the continental shelf of the northern Gulf of Mexico

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Approximately 13 km south of Gulf Shores, Alabama (United States), divers found *in situ* baldcypress (*Taxodium distichum*) stumps 18 m below the ocean surface. These trees could have only lived when sea level fell during the Pleistocene subaerially exposing the tectonically stable continental shelf. Here we investigate the geophysical properties along with microfossil and stratigraphical analyses of sediment cores to understand the factors that lead to this wood’s preservation. The stumps are exposed in an elongated depression (~100 m long, ~1 m deep) nestled in a trough of the northwest–southeast trending Holocene sand ridges and troughs with 2–5 m vertical relief and ~0.5 km wavelength. Radiocarbon ages of the wood were infinite thus optically stimulated luminescence (OSL) dating was used to constrain the site’s age. Below the Holocene sands (~0.1–4 m thick), separated by a regional erosional unconformity, are Late Pleistocene mud-peat (72±8 ka OSL), mud-sand (63±5, 73±6 ka OSL), and palaeosol (56±5 ka OSL) facies that grade laterally from west to east, respectively. Foraminiferal analysis reveals the occurrence of the terrestrial-marine transitional layer above the Pleistocene facies in an interbedded sand and mud facies (394±30 (1σ) 14C a BP), which is part of a lower shoreface or marine-dominated estuarine environment. The preservation of palaeosol and swamp facies of broadly similar ages and elevation suggests the glacial landscape possessed topographic relief that allowed wood, mud and peats to be preserved for ~50 ka of subaerial exposure before transitioning to the modern marine environment. We hypothesize that rapid sea-level rise occurring ~60 or ~40 ka ago provided opportunities for local flood-plain aggradation to bury the swamp thus preserving the stumps and that other sites may exist in the northern Gulf of Mexico shelf.

In September 2004, Hurricane Ivan produced extreme wave heights (the largest was 27.7 m) in the Gulf of Mexico, resulting in substantial sea floor bottom scour (Wang et al. 2005; Teague et al. 2006) before making landfall in Gulf Shores, Alabama, United States (US) (Fig. 1A). After Hurricane Ivan made landfall, a site ~13 km offshore of Alabama in ~18 m water depth (Fig. 1A) was found that was later confirmed to contain *in situ* baldcypress (*Taxodium distichum* (L.) Rich.) stumps, presumably uncovered by the hurricane (Raines 2017). The wood is well preserved with primary cellulose structure intact and no visible indications of permineralization or fossilization by replacement of cellulose with minerals, i.e. the petrifying of wood (Buurman 1972). Normally, wood decomposes in the marine and freshwater environments due to bacteria, fungi, and wood-boring organisms (Kirk & Cowling 1984); therefore, finding *in situ* tree stumps in the marine environment 13 km offshore is unexpected. The preservation of woody material is possible in anoxic sediments and waters that limit biological organisms, thus reducing decomposition (Dimichele & Falcon-Lang 2011). Preserved wood has been found in anoxic peat bogs in freshwater environments (Stoll et al. 1994; Szumigalski & Bayley 1996; Ramil-Regó et al. 1998; Wheeler & Proctor 2000), and fluvial sediments (Heinrich 2002, 2005). Wood is rarely preserved in the marine environment unless the wood is buried (e.g. Fojutowski et al. 2014; Lee et al. 2019) or in anoxic waters (e.g. Brennan et al. 2011). Buried and preserved wood along the northern Gulf of Mexico coastal areas is not uncommon with buried stumps found in sediment cores recovered from the Trinity-Sabine river complex in Texas (Pearson et al. 1986), and Mobile Bay, Alabama (Greene et al. 2007), and the wood in cores recovered from the inner continental shelf of...
Mississippi-Alabama (Hollis et al. 2019), some of which was determined to be radiocarbon dead (Greene et al. 2007; Hollis et al. 2019).

The location of the stumps offshore at a water depth of 18 m suggests these trees were alive when sea level was lower than the present (Waebroeck et al. 2002; Fig. 1B); further suggesting these stumps are deglacial or glacial in age. The northern Gulf of Mexico sea level (Simms et al. 2007; Donoghue 2011; Anderson et al. 2014) and stratigraphical record (Kohl et al. 2004) for the last glacial interval or Marine Isotope Stage (MIS) 2 to 4 have not been studied extensively as a result of the Holocene submergence of the continental shelf and erosional processes (Fisk 1960; see the review of Hollis et al. 2019). This report investigates the geophysical, depositional and stratigraphical setting of this glacial age forest to better understand how such sedimentary deposits could be preserved at relatively shallow depths on the continental shelf through a glacial–interglacial transition. Our study incorporates foraminiferal assemblage and sedimentological analyses with radiocarbon (^{14}C) and optically stimulated luminescence (OSL) dating to interpret the site chronology coupled with previous pollen and sediment core results (Gonzalez et al. 2017; Reese et al. 2018). Here we establish a site chronology to place the forest in context with the evolution of the northern Gulf of Mexico continental shelf during the last glacial cycle and to develop an integrated framework in which to examine the conditions that allowed for the preservation of these tree remnants despite the highly destructive erosional processes associated with marine regression and transgression.

Study area and geological setting

Our study site is located south of Gulf Shores, Alabama, on the outer continental shelf (Fig. 1A) and contains a ~1-m-deep depression in the sea floor where tree stumps are exposed as a sediment ledge erodes. This site is within the Mississippi-Alabama-Florida (MAFLA) sand sheet province of the northern Gulf of Mexico passive outer continental shelf (McBride et al. 1999) that was deposited over the sea floor during the Holocene and exhibits a northwest–southeast shore-oblige ridge and trough morphology with relief up to 5 m (McBride et al. 1999). The evolution of the MAFLA sand sheet is largely tied to the retention of sandy sediment discharged by small rivers (Anderson et al. 2004). Below the MAFLA sand sheet is the Last Glacial Maximum (LGM) lowstand deeply incised valley carved out by the Mobile-Tensaw River system (Anderson et al. 2004; Bartek et al. 2004) initiated before the Wisconsinan glaciation (Kindinger et al. 1994). During glacial intervals, depocentres shift up to 200 km seaward of their highstand locations (Van Wagoner et al. 1988) with the northern Gulf of Mexico’s relative sea level falling by ~90 m (Simms et al. 2007). With falling sea levels, interfluve vegetation is established on the newly exposed continental shelf landward from the basinward-shifting shoreline. This flood-plain environment and its associated peat accumulations responded directly to base level change (Fisk 1960; Shen et al. 2012; Anderson et al. 2016).

Regional stratigraphy of the northeastern Gulf of Mexico outer continental shelf consists of Holocene shelf sands with abundant shells, underlain by estuarine and other coastal deposits from the Holocene to Pleistocene (McBride & Byrnes 1995; McBride et al. 1996, 1999; McBride & Byrnes 1995; McBride et al. 1996, 1999; McBride et al. 2004). Only a few Gulf of Mexico stratigraphical studies have focused on the Pleistocene–Holocene evolution of the MAFLA area (McBride et al. 1999; McBride et al. 2004; Flocks et al. 2011). Those studies described seven environmental facies (sand sheet, lower shoreface, central estuary or open bay, bay beach, lower bay shoreface, and two

Fig. 1. Northern Gulf of Mexico continental shelf and sea-level changes for the last 140 ka. A. The shaded area is bathymetry (Weatherall et al. 2015) and the study site (black box) is 13 km offshore from Gulf Shores, Alabama; the exact location is not given to protect the site. The central track of 2004 Hurricane Ivan (black line) (Landsea & Franklin 2013) passed within 8 km of the study site. Inset grey contours are isopachs of the acoustic two-way travel time (30 to 150 ms with 10 ms spacing) to the erosional base of the MIS 2 lowstand sequence (Bartek et al. 2004) showing the locations of the Pascagoula (west side) and Mobile (east side) palaeovalleys, which have been infilled by marine transgression and are no longer bathymetric features. B. Relative global sea-level estimates (grey line) with shaded areas for minimum and maximum estimates (Waebroeck et al. 2002). Marine Isotope Stage (MIS) numbers (Lisiecki & Raymo 2005) appear along the bottom with dotted vertical lines to denote the MIS interval. Dashed lines (25 and 100 m) in B correspond to contour dashed lines in A approximating coastline as sea level dropped. The solid horizontal line is the water depth of the stump exposure (18 m) and above this line, the site is marine and below is terrestrial.
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Pleistocene soil horizons) alongside local erosional unconformity (sequence boundary) as a result of bay and shoreface ravinement. Four primary and eight secondary foraminiferal assemblages are interpreted and their environmental affiliations have been identified for the MAFLA region (McBride et al. 1999: Table 1). This paper is part of a larger project (DeLong et al. 2020) with dendrochronological results in that report, preliminary sedimentological analysis of core 15DF1 (Gonzalez et al. 2017), and palynological analysis (Reese et al. 2018) reported elsewhere.

Material and methods

Fieldwork

The wood pieces that were initially $^{14}$C dated were collected by local divers in 2012. In October 2013, our diving team recovered 23 specimens of wood from the site

| Core ID  | Year collected | IGSN     | Depth (m b.s.l.) | Core length (m) | Interval (m) | Facies | Age (cal. a) and dating method |
|---------|----------------|----------|-----------------|-----------------|--------------|--------|-----------------------------|
| 15DF1   | 2015           | IEADF151A| 15.3            | 4.90            | 0–3.10       | HS     | 3920 $^{14}$C               |
|         |                |          |                 |                 |              |        |                             |
| 15DF2   | 2015           | IEADF152A| 15.8            | 3.30            | 0–2.75       | HS     |                            |
|         |                |          |                 |                 |              |        |                             |
| 15DF3A  | 2015           | IEADF153A| 15.8            | 1.41            | 0–1.06       | HS     |                           |
| 15DF3B  | 2015           | IEADF153B| 15.8            | 4.53            | 0–1.06       | HS     |                           |
| 15DF4   | 2015           | IEADF154A| 16.3            | 1.99            | 0–1.20       | HS     |               |
| 15DF5   | 2015           | IEADF155A| 17.1            | 1.23            | 0–1.20       | HS     |                 |
| 15DF6   | 2015           | IEADF156A| 16.7            | 0.94            | 0–1.20       | HS     |                 |
| 16DF1A  | 2016           | IEADF161A| 15.3            | 0.93            | 0–1.20       | HS     |                           |
| 16DF1B  | 2016           | IEADF161B| 15.3            | 1.71            | 0–1.20       | HS     |                           |
| 16DF1D  | 2016           | IEADF161D| 15.3            | 3.97            | 0–1.20       | HS     |                           |
| 16DF3A  | 2016           | IEADF163A| 16.0            | 2.32            | 0–1.20       | HS     |                           |
| 16DF5   | 2015           | IEADF155A| 17.1            | 1.23            | 0–1.20       | HS     |                             |
| 16DF6   | 2015           | IEADF156A| 16.7            | 0.94            | 0–1.20       | HS     |                             |
| 16DF7B  | 2016           | IEADF167B| 15.7            | 4.69            | 0–1.20       | HS     |                             |
| 16DF8A  | 2016           | IEADF168A| 16.2            | 0.87            | 0–1.20       | HS     |                             |
| 16DF8B  | 2016           | IEADF168B| 16.2            | 0.75            | 0–1.20       | HS     |                             |
| 16DF9A  | 2016           | IEADF169A| 14.4            | 2.73            | 0–1.20       | HS     |                             |
| 16DF9B  | 2016           | IEADF169B| 14.4            | 2.39            | 0–1.20       | HS     |                             |

1The first two numbers are for the year collected, followed by DF (Drowned Forest), and then by the station’s number and additional cores (if any) labelled A, B, C, and D.
2IGSN is the International GeoSample Number catalogued in the System for Earth Sample Registration.
3Water depths for cores are estimated from DEM (1-m horizontal resolution; Fig. 2) with an uncertainty of ±0.2 m ($2\sigma$) from Obelcz (2017).
4Vibracore length measured in the field directly after collection, may be slightly different length after splitting, imaging, and facies description in the laboratory.
5HS = Holocene sand; HISM = Holocene interbedded sand and mud; LPIMP = Late Pleistocene interbedded mud and peat; LPISM = Late Pleistocene interbedded sand and mud; and LPP = Late Pleistocene palaeosol. Facies examples are shown in Fig. 5.
6Intercept of conventional $^{14}$C age with calibration curve or OSL age (ka); see Tables 2 and 3 for dating details.
with exposed stumps on the sea floor (Fig. 2). The wood was labelled, photographed, cut with a chainsaw (Fig. 2C), and smaller pieces were removed from select wood pieces for $^{14}$C dating.

In August 2015 and July 2016, field operations were performed aboard the R/V ‘Coastal Profiler’ of the Coastal Studies Institute of Louisiana State University (LSU). In 2015, the study site where the exposed stumps are located was surveyed and sediment cores were recovered from within the depression with exposed wood and the surrounding area. This site was revisited in 2016 for a higher resolution geophysical survey of the 2015 area and a survey of the area to the east and south of the previous survey area with additional cores recovered from this survey area in duplicate for OSL dating. Geophysical equipment used in the surveys included: Edgetech 0512i CHIRP sub-bottom seismic profiler (~0.3-m vertical resolution, 1–2 m horizontal resolution), Edgetech 4600 interferometric and side-scan sonar (~2.5-mm vertical resolution, 1-m$^2$ horizontal resolution with a 540-kHz transducer), Edgetech DS2000 combined CHIRP sub-bottom and side-scan unit (in 2016 only), Valeport sound velocity profiler, Hemisphere Differential GPS SMC motion compensation system and a Geometrics G882 magnetometer. The Edgetech 4600 produces high-resolution three-dimensional (3D) maps of the sea floor while providing co-registered simultaneous side-scan (backscatter) data. Vibracores were collected using 6-m-long, 75-mm-diameter aluminium tubing attached to a vibrating head encapsulated within a steel tripod deployed from the R/V ‘Coastal Profiler’. Once retrieved, cores were cut into ~1.5-m-long sections onboard, labelled, capped, and sealed for transport to LSU. In 2016, two cores were collected at each new station (three stations), and two of the 2015 core locations were reoccupied. All 2016 cores were wrapped in black plastic bags to limit sunlight penetration, which could alter OSL dating results. Core water depth was referenced to the NAVD88 vertical datum and corrected for tides using the closest station at Dauphin Island, Mississippi (station ID 8735180); data available from National Oceanic and Atmospheric Administration (NOAA) tidal station (https://tidesandcurrents.noaa.gov/stationhome.html?id=8735180). The study area is microtidal; therefore, the tidal correction was minor.

**Core analyses**

The cores were stored in the refrigeration unit at 4 °C at LSU. Cores were logged using a Geotek Multi-Sensor Core Logger (MSCL) for the whole-core gamma density of sediments. For the 2016 cores, one of the cores from each station was logged whereas the other core was retained for OSL dating and logged after dating was complete if enough of the core remained. Cores were split in half longitudinally and one half of each core was retained for an archive. High-resolution images for each archive half were generated using the Geotek MSCL-XZ digital imaging system. The working half of each core was subsampled at 20-mm intervals for granulometric and organic content analyses. The granulometric analysis was conducted on a Beckman Coulter LS 13-320 Laser-Diffraction Particle Analyzer. Subsamples were wet sieved at 850 μm to remove large particles (mostly shelly debris that were not reincorpo-
rated into the size distribution), deflocculated in a 0.05% sodium metaphosphate solution to which 30% hydrogen peroxide was added in a hot bath to remove organic particulates; samples were further diluted with sodium metaphosphate for grain-size analysis. Loss on ignition analysis (Heiri et al. 2001) was used to determine organic content (OC).

**Geophysical data processing**

Bathymetric data were cleaned and referenced to the mean sea level of the closest NOAA tidal station (Dauphin Island, ID 8735180) using Caris HIPS and SIPS software. The bathymetric data were gridded into digital elevation models (DEMs) at 25-m² resolution and merged into a single surface. The side-scan data were mosaicked at 0.2-m² resolution using SonarWiz software. Sub-bottom data were processed (swell filtering, water column muting, and secondary predictive deconvolution) using Sioseis software. Processed sub-bottom profiles were then loaded into IHS Kingdom Suite software for interpretation and Fledermaus software for 3D visualization and analysis. The DEM, two seismically resolvable surfaces from two-dimensional (2D) sub-bottom surveys, core imagery, and physical measurements were imported into Schlumberger’s Petrel E&P software platform. Acoustic impedance from density and P-wave velocities were used to create a time–depth relationship between core and seismic data. The base of the Holocene sand sheet and the sea floor were used as tie points for a time–depth relationship. A velocity model was generated assuming a water velocity of 1500 m s⁻¹ and an unconsolidated sediment velocity of 1750 m s⁻¹ (Bourbie et al. 1987). Interpretation of the geophysical data was aided by seismic data collected in the 1990s by the United States Geological Survey for the MAFLA inner shelf region (Sanford et al. 2016).

**Micropalaeontology**

A coarse sampling scheme was used through the sand section in the upper portion of core 15DF1. Samples from the transitional interbedded sand and mud sediments were sampled at 100-mm intervals at first and then resampled at 50-mm intervals as a result of lithological variability. A 100-mm sampling scheme was applied through the mud-peat sediments for freshwater and terrestrial microfossils. About 15 000 mm³ of sediment was collected for each depth interval (Fig. S1). Standard micropalaeontological processing techniques were used (Scott et al. 2001). Sediment was wet sieved with deionized water over 1000-, 125- and 63-µm sieves. The residue was transferred to a drying plate and left to dry at 50 °C. The residue was thinly spread over a picking tray and >300 foraminifera were picked from the 125 to 1000 µm and 63 to 125 µm fractions under a binocular stereo microscope, identified, and stored on micropalaeontological assemblage slides. The >1000-µm fraction was screened for soritids and peneroplids on a presence basis only. The >125-µm fraction was used to eliminate small, hard to identify foraminifera. Foraminifer abundance (counted foraminifera, both planktic and benthic, per mass of dry sediment picked) was calculated for all samples. Foraminifer identification to the genus level followed the classification of Loeblich & Tappan (1988), and to the species level, when possible, using Phleger & Parker (1951), Bandy (1954, 1956), Andersen (1961), Pickett (1992) and Poag (2015). Specimens were compared with samples housed at the LSU Natural Science Museum’s Collection of Fossil Protists and Invertebrates. Triloculina spp., Nodobaculariella sp., Spiroloculina sp., and Milolinella sp. were grouped into ‘Other Milolids’. Indeterminate specimens were defined as those too small, degraded or broken for positive identification. Seeds and seed fragments were separated from the samples in the terrestrial sediments and identified to genus or species level using modern type samples.

**Dating**

Smaller samples were cut from the centre of the diver-collected wood specimens for ¹⁴C dating at the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory. Sample preparation backgrounds were subtracted, based on measurements of samples of ¹⁴C-free wood. Backgrounds were scaled relative to sample size. Sediment samples were sent to Beta Analytic Inc. for ¹⁴C dating. Bulk sediment samples were extracted from the flood-plain sediments containing wood in sediment cores recovered in 2015. The sediment samples were pretreated, rinsed over a 150-µm sieve, and examined under a microscope to ensure the residue was woody debris. Only this woody debris was used for ¹⁴C dating. A 4.0-mg sample comprised of mixed genera benthic foraminifera was taken from core 15DF1 in the deepest core section (3.30 m) where there was sufficient foraminifer carbonate material for ¹⁴C dating and sent to Beta Analytic for dating. All ¹⁴C measurements were corrected for isotope fractionation to conventional ¹⁴C ages based on separate determinations or assumed values for δ¹³C used by each laboratory. Calibrated ages were calculated using IntCal13 (Reimer et al. 2013) for the wood and woody debris samples and MARINE 13 (Reimer et al. 2013) with no local reservoir correction for the foraminifer sample. No marine reservoir correction was used for wood and woody debris samples because they were originally terrestrial.

To help refine the chronology of the site, the 2016 cores were examined for OSL dating at the Luminescence Dating Laboratory at the University of Liver-
pool. Five sections (0.2–0.43 m in length) from cores 16DF3A, 16DF9A, 16DF7B, 16DF7A and 16DF8A were selected based upon sampling a lithologically homogenous unit at least 100 to 200 mm below a prominent erosional surface in each core. OSL measurement and age determination followed established procedures (Data S1). The OSL ages, with 1σ ranges, are reported as before AD 2016, which is different from the calibrated 14C ages that are referred to AD 1950. The difference in reference age between the two dating methods (66 years) is well within the rounding uncertainty of our OSL data and therefore not considered further.

Results

Divers found several in situ tree stumps and numerous pieces of wood emerging from a dark peat sediment ledge in a depression at 18 m below sea level (m b.s.l.; Fig. 2). Divers were able to identify the baldcypress stumps underwater by their iconic buttresses and knees. The majority of the wood specimens retrieved by the divers in 2013 were identified as *T. distichum.*

Geophysical data

The most prominent feature is a northwest–southeast trending ridge and trough with 2 to 5 m vertical relief and ~0.5 km wavelength (Fig. 2). The tree stumps are located within and around an elongated depression in the sea floor (~1 m relief, ~100 m long, <10° walls) nested in the trough (Fig. 2). Sea floor backscatter is uniformly lower within the trough compared with the ridge (Fig. 3) and is particularly low within the depression where tree stumps are exposed. Individual tree stumps can be identified via side-scan sonar and appear to have lower reflectivity than the surrounding sea floor (Fig. 3). Buried stumps could not be confidently identified in the subsurface through CHIRP sub-bottom profiling as a result of the resolution used.

The dense CHIRP sub-bottom grid resolved strata to ~30 m below the seabed and can be projected into 3D space and viewed as a fence diagram to aid analysis and interpretation (Fig. 4). Based on seismic facies and stratigraphic geometry, the subsurface is divided into two units, Unit 1 and Unit 2, from deepest to shallowest. Unit 1 (red annotation, upper bounded by green horizon in Fig. 4) extends from the deepest resolvable reflectors to 0 to 5 m below the sea floor and is characterized by concordant, subparallel reflectors that dip south-southwest. The dip angle of these reflectors generally decreases from east to west (particularly flat-lying reflectors underlying the exposed trees), with the deepest resolvable reflectors in the east displaying sigmoidal geometry. Localized cross-cutting is apparent within Unit 1 (blue annotation in Fig. 4) and regional but discontinuous unconformities truncate dipping strata from overlying flat-lying reflectors. Unit 2 (bounded below by green horizon and above by yellow horizon in Fig. 4) varies in thickness from 0 and 5 m and overlies a strong and laterally continuous reflector. Unit 2 has no internal reflectors and is acoustically homogeneous.

Sediment cores

A total of 18 vibracores were collected in 2015 and 2016, spanning multiple sediment types, both inside and outside of the depression containing the exposed stumps (Fig. 2, Table 1). Initial sediment analysis

![Fig. 3. Side-scan sonar mosaic illustrating sea floor sediment texture variation. A. Light and dark colours indicate higher (coarser sediment) and lower (finer sediment) backscatter, respectively. Backscatter is lowest between ridges (dashed black lines) and particularly where trees and Pleistocene swamp sediments are exposed (purple box). B. Side-scan sonographs of trees exposed to the sea floor (purple boxes). Left and right panels are from the same approximate area (purple box in A) but acquired on adjacent track lines. [Colour figure can be viewed at www.boreas.dk]
results for core 15DF1 (Gonzalez et al. 2017) were conducted at 50-mm intervals whereas this study used a 20-mm interval for this core. Core 15DF1 is comprised of three facies (Gonzalez et al. 2017): Holocene sand facies (0–3.10 m core depth), interbedded sand and mud facies (3.10–4.05 m core depth), and an interbedded mud and peat facies (4.05–4.78 m core depth; Table 1, Fig. S1).

The combined mean grain size, gamma density, and OC are compiled into core comprehensive graphs (Fig. 5, see Figs 7, 8, S1, S2 for other cores), and these properties together define distinct lithologies for each core profile (Table 1). Surficial units of each core (up to ~3 m thick) are generally >95% sand, have the highest gamma density and contain up to ~1% OC. Uppermost sands have high and relatively constant gamma densities (~2.3–2.5 g cm⁻³). Below the surficial sandy unit, interbedded sand and mud are evident in some cores (e.g. 3.1–4.05 m in core 15DF1 and 0.60–2.96 m in 15DF3B; Table 1). A slight increase in OC is found in the interbedded sand and mud unit (1.3–2.6%) with intermediate gamma densities with saw-tooth density profiles (e.g. ~1.8–2.3 g cm⁻³ for 3.1–4.05 m in core 15DF1). Below units of interbedded sand and mud, the dominant modal grain size is in the silt range. For the interbedded mud and peat unit, OC is as high as 20.3% and gamma density is the lowest with variable densities exhibiting saw-tooth density profiles (~1.2–1.9 g cm⁻³) for 4.05–4.78 m in core 15DF1). A palaeosol is found only in the base of cores 16DF8A (~0.1–0.8 m) and 16DF8B (~0.1–0.6 m) that displayed low OC (0.6–3.8%) and gamma densities of 1.9–2.4 g cm⁻³. Overall, sandy units contain the lowest OC, peaty units the highest, with intermediate values in muddy units. Some sandy sections were found to have settled during transport and storage creating gaps and disturbed units of sediment in cores and thus noted.

**Dating**

Eight of the ¹⁴C ages from core 15DF1 (Gonzalez et al. 2017; Reese et al. 2018) are summarized here along with 11 wood and two additional core samples from this study for completeness (Table 2). Radiocarbon ages for 18 out of the 21 wood and sediment samples are infinite ages (measured ¹⁴C is not discernible from background levels, thus older than ~50 ka; Stuiver & Polach 1977) with the exceptions noted here. The sample of mixed genera benthic foraminifera from core 15DF1 (sample 15DF1-330) had a conventional ¹⁴C age of 3940±30 (1σ) a BP (calibrated 95% age range 4045–3830 cal. a BP), thus providing a depositional age for the top of the interbedded sand and mud facies in this core. The woody debris sample from core 15DF3B at 3.10 m (sample 15DF3B-310) in the interbedded mud and peat facies has an infinite age. The radiocarbon dating of eight woody debris samples from the mud and peat...
intervals of core 15DF1 resulted in six $^{14}$C dead samples. Woody debris samples from 4.05 and 4.14 m in core 15DF1 yielded conventional $^{14}$C ages of 41,830±880 (1σ) a BP (46,690–43,625 cal. a BP) and 37,350±330 (1σ) a BP (42,235–41,350 cal. a BP), respectively; the latter was analysed for a second sample from the same core depth (4.14 m) and that sample was determined to be infinite in age (Gonzalez et al. 2017; Reese et al. 2018). All wood samples have infinite ages or ages near the $^{14}$C detection limit including two wood samples that were dated twice each. Stratigraphical inversion, bulk dating methodology and the limitations of $^{14}$C dating have caused these ages from cores 15DF1, 15DF3B, and all the wood samples to be treated cautiously as a minimum age estimate of the forest.

Four samples for OSL dating were collected from core depths with possibly undisturbed sediment overlying the mud and peat facies that contain wood and one sample (16DF7A; Table 3) was collected from the palaeosol found in the eastern section of the survey area (Fig. 2). The five OSL ages range from 56±5 (1σ) ka (16DF8A) to 73±6 (1σ) ka (16DF7A). Silt and sand quartz ages from core 16DF7B are statistically identical and a weighted mean age of 70±5 (1σ) ka is used for this core. The core with the
palaeosol (16DF8A) has the youngest OSL age. These dating results suggest the forest’s age is between 56 and 73 ka, mostly likely during MIS 4.

**Micropalaeontology**

Micropalaeontology results from core 15DF1 are reported with the pollen results (Reese et al. 2018) in
| Sample ID | Facies Type | Grain Size (m) | d_{1000} (Gy ka^{-1}) | d_{200} (Gy ka^{-1}) | d_{100} (Gy ka^{-1}) | d_{20} (Gy ka^{-1}) |
|-----------|-------------|---------------|------------------------|----------------------|----------------------|----------------------|
| LV839     | Sand        | 2.42          | 1.48±0.17              | 10.6±1               | 72.5                 | 63±5                 |
| LV840     | Sand        | 2.97          | 2.89±0.21              | 18.9±2               | 71±6                 | 56±5                 |
| LV841     | Sand        | 2.42          | 2.64±0.22              | 23.1±2               | 71±6                 | 56±5                 |
| LV853     | Sand        | 2.97          | 2.61±0.22              | 21.9±2               | 73±6                 | 57±5                 |
| LV854     | Sand        | 2.42          | 3.30±0.29              | 38.1±2               | 71±6                 | 56±5                 |
| LV855     | Sand        | 2.97          | 2.60±0.21              | 21.9±2               | 73±6                 | 57±5                 |

1. See Table 1 for facies abbreviations.  
2. 0.09–0.04 was the minimum grain size reported for this sample.  
3. Cosmic dose rates were calculated with and without seawater at the coring site. The cosmic dose rates for age calculation were derived by assuming -15% burial history with seawater of present-day depth at the coring sites, considering sample ages, water depth at the sites, and sea-level history.

Fig. 6 with full foraminifer counts in Fig. S3 and Table S1. Rosalina spp., Hanzawaia concentrica, Elphidium spp., Cibicidoides spp. and milolid taxa account for >70% of all the genera in the top 3.3 m of core 15DF1 and are similar to the milolid, Rosalina and A. carinata assemblages of McBride et al. (1999). Soritids and peneroplids are present in assemblages down to 3.2 m. Foraminiferal abundance (per gram of dry sediment) from 0.4 to 2.75 m is between 134 and 285 specimens g⁻¹ and then increases to 1625 specimens g⁻¹ at 3.1 m. The number of shell fragments in samples decreases down the core and no foraminifera are present from 3.35 to 3.55 m with the exception of one Oolina sp. at 3.5 m. A unit of coarser grain size and increased shell fragments corresponds with increased foraminiferal abundances similar to that observed within the Holocene sand assemblages at 3.6 and 3.8 m. A distinguishing feature from the interbedded sand and mud facies is that porcelainaceae taxa represent a smaller percentage (<2%) of the assemblage at 3.6 and 3.8 m. An interval of no foraminifer and few shell fragments is noted from 3.85 to 3.95 m. Two broken and poorly preserved Textularia tests are present at 4.0 m. Indeterminate specimens accounted for <2% of each sample. Foraminiferal abundances from the interbedded sand and mud facies are less than those in the Holocene sand facies and range from 0.7 to 73.10 specimens g⁻¹. The presence of preserved foraminifera is found only within the sandy sediments in the interbedded sand and mud facies and combined with observed test discoloration suggest taphonomic alteration for this core section rather than poor living conditions (Scott et al. 2001; Berkeley et al. 2007). Planktic foraminifera are found in low abundance throughout this core. From 4.05 to 4.785 m, no foraminifera or ostracods are present and the sediments contained relatively high percentages of OC (4.15–19.15%) in the mud and peat facies that characterized this section of the core. Pollen is well preserved in the mud and peat facies (4.05–4.75 m) in core 15DF1 (Fig. 6: Reese et al. 2018). Intact preserved seeds of T. distichum, Hibiscus, Carex, Nyssa, Tridacnum, Cephalanthus occidentalis and Liquidambar styraciflua are found in these mud and peat facies (Fig. S4, Table S2) and generally agree with the pollen results.

Samples were taken near the inferred erosional surfaces in three other cores (15DF3B, 16DF7B and 16DF9B) and these samples were examined for the presence of foraminifera only (Table S3). Analysis of samples from cores 15DF3B (2.5 m), 16DF7B (2.0 m) and 16DF9B (1.9 m) found A. parkinsoniana, Quinqueloculina, Rosalina spp., Elphidium spp., A. carinata and Cibicidoides spp. present in all samples that contained foraminifera. Marine microfossils are absent from sample depths 2.25 and 4.0 m in core 16DF7B.
Fig 6. An abbreviated chart of the foraminiferal (left, %) and pollen assemblages (right, %) for core 15DF1 is shown with core sediment properties, facies (Fig. 5; see Table 1 for facies abbreviations), and conventional radiocarbon ages (Table 2, Fig. S1). Pollen results (Reese et al. 2018) are shown for comparison. TCT (Taxaceae-Cupressaceae-Taxodiaceae) pollen is interpreted as T. distichum.
Discussion

We propose that mud-peat sediments found in cores located in topographic lows (Fig. 2) were buried and preserved by fluvial flood-plain sediment accumulation.

Stratigraphical interpretation

Five lithological units (i.e. lithofacies) characterize the sedimentary deposits found in the study area based on litho-, bio-stratigraphical descriptions and dating results (Fig. 5, Tables 1, 4). These facies include the three previously defined for core 15DF1: (i) Holocene sand, (ii) Holocene interbedded sand and mud, (iii) Late Pleistocene interbedded mud and peat (Gonzalez et al. 2017), and two new facies, a (iv) Late Pleistocene interbedded sand and mud, and (v) a Late Pleistocene palaeosol. The Holocene interbedded sand and mud facies are lithologically comparable to facies 4 described by McBride et al. (1999) with a slightly different foraminiferal assemblage (Fig. 5). Facies 4 of McBride et al. (1999) exhibits an Elphidium-Haynesina assemblage that can be found in many modern bays across the northern Gulf of Mexico (Bandy 1956; Gangopadhyay et al. 1996; Osterman & Smith 2012; Poag 2015), whereas our interbedded facies host more neritic genera (Rosalina, Asterigerina, Cibicides and Hanzawaia). The Late Pleistocene interbedded mud and peat facies has woody debris and fragments that correlate stratigraphically to the T. distichum stumps and larger wood pieces exposed in the depression and nearby sea floor (Figs 2, 3). The Late Pleistocene palaeosol features zoning similar to soil horizons, root traces, and nodular structures that are consistent with identification as a palaeosol (Retallack 1988), thus providing evidence of subaerial exposure. This facies was also identified by McBride et al. (1999) as Pleistocene in age from a continental-coastal environment with oxidized sediments from subaerial exposure.

Integration of core and geophysical data

The CHIRP sub-bottom profile (Fig. 7) crossing over the trough where stumps are exposed (A–A’ in Fig. 2) is interpreted along with the comprehensive graph for core 15DF6 to illustrate the physical properties related to the acoustic properties. In this profile, four seismic units are identified: (i) a surficial Holocene sand sheet separated from subjacent deposits by a reflector that occurs near the same depth as the sand–mud boundary in the density profile of core 15DF6 and is likely the previously identified Holocene ravinement surface (Kindinger et al. 1994; McBride et al. 1999). (ii) Undifferentiated deposits that are laterally contiguous below the sand sheet with horizontal reflectors most likely represent delta top deposits. The delta top interpretation of (ii) is in good agreement with the interbedded mud and sand deposits found in cores and similar deposits found in the Mississippi Delta. The stratigraphical model is in agreement with the classical river-dominated delta (Fisk et al. 1954; Chamberlain et al. 2018). (iii) More strongly reflective adjacent deposits below the trough. (iv) The deepest deposits have steeply dipping reflectors. This deepest unit is similar to seismic strata interpreted by Kindinger et al. (1994) to be bay-head deltas of the Late Pleistocene.

Fig. 7. CHIRP sub-bottom profile along trough where the wood and stumps were found (Fig. 2 for the location of A–A’). Uninterpreted (A) and interpreted (B) CHIRP sub-bottom profiles dip-oriented across the subaqueously exposed tree stumps. Facies are Holocene sand (pink), Late Pleistocene terrestrial deposits (yellow) either swamp, palaeosol, or flood-plain facies, Late Pleistocene interbedded mud and peat below the trough (green), and below that are bay-head delta facies (blue) with clinoform dipping directions (solid black lines). C. Comprehensive graph of core 15DF6 that was acquired in the vicinity of the trough (Fig. 2). [Colour figure can be viewed at www.boreas.dk]
Fig 8. A. East–west cross-section and B is a north–south cross-section of the study area. Cores are georeferenced to their respective seabed depth and location (Table 1). Core images are shown alongside mean grain size (red), OC (green), facies type (Table 1), and dating results (cal. a BP are ¹⁴C ages and ka are OSL ages; Tables 2, 3). Hatch areas in core images are void areas. Inset displays site bathymetry with cross-section’s orientation, core locations, and red dots indicating stump contacts imaged via side-scan sonar. [Colour figure can be viewed at www.boreas.dk]
Table 4. Geological framework of the baldcypress forest exposure area offshore of Alabama in the northeastern Gulf of Mexico.

| Facies or surface | Cores | Sedimentology | Palaeontology | Age (BP) | Primary environment | Sub-environment | Elevation (m) | Sequence stratigraphy | Thickness (m) |
|-------------------|-------|---------------|---------------|----------|---------------------|----------------|--------------|-----------------------|---------------|
| Surface           | HS    | Light, beige-grey, fine-medium grain quartz sand that is moderate to well sorted. Shell bed (50–150 mm thick) is typically found at the base of the sand bed. | Marine molluscs, foraminifera (Rosolina-\textit{Hanzawaia}-\textit{Elphidium}-milolid, and CBF), and bioclasts. | Holocene | Neritic open marine environment | Shelf surficial sand sheet (MAFLA) | Up to 18 | Future max. flooding surface | Up to 4.05 |
|                   | HISM  | Light-medium dark grey mud interbedded with fine-grained sub-bioclastic sand and shell fragments in prominent sand-mud interbedding. Individual layers have relatively uniform thickness, and some intervals have more mud than sand. | Little-to-no preservation of foraminiferal assemblages with no miliolids. Lack of CBF. | Holocene | Marine | Estuarine and middle-to-inner shelf (Bentley et al. 2002; Keen et al. 2004) | 0 to 3 | Up to 4.05 | |
| Erosional surface | LPIMP | Dark grey, tan to dark brown muds, peats, and peaty mud. Prominent bedding of mud and peat layers. Highest OC. | Woody debris, wood fragments, and seeds in muds. Basal pollen assemblage similar to modern baldcypress-tupelo-gum forest that grades into grass-sedge then a cypress-alder community. | 41,830–72 ka | Continental | Bulbypress forest in a river flood-plain with mud beds from episodic flooding | 0–80 | Highstand and falling stage systems tracts | 0.27–1.57 |
|                   | LPISM | Darker colour with more OC. Bedding patterns and grain size similar to HISM but with fine sand. | Marine microfossil and pollen analyses have not been performed. | 63–73 ka | Continental | Terrestrial, fluvial over bank deposits | 0–80 | 0.22–2.32 |
|                   | LPP   | Variable yellow and orange mottled silt and clay-sized sediments that grades downward into unmottled light grey muddy sands. Mottled zones have bright orange nodular lumps resembling rhizo-concretions and are likely root traces (Fig. 5). Low OC. | No macrofossils are evident, detailed pollen analysis has not been performed. | 56 ka | Continental | Terrestrial environment, palaeosol with subaerial exposure | 15–60 | 0.52–0.7 |

1See Table 1 for facies abbreviations and Fig. 5 for examples of facies. HS, HISM and LPP are consistent with the lithological and microfossil descriptions of McBride et al. (1999).
2Foraminifera were examined in core 15DF1 in detail (Figs 6, S3, Table S1) and cores 15DF3B, 16DF7B and 16DF9B for presence-only (Table S3). The marine microfossil framework of McBride et al. (1999) was used to interpret microfossil results along with other Gulf of Mexico foraminifer studies (Phleger & Parker 1951; Bandy 1954, 1956; Phleger 1960, 1964; Murray 1991; Puckett 1992; Gangopadhyay et al. 1996; Scott et al. 2001; Kohl et al. 2004; Poag 2015). Calcareous-bank microfauna (CBF) consists of Amphistegina, \textit{Archaias}, \textit{Asterigerina}, \textit{Nodobucalciella}, soritids and peneroplids, and is a reflect product of shoreface ravinement (Kohl et al. 2004); all but \textit{Archaias} are present in core 15DF1.
3Intercept of conventional 14C age with the calibration curve for radiocarbon dates are reported as cal. a BP and OSL ages are reported as ka (Tables 2, 3).
4Elevation is estimated from age and global sea level (Waelbroeck et al. 2002) and northern Gulf of Mexico sea level estimates (Simms et al. 2007; Donoghue 2011; Anderson et al. 2014); – is m b.s.l.
Holocene sand is thin or absent near the Late Pleistocene interbedded mud and peat below the trough. Below the sand sheet lie undifferentiated Late Pleistocene terrestrial deposits that may include mud and peat, palaeosol, or flood-plain facies, and below that are bay-head delta facies with clinoform dipping directions.

**Core depth–age relationships and lateral correlation**

A roughly east–west cross-section across the trough and ridge and a north–south cross-section reveal the depth and age relations among facies (Fig. 8, Fig. S5). Peats are preserved in the western part of the study area, where relief is lower, with 15DF3B hosting the longest section of recovered terrestrial peat (1.57 m; Table 1). The southern and eastern areas did not preserve any peats and are populated instead by the Late Pleistocene interbedded sand and mud facies, and Late Pleistocene palaeosol facies. The cross-sections show both Holocene interbedded sand and mud and Late Pleistocene interbedded sand and peat facies occur in topographic lows. Both of these facies are missing from the topographic high (sand ridge; 16DF9A, 16DF9B) and in the easternmost cores (16DF8A, 16DF8B) where the Holocene sand sheet lies directly upon the Late Pleistocene palaeosol and on Late Pleistocene interbedded sand and mud at slightly deeper depths (16DF9A and 16DF9B; Table 1). The Holocene interbedded sand and mud facies is discontinuous, and this facies is missing from cores 15DF5 and 15DF6 inside the trough where the stumps are exposed (Table 1). Higher elevation Late Pleistocene interbedded sands and muds facies (16DF7B and 16DF9) in the ridge area and southern extent could have been deposited as part of a fluvial system with a natural levee. Observations are similar to elevation and morphology in modern-day flood-plain channel-levee complexes (Lewin & Ashworth 2014). The relatively younger age for the Late Pleistocene palaeosol suggests that Pleistocene sediments were not eroded uniformly across the study area after the region became exposed during sea-level fall.

A consequence of the Holocene interbedded sand and mud facies in core 15DF1 being deposited in a coastal environment (Fig. 6) constrains the chronology of the site such that the Holocene interbedded sand and mud facies is above the Holocene-Pleistocene unconformity (sequence boundary) and the flood-plain facies (LPIMP and LPISM) is below (Fig. 8; Table 4). In the study area, the sequence boundary and bay-ravinement transgressive surfaces become amalgamated. The occurrence of peats is assumed to mark the base of the sequence boundary and termination of coastal foraminifera deposition (Culver 1988; Kohl et al. 2004) is assumed to mark the top of the sequence boundary. Mapping the sequence boundary reveals an eastern high and a western low in our study area displaying ~1 to 2 m of negative relief dating before the MIS 2 lowstand (assuming negligible differential compaction).

**Subsurface DEM**

Guided by core data and background literature, three seismically resolvable surfaces are identified in the 3D subsurface DEM generated with Petrel (Fig. 9) including the sea floor, a transgressive surface, and a basal surface truncating steeply dipping clinoform packages. Two seismic units are resolved from the three surfaces.
Unit 1 (U1) is bounded above by the sea floor and below by a relatively flat-lying shoreface ravinement contact consisting of amalgamated shell hash and sand produced by Holocene marine transgression. Unit 2 (U2) is truncated above by the transgressive surface and below by the basal surface. U1 is interpreted to be the Holocene sand sheet (0–5 m thick) with age confirmed by the $^{14}$C dating of foraminifera in core 15DF1 (Table 2). This uppermost stratigraphical layer, the Holocene sand sheet, is present across the entire survey site and is thinnest where the tree stumps are exposed (Fig. 9C). Bathymetry and sand sheet thickness generally correlate well, which indicates that strata underneath the sand sheet are relatively flat, and sand distribution is not primarily controlled by precedent stratigraphy. U2 is defined to be undifferentiated Pleistocene alluvial plain deposits, including the interbedded mud and peat facies and the interbedded sand and mud facies. The dipping layers below U2 maybe point bar deposits but are more likely Pleistocene delta front deposits because of geometry, previous literature (Bartek et al. 2004), and the constraint by the overlying swamp-terrestrial facies, yet none of our cores penetrated U2. These sequences are prograding and generally dip southwest with the inclination increasing towards the east and with channel cross-cutting apparent to the south.

The base of U2 exhibits variable topography (Fig. 9A) and the presence of a palaeosol (cores 16DF8A, 16DF8B) on top of one of these palaeohighs suggests there was palaeorelief. The thickness of the alluvial fill package (U2) is thickest in the central area of our study site and thinnest in the northern and eastern corners, the latter where palaeosol is present. There is enough accommodation space to allow at least 8 m of terrestrial sediment accumulation (possibly in pulses) before being eroded during lowstands and Holocene transgression.

### A case for forest preservation

If all of the $^{14}$C and OSL ages are reliable and the actual ages are within the uncertainty estimates (2σ) for each age and are representative of depositional age, then both of the muddy Pleistocene facies may have been deposited near the same time. These conditions are consistent with the conditions producing nearby modern coastal plain where Pleistocene coastal and fluvial deposits (from MIS 5 and earlier) deposited at or uplifted to higher elevations are being eroded, incised and weathered to form soils, and where topographic lows are being filled with modern fine-grained sediments and wetland vegetation.

These observations suggest local palaeotopography (Figs 8, 9) played a role in both deposition and preservation of the muddy wood-bearing deposits. Holocene interbedded sand and mud were likely deposited in palaeotopographic lows on the Holocene ravinement surface and may have been eroded at the location of cores 15DF5 and 15DF6 at or near the time the surficial trough was eroded exposing the stumps or possibly earlier during transgression. Similarly, the Late Pleistocene interbedded mud and peat facies appear to have been deposited, or at least preserved, in a topographic low with respect to the elevation of Late Pleistocene interbedded sand and mud and palaeosols found in cores to the east. The accommodation space provided by palaeorelief with peats being preserved in the lower-lying areas is conducive for forest preservation as sediment generally infills the lower-lying areas under the control of gravity first, and higher relief areas are either preferentially eroded or deposited later. Palaeosols and the low-lying sequence boundary (MIS 2; Fig. 8, Table 4) suggest palaeorelief was established before 56 ka and existed until Holocene transgression and is a contributing factor for forest preservation in the western area of our study site. Whereas natural subsidence can account for the stumps being buried, subsidence of the study area is suggested to be minimal for the last glacial interval (Anderson et al. 2004; Bartek et al. 2004).

Current swamp environments in the southeastern US have low oxygen water with slow decomposition and high amounts of wood preservation (Conner & Buford 1998). Another possibility for promoting wood preservation is rapid burial by a large volume of sediment from either river overbank flooding or marine transgression (Heinrich 2005; Shen et al. 2015). Two sites in Louisiana along the Mississippi River contained buried baldcypress stumps 1.5 m high that would have required burial rates of 1.5 to 2 m in 100 years for preservation (Heinrich 2005). The stump sampled by divers was ~1 m tall (Raines 2017) but the height of stumps at the site has not been fully investigated. Dendrochronological analysis of diver recovered wood found evidence the stumps could have been buried rapidly (DeLong et al. 2020). That analysis developed a floating tree-ring chronology (489 years long with annual resolution) consisting of 10 wood specimens with intact bark. The chronology ends in the same year for all trees suggesting these trees experienced a rapid stress event that resulted in synchronous tree mortality. The bark is generally shed first while the snag is still standing for many years (Mobley et al. 2013) suggesting rapid burial occurred. An example of such an event could be a hurricane causing treed death from saltwater intrusion (Middleton 2016).

If other locations on the northern Gulf of Mexico have similar geomorphology and environmental conditions, then other sites located within or adjacent to the Gulf of Mexico incised valleys at similar elevations may also contain preserved glacial age forest remains. The Trinity-Sabine complex on the Texas coast (a Holocene
Fig. 10. Reconstruction of forest site palaeolandscape evolution. (top) Relative sea-level estimates below modern sea level (0 m) are shown as a blue line with shaded areas for minimum and maximum global sea level (Waelbroeck et al. 2002). Green circles and red squares are ages from $^{14}$C and OSL dating (1σ error bars), respectively (Tables 2, 3), shown with respect to dating sample depth below modern sea level. A–F. Sea-level model reconstructing the coastal plain and continental shelf at times during changes of sea level from the Late Pleistocene to the Holocene. Regional elevation and bathymetry from Love et al. (2018). See Table 1 for facies abbreviations. [Colour figure can be viewed at www.boreas.dk]
site) hosts preserved swamp deposits and baldcypress wood (Pearson et al. 1986) that were possibly preserved in a similar manner to the stumps detailed in this study. Those authors concluded that topography was the most important factor in site preservation, and subsidence and compaction were secondary. The Trinity-Sabine complex provides evidence that preservation processes at our site are not necessarily localized but could occur all along the northern Gulf Coast. It should be noted, however, that the preservation observed at our study site could have also been caused by local processes not linked to large-scale sea-level fluctuations, such as autogenic river avulsion and crevassing (Heinic 1982; Shen et al. 2015).

**Role of sea-level change and flood-plain aggradation in forest preservation**

We have reconstructed the coastal plain and continental shelf at various intervals (80.0, 65.0, 60.5, 44.0, 39.5 and 4.0 ka) for our dated sediments using their mean OSL and central $^{14}$C ages to illustrate sea-level changes, shoreline locations, and transgression-regression using global sea-level estimates (Waelbroeck et al. 2002; Fig. 10). A regional digital elevation model (Love et al. 2018) was trimmed to highlight the study area and demark the probable land–sea boundary at each of those intervals. This approach ignores topographic change by uplift, subsidence, sedimentation, and erosion from the last glacial to present, and also assumes the Waelbroeck et al. (2002) global sea-level record applies to the northern Gulf of Mexico, which is not well understood or documented before the LGM (Simms et al. 2007; Donoghue 2011; Anderson et al. 2014). Nevertheless, these illustrations schematically show the relative magnitudes of distances, elevations, and topographic gradients relating our study area to the location of the coastline for these intervals.

From 80 to 65 ka (Fig. 10A, B), sea level fell from ~20 to 85 m b.s.l. exposing a new coastal plain that is more than 50 km wide where baldcypress trees could become established. During this time, the oldest flood-plain deposits of the Late Pleistocene interbedded mud and peat, and Late Pleistocene interbedded sand and mud facies were deposited (Tables 3, 4). From 65 to 60.5 ka (Fig. 10B, C), sea level rose to ~48 m b.s.l. but because of the steep gradient of the outer continental shelf, the shoreline transgressed less than ~15 km. During this interval, the youngest deposits of the Late Pleistocene interbedded sand and mud facies accumulated (Tables 3, 4). The interval from 60.5 to 44 ka (Fig. 10C, D) encompasses a sea-level rise of ~7 m near 54 ka, falling to ~76 m b.s.l. near 44 ka resulting in an overall coastal regression of ~10 km based on this elevation model. During this interval, the sediments of the younger (56 ka) palaeosol were deposited, and some of the dated Late Pleistocene interbedded mud and peat sediments accumulated (~45 ka) in a topographic low west of the sampled palaeosol. From 44 to 39.5 ka (Fig. 10D, E), sea level rose ~14 m producing a transgression of less than 10 km during which time the Late Pleistocene interbedded mud and peat sediments continued to be deposited. After 39.5 ka, sea level fell with a pause near 32 ka and then continued to fall until the LGM lowstand. During this interval, the site was buried and subaerially exposed with no more deposition. During the deglacial interval (18–10 ka), sea level rose and the marine Holocene interbedded sand and mud facies was deposited and then covered by Holocene sand.

Three of these depositional intervals coincided with short pulses of sea-level rise at 42, 56 and 63 ka. One depositional interval coincided with a still stand at 45 ka and another depositional interval within the falling stage from 70 to 74 ka. There are not sufficient data to conclusively identify mechanisms for each case, but previous studies yield some suggestions. Rapid aggradation has been observed many kilometres inland in other coastal-plain alluvial valleys where rivers aggrade rapidly to ‘keep up’ with pulses in sea-level rise (Shen et al. 2012). During MIS 5a, flood-plain aggradation occurred in numerous fluvial systems along the northern Gulf of Mexico (Shen et al. 2015). The study of Anderson et al. (2016) also observed flood-plain aggradation coinciding with rise in local sea level for small- to medium-sized rivers along the northwestern Gulf Coast in Texas during the Late Pleistocene (MIS 5–3). Alternatively, where deposition occurs during stillstands and falling stages, river avulsion driven by regional gradients (Aslan et al. 2005) could produce autogenic burial, which could have been augmented by subsequent regional aggradation. Lastly, the cluster of OSL ages at the start of a relatively short period of sea-level falling (Fig. 10A, B), which was followed by another pulse of sea-level rise ~60 ka, suggests flood-plain aggradation is not a plausible explanation because sea level rose soon after the dated sediments were deposited. If the sediment ages are correct and immediate sediment burial did occur, then another mechanism needs to be invoked. The apparent elevation of the study area above sea level at ~60 ka suggests that delta progradation is not a likely explanation. However, autogenic avulsion driven by local river gradients could also enhance flood-plain sedimentation, as occurs in low-gradient river systems (Aslan et al. 2005; Bentley et al. 2016).

A previous study examined the response of coastal-plain rivers to sea-level change and found that both degradation and aggradation can occur in one river system simultaneously during sea-level falling (Swenson & Muto 2007). Both processes can occur when and where the intrinsic time scale of sediment delivery matches the time scale of sea-level fall. In this case, sediment supply can be sufficient to produce aggradation in the
upper reaches of a catchment for the duration of the sea-level fall, but the seaward part of the catchment experiences degradation (Fig. S6). The rates of sea-level change addressed by that study (<1 mm year⁻¹) are less than rates evident during MIS 4 (rises and falls at rates of 4–5 mm year⁻¹), but the relatively small spatial size of rivers feeding our study area suggests that they should have rapid response times as described by that study. One final consideration is the relative sea-level change in the northern Gulf of Mexico could differ from that of global sea-level reconstructions (e.g., Waelbroeck et al. 2002) or there are alternative age models within our dating uncertainty, in which case the mechanisms for forest burial and preservation remain unknown. Another possibility is rapid sediment accumulation in palaeotopographic lows during massive river overbank floods and avulsions.

This study suggests an approach that can be used to identify other locations where sediments may contain preserved swamp-forest remnants of similar age around the Gulf of Mexico, because other locations may have also been occupied by swamps within topographic lows as sea level dropped exposing the continental shelf during the ice age forming a ‘bathtub ring’ of preserved forests on the new submerged Gulf of Mexico continental shelf. The highest chance of finding additional still buried stumps is to the east and northeast of the stump exposure area where peats are currently preserved in our cores and in troughs of the MAFLA sand sheet. Such locations may contain other well-preserved sediments, wood, and other artifacts, which could provide new insights into glacial–interglacial processes and environmental conditions of continental margins around the world.

Conclusions

This previously buried forest provides a unique opportunity to study the conditions that allowed for stumps, wood, pollen, seeds and other organic materials to be preserved for up to 73 ka in the now marine environment. The forest is located within an area with a palaeotopographic low that provided accommodation space for forest growth and sediment capping to preserve the forest from erosional processes during the last glacial cycle. This uncommon site represents a perplexing palaeotopographic low that provided accommodation for different reasons at varying times. Overall, the fluvial sediment accumulation prevented exposure by channel incision and coastal erosion during the latest Pleistocene regression and Pleistocene–Holocene transgression, thus preserving the tree stumps and woody debris.

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Author contributions. – KLD and GLH conceived, developed the project with AC, and acquired funding for the project, and collected the wood offshore. KLD, SJB, KK, JBO, SG, AC and JTT conducted fieldwork. GLH conducted wood and dendrochronological analysis. GLH and KLD conducted radiocarbon dating. JBO completed OSL analysis. JBO and KK conducted the geophysical surveys and data analysis. SG and SJB completed sediment core analysis. JTT and KLD performed the microfossil analysis in sediment cores with BAM providing seed identification. CAR conducted pollen analysis. All authors participated in preparation of figures drafting, and revising, the manuscript.

Data availability statement. – Core metadata and IGSN are archived at System for Earth Sample Registration (www.geosamples.org/). The core, dating, and marine microfossil data that support the findings of this study are openly available at from the National Centers for Environmental Information - Paleoclimate (www.ncdc.noaa.gov/paleo/study/29932) and Neotoma Paleoecology Database (http://apps.neotomadb.org/Explorer/?datasetid=48885 & http://apps.neotomadb.org/Explorer/?datasetid=48884). The geophysical and geographical information system data that support the findings of this study are available on request from the corresponding author and are not publicly available due to privacy or ethical restrictions to protect the location of the site.

References

Anderson, H. V. 1961: Genesis and paleontology of the Mississippi River mudflats; Part 2. Foraminifera of the mudflats. Lower Mississippi River Delta. Louisiana Geological Survey, Baton Rouge, LA.
Anderson, J. B., Rodriguez, A. B., Abdulah, K. C., Fillon, R. H., Banfield, L. A., McKeown, H. A. & Wellner, J. S. 2004: Late Quaternary stratigraphic evolution of the northern Gulf of Mexico margin: a synthesis. In Anderson, J. B. & Fillon, R. H. (eds.): Late Quaternary Stratigraphic Evolution of the Northern Gulf of Mexico Margin, 1–23. SEPM Special Publication 79, Tulsa. https://doi.org/10.2110/pec.04.79
Anderson, J. B., Wallace, D. J., Simms, A. R., Rodriguez, A. B. & Milliken, K. T. 2014: Variable response of coastal environments of the northwestern Gulf of Mexico to sea-level rise and climate change: Implications for future change. Marine Geology 352, 348–366. https://doi.org/10.1016/j.margeo.2013.12.008
Anderson, J. B., Wallace, D. J., Simms, A. R., Rodriguez, A. B., Weight, R. W. R. & Taha, Z. P. 2016: Recycling sediments between source and sink during a eustatic cycle: systems of Late Quaternary northwestern Gulf of Mexico Basin. Earth-Science Reviews 153, 111–138. https://doi.org/10.1016/j.earscirev.2015.10.014
Aslan, A., Autin, W. J. & Blum, M. D. 2005: Causes of river avulsion: Insights from the Late Holocene avulsion history of the Mississippi River, U.S.A. Journal of Sedimentary Petrology 75, 650–664. https://doi.org/10.2110/jsr.2005.053
Supporting Information

Additional Supporting Information may be found in the online version of this article at http://www.boreas.dk.

Fig. S1. A. The micropalaeontological and $^{14}$C dating sample locations for core 15DF1. B. The bottom of the core (3.0–4.78 m) is magnified to show sampling details and conventional $^{14}$C ages (a BP) (Table 2). The pollen (Reese et al. 2018) and microfossil sampling locations, as well as facies are noted to the right of the core. Seeds were also recovered from the core catcher sample from this core. C. Core comprehensive graph with gamma density, mean grain size, and OC, similar to Fig. 5. Updated from Gonzalez et al. (2017).

Fig. S2. Other sediment core comprehensive graphs with gamma density, mean grain size, and OC (other core graphs in Figs 5, 7, 8, S1).

Fig. S3. Full foraminiferal counts for core 15DF1, similar to Fig. 6.

Fig. S4. Examples of seeds found in sediment core 15DF1 from 4.2 to 4.3 m in the Late Pleistocene mud and peat facies are shown with modern seeds for comparison.

Fig. S5. Stratigraphical cross-section across the study area approximately west to east.

Table S1. Full foraminiferal counts from core 15DF1.

Table S2. Preliminary seed presence analysis in core 15DF1.

Table S3. Foraminiferal genera presence for cores 15DF3B, 16DF7B and 16DF9B.

Data S1. Supporting methods for OSL dating.