Spring 5-3-2023

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Recommended Citation

Lizarraga Garcia, Karla, "NEW INSIGHTS INTO THE PALEOVEGETATION OF THE ANCIENT UNDERWATER FOREST LOCATED IN THE NORTHERN GULF OF MEXICO" (2023). *Master's Theses*. 976.
https://aquila.usm.edu/masters_theses/976

NEW INSIGHTS INTO THE PALEOVEGETATION OF THE ANCIENT UNDERWATER FOREST LOCATED IN THE NORTHERN GULF OF MEXICO

by

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A Thesis
Submitted to the Graduate School,
the College of Arts and Sciences
and the School of Biological, Environmental, and Earth Sciences
at The University of Southern Mississippi
in Partial Fulfillment of the Requirements
for the Degree of Master of Science

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May 2023

Published by the Graduate School

THE UNIVERSITY OF
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ABSTRACT

A well-preserved remnant of an ancient bald cypress forest (hereafter, Underwater Forest) constitutes the only known archive of a glacial refuge on the once exposed continental shelf of the Northern Gulf of Mexico. This forest existed around 41-72 yBP (MIS 3-5) according to the existing dating methods applied on previous studies. As the climate conditions and sea levels changed, the vegetation of this glacial refuge shifted from bald cypress forests to open marshes, altering the vegetation dynamics. The present research analyzed four new cores (21DF-5A, 21DF-5B, 15DF-6, and 16DF-3A), which provided additional insights into the vegetation that once existed in this Late Pleistocene forest. Comparative analysis was conducted on the four analyzed cores with the 15DF-1 and 15DF-3 cores taken previously from the study area, and these shared strong similarities in vegetation composition and transitional patterns. In all cores, high percentages of *Taxodium* were evident, resembling a cypress backwater forest that later transitioned to grass dominant environment with high percentages of Poaceae. Cores 16DF-3A and 15DF-6 contain the no-modern analog cypress-alder communities previously described in 15DF-1. Since the pollen assemblages shared strong similarities, the sediments present in these cores correspond to the same event, and existed either 72,000 yBP according to the OSL dating method, or 41-45,000 yBP as determined by the radiocarbon (^{14}C) technique. Additional dating is necessary to establish an accurate date for the existence and burial of this forest, thus allowing a complete story to be told.

ACKNOWLEDGMENTS

First and foremost, I am extremely grateful to my supervisor Dr. Andy Rese for his invaluable advice, support, and immense patience during this process. My presence in this country and my ability to conduct this research would not have been possible without his help. His extensive knowledge and experience have encouraged me throughout the entirety of my academic journey and daily life. Also, I would like to thank Dr. David Cochran and Dr. George Raber for their support during my master’s program. Their teachings and insight were highly valuable and will remain with me for the rest of my life.

Members of the Underwater Forest project, Drs. Kristine DeLong, Samuel Bentley, Kehui Xu, Andy Reese, Suyapa Gonzalez and Jonathan Troung, thanks for all the help and for making my thesis possible. The work you do is of great importance, and you have allowed me to continue studying paleoenvironments, something I have loved my entire life.

Ms. Gina Barker and Ms. Leah McSorley from USM, you have been incredibly supportive since my first day at USM. Thank you for everything. Keep helping other international students achieve their dreams.

DEDICATION

To my dear uncle Domenico Voltolina, for inspiring my path in science. Your passion and love for work is something that will stay with me for the rest of my life. I'm not even close to being the person that you were, but I hope your prophecy of me surpassing you can become real one day. Ti bacio e ti abbraccio, al cielo.

Grandma Martha, thank you for raising me and making me the brave woman I am today. I hope you keep taking care of me from heaven, or from a more beautiful place.

To Randy, thank you for all the love and emotional support you've provided, you kept me going even during my most difficult times.

"O Mighty Ocean, guide us as we journey through
the darkest pit of night.
May time, ever fleeting, forgive us;
we, who have forsaken our song
and buried our future."

Baten Kaitos: Eternal Wings and the Lost Ocean (2003)

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LIST OF ABBREVIATIONS

MIS	Marine Isotope Stage(s)
ka BP	Kilo *annum* (a thousand years) Before Present
yBP	Years Before Present
cal yBP	Calibrated years Before Present
LGM	Last Glacial Maximum
MAFLA	Mississippi-Alabama-Florida (sand sheet)
OSL	Optically Stimulated Luminescence
^{14}C	Carbon-14 or radiocarbon
KOH	Potassium hydroxide
HF	Hydrofluoric acid
$\mathrm{SO_2}$	Sulfur dioxide
LPIMP	Late Pleistocene interbedded mud and peat

CHAPTER I - INTRODUCTION

1.1 Background: The Underwater Forest

Fossil pollen grains archived in terrestrial sediments have been widely used to reconstruct paleoclimatic conditions for late-Quaternary eastern North America (Webb *et al.* 1998). These grains are a useful proxy that can provide an accurate reconstruction of Quaternary vegetation dynamics, including the past vegetation assemblages during the Last Ice Age in the Southeastern United States (Sadori *et al.* 2016; Prentice, 1988). Acknowledging these dynamics is fundamental to understanding the plant's biotic response to changing climatic conditions and vegetational stability through space and time (Delcourt and Delcourt, 1983; Watts, 1973).

As a result of climate change during the Wisconsin glaciation, vegetation in the Southeastern United States underwent dramatic changes. During this period, global sea levels drastically fell below the present (Blum *et al.* 2008), exposing most of the continental shelf in the Northern Gulf of Mexico and allowing terrestrial ecosystems to become established (DeLong *et al*. 2020). Moreover, the retreat of the Laurentide Ice Sheet opened up new land in the northern United States (Watts, 1979), and allowed plant communities to change and migrate to other areas, which transformed the forest assemblages.

After these events, the composition of terrestrial plant communities became stable. Following the end of the Last Glacial Maximum, the Holocene vegetation of the Gulf Coastal Plain has been in dynamic equilibrium, subjected to minor changes in the relative abundances of species (Braun, 1974; Watts, 1975; Watts and Stuiver, 1980; Delcourt and Delcourt, 1983).

Aside from the studies previously mentioned, the vegetation dynamics prior to the Last Glacial Maximum period in the Southeastern United States, is a topic poorly documented. Even less is known about the vegetation of the continental shelf in the present-day Gulf of Mexico that would have been exposed during the last glacial period due to lower sea levels. To date, there are no known studies from the previously exposed continental plain, or glacial refugia.

The well-preserved remnants of an ancient bald cypress (*Taxodium distichum*) forest (hereafter, Underwater Forest), still rooted in terrestrial soil, located off-shore Gulf Shores (Alabama) represents a unique environment, being the only known example of a preserved glacial refuge on the once exposed continental shelf during the Last Ice Age. This buried bald cypress forest was discovered in 2012 by a group of divers at approximately 18 m of water depth (Reese *et al.* 2018).

It is speculated that these sediments became exposed due to seabed erosion caused by Hurricane Ivan in 2004, which passed within 10 km of the site (Gonzalez-Rodriguez, 2018) (Figure 1.1). The majority of the exposed cypress stumps are located along northwest-southeast trending troughs with 2–5 m vertical relief (DeLong *et al.* 2020) (Figure 1.2).

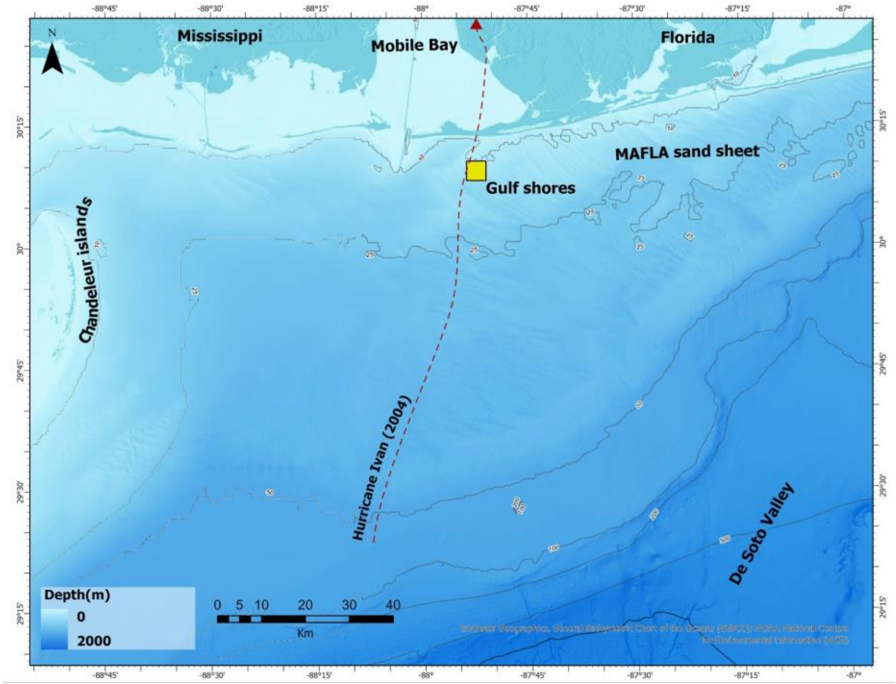


Figure 1.1. Northern Gulf continental shelf and study site location.

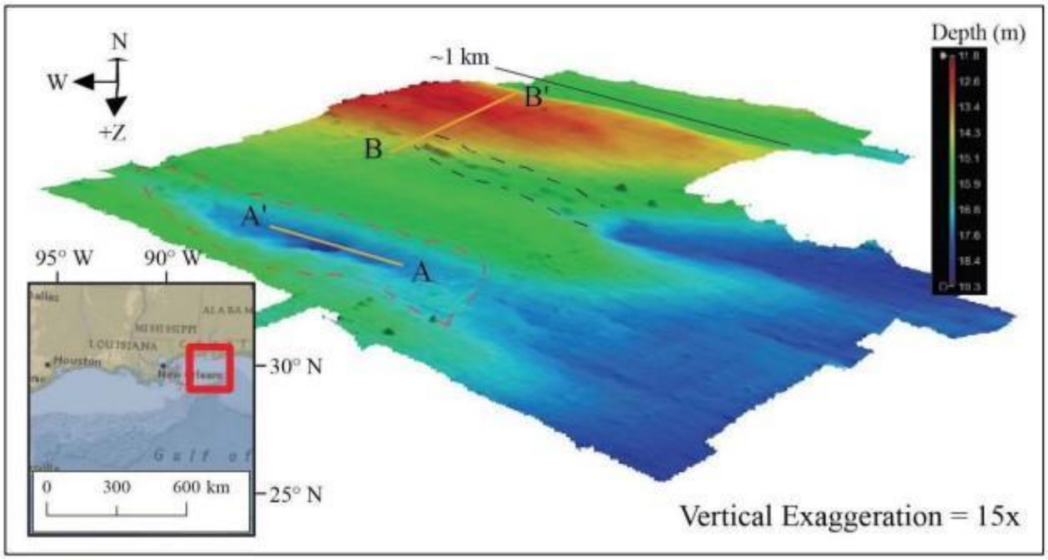


Figure 1.2. Bathymetric chart of the study site.A'-A transect outlines the depression where tree stumps are exposed (DeLong *et al*. 2020).

The continental shelf where the site is located was dry land approximately ~60-70 kaBP ago during the Late Pleistocene. While exposed, this area was likely a bald cypress/black tupelo (*Nyssa aquatica*) swamp until its burial (Reese *et al.* 2018). The high preservation of the sediments indicates a rapid burial, but the exact mechanism and timing are still unknown.

After its discovery, fieldwork was conducted on the site on board the R/V Coastal Profiler (LSU Coastal Studies Institute) between August 2015 and July 2016 for geophysical surveying and sediment sampling purposes. Aided by the survey data, a submersible vibracoring system operated on the seafloor at depths ranging from 14 m to 18 m and retrieved a total of eighteen sediment cores. Only two cores from the 2015 expedition contained sufficient sections with carbonate material for radiocarbon dating (15DF-1 and 15DF-3A), while a single core from 2016 was dated using optically-stimulated luminescence method (OSL) (16DF-3A) (DeLong *et al*. 2020).

The samples taken from the peat section of core 15DF-1 revealed dates between ~41,830-45,210 cal yBP corresponding to the Marine Isotope Stages 3-4 (MIS 3-4). Six of these samples came back radiocarbon 'dead' possibly due to the radiocarbon reliable detection limits (Gonzalez *et al*. 2017; Reese *et al*. 2018). In contrast, core 16DF-3A which was dated using the OSL method, revealed an age of ~72,000±8 yBP, but was considered to have large errors (±8000 years) that span 32,000 years when considering the 95% confidence interval (Gonzalez *et al*. 2021).

Additional dating is needed to provide an accurate date of this forest, but pollen analysis can provide useful data to inform about the past vegetation assemblages and thus, infer in time. The two descriptions of the paleovegetation of this area are based on earlier pollen analyses on core 15DF-1 (Reese *et al.* 2018) and 15DF3-B (Garretson, 2022), suggesting that this forest was originally composed of bald cypress (*Taxodium*), tupelo (*Nyssa*) in a back swamp area (DeLong *et al.* 2017). At the end of the exposure, the vegetation changed to mostly grasses (Poaceae) and sedges (Cyperaceae) (Reese *et al.* 2018).

These previous researchers have interpreted this as a change from the initial cypress and tupelo backwater forest to a more open marsh. During this transition, there is also evidence of a non-modern analog cypress and alder (*Alnus*) community. Though the dynamics of this community are not fully understood, this may be a key piece of information that helps us understand the burial of the site.

However, additional research is needed to better understand the vegetation dynamics of the site (Reese *et al.* 2018). This thesis presents the pollen results from 4 additional cores retrieved from the Underwater Forest. New cores obtained from the site in 2021 will be analyzed to amplify the current knowledge about the paleovegetation of this buried forest, along with two retrieved in 2015 and 2016; cores 21DF-5A, 21DF-5B, 15DF-6 and 16DF-3A. Furthermore, these results will be compared to the existent pollen data obtained from core 15DF-1 (Reese *et al.* 2018), as well as core 15DF-3B (Garretson, 2022).

Aside from providing new vegetation assemblages, I intend to emphasize the importance of these vegetational patterns to infer about the past climatic conditions and sea level variations in this glacial refuge of the southern United States. Moreover, I will address the dating inconsistencies and vegetation assemblage differences between these cores. To achieve my objectives, I will test the following hypotheses:

1. Despite the discrepancies in dates between 15DF-1 (~41,830- 45,210 cal yBP) and 16DF-3A (~72,000±8 yBP OSL), and considering the unknown dates for 15DF-6, 21DF-5A and 21DF-5B, all these cores will display similar pollen assemblages and concentrations.

2. The non-analog *Cypress*-*Alnus* community that was present in previous studies (Reese *et al.* 2018), will also be present in the pollen assemblages from the new cores.

3. The consistency of the *Cypress*-*Alnus* community across the cores will rule out the possibility that the appearance of this assemblage is a result of bioturbation or disturbance, and is an actual representative of a paleovegetation community.

CHAPTER II– LITERATURE REVIEW

2.1 Overview

The analysis of pollen is a common method used to investigate paleovegetation and past environments since pollen is widely dispersed in the environment as part of the plant reproductive cycle. One of the advantages of this technique is that the grains are usually well-preserved in lakes and bogs, where a progressive accumulation of sediment over time is common. This allows the extraction of core sediments that reflect pollen assemblages and, therefore, observe changes in vegetation over time (Bunting *et al.* 2013).

Observing these changes can be possible because pollen is enclosed within a complex outer membrane, considered by some as the most complicated wall of all plant cells (Wang *et al.* 2018). Sporopollenin is a highly resistant biopolymer composed of aliphatic acids, phenolics and aromatics. In addition, this substance is more resistant to degradation than most other compounds. It can be found well preserved in soils and sediments and is stable in organic solvents, as well as insoluble in acids (Piffanelli *et al.* 1998; Khandekar *et al.* 2020).

Despite the high resistance of this component, pollen grains are not exempt from degradation and corrosion due to numerous causes, such as microbial attack, high temperature, chemical oxidation and mechanical forces (Havinga, 1967). Among these factors, microbial attack is the most common cause of pollen degradation occurring where the pH and oxygen pressure are sufficiently high, which is the case in fertile soils with high microbial activity. Oxidation also plays a vital role in degradation since grains that are long exposed to the air (well-aerated environments) are subjected to rapid oxidation and thinning of the pollen wall, which will subsequently be decayed by microbial activity (Havinga, 1964; Cushing, 1967). Among the mechanical forces, freeze-thaw and wet-dry cycles in the environment can also degrade grains by causing crumpling, thinning, and distortion of the exine. Freeze-thaw processes form intracellular ice crystals and rapidly remove water from cells, which can denature proteins and tear the cell wall affecting identification (Holloway, 1989; Beaudoin amd Vinebrooke, 2015).

Another important characteristic that contributes to preservation is sediment stratigraphy. A good example of this is observed in lake basins, where grains are evenly mixed in the water column before reaching the bottom and being embedded in the sediment; this allows the pollen assemblages to be consistent for a particular time. However, reworking and redeposition of grains can often occur as a consequence of water and wind movements (Xu *et al.* 2016; Sun and Wu, 1987).

For these reasons, grains accumulated in peat and lake sediments under a steady anoxic environment and uninterrupted sediment stratigraphies, are often preferred for pollen analyses since they are expected to provide a continuous and undisturbed pollen record (Cheddadi *et al.* 1991), which will aid in providing information about vegetational history.

Since vegetation composition is strongly correlated with environmental parameters, fossil pollen grains can also inform about paleoclimatic conditions, including the climatic history of the Last Glacial period (Kramer *et al*. 2010). As long as grains are preserved under the previously mentioned conditions, sediments can accumulate undisturbed by the glacial advances and interglacial processes that are often problematic for stratigraphic preservation, and can provide an opportunity to analyze shifts in vegetation assemblages over many glacial-interglacial cycles (Tzedakis, 1994).

During the Late Pleistocene, the Northern Gulf of Mexico's continental shelf became exposed as sea levels dropped as a result of the continental ice sheet contraction and expansion (Fernandez-Iriarte *et al.* 2020). Sea levels fell approximately 120 meters during this period, allowing a terrestrial ecosystem to establish itself on the exposed land. These areas served as glacial refuges for cold-temperate species that migrated to less ice-impacted and non-glaciated areas, altering their geographic distribution of species (Fisk, 1960; DeLong *et al.* 2020; Provan and Bennet, 2008; Hewitt, 1999).

Nonetheless, the paleoecological characteristics of this exposed continental shelf have not yet been studied extensively. Despite the lack of knowledge in geomorphology, glacial age sediments, climatic and environmental conditions that occurred in the Gulf region, the preservation of terrestrial sediments in the Underwater forest represents a rarity in this setting (DeLong *et al.* 2020).

The wood contained in the terrestrial sediments of this site survived the bacteria, fungi and wood-boring organisms common in marine and aerobic environments, which can accelerate the decomposition of wood (DeLong *et al.* 2020). The fact that these sediments have excellent preservation makes this offshore site an excellent opportunity to aid in reconstructing the glacial paleoenvironmental conditions in the Northern Gulf.

2.2 The origins of Palynology: a method to reconstruct the history of vegetation

Dramatic changes in climate and vegetation have occurred since the beginning of the Quaternary Period (~2.6m years before the present). The emergence of glaciers, followed by their expansion and retreat, and the following interglacial period with drastic temperature oscillations have caused constant fluctuations in Earth’s vegetation. It is crucial to understand how vegetation has changed over time, not only to understand evolutionary changes in plants and their adaptation to the environment, but also to understand geological and atmospheric changes over time. Palynology allows us to study these changes through the analysis of pollen grains (Davis, 1969).

The history of this science can be traced to the late 16th century with the invention of the first microscopes and the first examination of pollen morphology by Nehemiah Grew and Marcello Malpighi (Ducker and Knox, 1985). Although these first examinations were significant, early microscopes only allowed the discovery of outer coats in pollen grains. Further descriptions were not achieved until the end of the 18th century with the research of Francis Bauer (1790), which provided very accurate and descriptive drawings of pollen grains (Manten, 1966).

The 19th century can be distinguished as one of the most symbolic periods for the improvement of pollen research. With Lindley (1830) establishing an appropriate classification of orchidaceous plants, Fritzsche (1833) and Von Mohl (1834) making major contributions to biology and physiology, the study of pollen grains became increasingly linked to two of the most important disciplines of the time, geology and paleontology. A connection between this science and other disciplines may have been possible because of the work of geologist William Smith (1769-1839), who intensified studies of stratigraphy and recognized the value of fossils for stratigraphic studies (Manten, 1966; Laudan, 1976).

Shortly after, pollen grains became a regular stratigraphic tool for the reconstruction of Quaternary vegetation. As early as 1841, pollen grains were already analyzed to describe stratigraphic successions from the Last Glacial period. By analyzing the peat-bogs from Denmark, Johannes Steenstrup (1842) distinguished four different forest types (*Pinus*, *Quercus*, *Populus* and *Alnus*) and argued that the changes in the assemblages were attributed to the gradual improvement of climatic conditions (Rowley-Conwy, 2004; Manten, 1966).

Similar to the previous study, Trybom (1888) examined Quaternary lake deposits in Sweden in which he found fossilized pollen grains of pines (*Pinus*) and spruce (*Picea*) trees, providing information about the floristic communities in Scandinavia during the Last Glacial Period (Manten, 1966). Nonetheless, the full potential of Quaternary palynology was not reached until the beginning of the 20th century.

In 1916, Lennart von Post established the solid basis for palynology as a scientific discipline with his work “Forest tree pollen in south Swedish peat bog deposits.” In this publication, von Post counted arboreal pollen grains and presented his results in pollen diagrams, arranging the samples' depths along the vertical axis and displaying the pollen percentages along the horizontal axis. The diagrams also reflected the variations in the abundance of a particular taxon during peat formation (De Klerk, 2017; Manten, 1966; Terasmae, 1970). By incorporating these concepts and new methods into pollen analysis, palynology developed into a mature science that flourished during the following century (De Klerk, 2017).

Later in 1935-1940, the glacial and post-glacial pollen assemblages were extensively explored. During a meeting of the Royal Society of London, Baird Simpson conducted a successful pollen analysis of a submerged post-glacial forest located in the Bridge of Earn, Perthshire. Moreover, he discussed the contemporaneity of vegetational changes and questioned if the assemblages were possibly affected by the ice retreat (Simpson, 1935; Seward *et al.* 1935; Edwards, 2018).

Although these ideas were not further discussed by Simpson (Sissons *et al*. 1966), an important observation was suggested by Firbas (1935), stating that vegetation would have existed simultaneously at different places depending on the geographical distance to the ice cap, assuming that the retreat of the land ice allowed vegetation to succeed. To support this idea, Firbas observed the percentages of herbaceous pollen grains, particularly grasses and sedges (Poaceae and Cyperaceae), suggesting that the minor occurrences of these plants indicated a forest-less ice surrounded territory (Manten, 1966; Firbas, 1935).

Almost one decade later, specifically in 1944, the term Palynology was established by Hyde and Williams (1944) and further developed by Gunnar Erdtman (1950), promoting this science as a tool to study Quaternary vegetation and paleoclimates. Erdtman was later recognized by Faegri and Iverson (1964) for his interest in expanding palynology. The construction of pollen diagrams, long-distance transportation, differential preservation, analytical identification keys, as well as the classification of fossil pollen grains were part of their contributions expressed in the *Textbook of Modern Pollen Analysis (1964)* (Birks *et al.* 2018).

In recent decades, palynology has also been useful in tracking plant migration over time. Using pollen data from multiple sites, Delcourt and Delcourt (1987) have provided isochrone maps that reflect the migrational history of temperate forests in North America over the last 20,000 years. Without dismissing the life-history characteristics of trees, tracking such migrations over time makes it possible to document the effects of climate change on forest dynamics (Delcourt and Delcourt (1987).

Observing the spatial variations of plants is possible because pollen is efficiently transported in the atmosphere (Bourgeois, 2000). Hence, palynology is also helpful in determining air mass movements in different environments. By analyzing pollen concentrations and the variablity of taxa in particular regions with sparse or no vegetation, it is possible to infer that grains were transported long distances under favorable atmospheric conditions, which involves major movement of air masses (Faegri and Iversen, 1989). These studies can also aid in the reconstruction of palaeoenvironmental records, specifically from arctic lakes and bogs (Burgeois *et al.* 2001).

Beyond being known as a useful tool that aids in the reconstruction of palaeoenvironments, palynology keeps growing and represents an important component of conservation biology, current vegetation modeling, archaeology, future climate change, and population dynamics, among other subjects (Birks *et al.* 2018).

2.3 Palynological Components

Before proceeding, it is essential to discuss how this science works and how it can help us to understand environmental changes. Pollen grains represent the transport unit for male gametes in seed plants, gymnosperms and angiosperms (Halbritter *et al.* 2018) and will serve as genetic material for the female flowers during fertilization. Grains can be transported by animals, aeolian and fluvial processes, from the flower's anther or catkins to the female reproductive parts of a plant (Pacini, 2018).

In plants, pollen production and morphology differ between species, even within the same species, likely due to genetic influences (Vidal *et al.* 2006). For this reason, identifying these grains is challenging because of the morphological differences and the varying amount of pollen produced. In general, anemophilous plants will produce substantially more pollen than zoophilous plants, making their prominence on the landscape difficult to interpret (Faegri, 1966).

Pollen production is also heavily influenced by climate variation. For example, mild climate conditions can increase flower production, but also decrease due to the increasing drought; similarly, pollen production of birch (*Betula*) trees decreases when summer droughts and increased temperatures occur (Emberlin, 1994; Rojo *et al.* 2021).

Furthermore, climate change significantly impacts soil fertility, affecting pollen production and growing conditions. Since pollen development depends completely on the sporophyte (spore-producing phase) for the provisioning of nutrients, the soil conditions under which this one is being developed can influence the amount of pollen produced.

During the stages of pollen development, nitrogen is a major component of all macromolecules in plants, so a deficiency of this element can adversely affect pollen production (Freeman and Vitale, 1985; Vasek et al. 1987; Lau and Stephenson, 1993).

2.4 Pollen sampling and analysis for paleovegetation reconstruction

Pollen grains can be found in almost every environment on Earth. However, sampling and preparation methods vary and depend on the material being studied, for example, if grains are obtained from live pollen, recently dried plant material, or from soils and sediments (Christensen, 1946). Fossil pollen is commonly present in sediments, extracted from the bottoms of ancient lakes, swamps, ice or marine deposits. Generally, the extracted cores containing these sediments are sampled and subjected to laboratory procedures, in which fossil pollen grains are treated for carbonate and organic matter removal before identification (Faegri and Iversen, 1975).

The results of pollen analyses are usually displayed in diagrams, in which the pollen percentages and height of the samples are plotted. These diagrams indirectly reflect the percentages of vegetation that once grew in the region when deposition occurred (Davis, 1963). As previously mentioned in Chapter 2.1, good preservation of the grains is necessary to obtain reliable information regarding the past vegetation assemblages. In some cases, preservation is not always possible since pollen grains are not exempt from the existent disturbances in these environments.

The microbiota present in the habitats (heterotrophic bacteria and fungi) can decompose particulate organic matter, including pollen (Wutzbacher *et al*. 2010). In addition, repeated wet-dry cycles in sediments from arid and semi-arid regions also aid in rapid pollen degradation, resulting in major folding, loss of definition and thinning of the outer grain wall (exine). Moderate exposure to molecular oxygen also accelerates pollen degradation, since it oxidizes the exterior sporopollenin coat (Campbell & Campbell, 1994; Keil *et al*. 1994). Therefore, ideal sampling sites are environments with anoxic conditions isolated from physical and biological disturbances.

Marine ecosystems are regions of high productivity and sedimentation, which are often accompanied by bottom waters with low oxygen content. Pollen grains present in sediment cores obtained from these environments are generally well preserved with little to no signs of degradation since anoxic bottom waters are normally isolated from disturbances in the surface and water column. Grains remain well-preserved for at least 100,000 years under these conditions (Keil *et al*. 1994).

Though the cores involved in the present study were obtained from the ocean, they were part of the once-exposed land. For as yet unknown reasons, these terrestrial sediments preserved in a marine environment survived weathering and erosion caused by sea level changes for more than 40,000 years (Flocks *et al.* 2011; DeLong *et al*. 2020).

2.5 Limitations

Like all sciences, palynology can be potentially affected by several types of limitations related to the analysis of fossil pollen grains, that still need to be addressed (Nieto-Lugilde *et al*. 2021), such as:

1. Since the age of fossil pollen samples needs to be determined, the time of deposition and exact date of the vegetation assemblages are often uncertain. Each dating technique has its own assumptions and limitations (^{14}C, luminescence dating, U/Th), leading to different levels of uncertainty. For example, obtaining reliable ^{14}C ages from pollen grains is possible by applying accelerator mass spectrometry (AMS). This can deal with common problems associated with conventional ^{14}C dating of marine, lake, and peat deposits (Brown *et al*. 1989; Mensing and Southon, 1999; Long *et al*. 1992).

Despite improvements in this method, deficiencies are present when the volume of sediment available is limited (Long *et al.* 1992; Mensing and Southon 1999; Vandergoes, 2003). Other limitations are related to the amount of charcoal present in the sediments. Generally, sites that contain abundant concentrations of charcoal are ideal for radiocarbon dating, since it is one of the most used materials for the AMS method. However, the excessive deposition and redeposition of charcoal from different sources can lead to age overestimations (Rittenour *et al.* 2015).

2. Relying on presence-only data is common when the absence of fossil evidence does not necessarily indicate the absence of such taxon, considering the possibility that the conditions for fossilization might not be present. A variety of factors can lead to uncertainty in the pollen record, including taphonomic processes. Fracturing, compaction,

and corrosion of grains are common taphonomic alterations that can be caused by freeze-thaw and wet-dry cycles, chemical and microbial effects, and the deposition and reworking of sediment. These alterations can be common in acid peats, sapropels, snowfields, and moss cushions. As a result, the state of preservation is affected by changes in the morphology of grains, degradation and progressive destruction of sculptures, ruptures, and corrosion of the exine (Val-Peon et al. 2019; Vasil'chuk, 2005; Delcourt and Delcourt (1980). The degree of destruction partially reflects the degree of exine resistance in a particular taxon. Species with low sporopollenin contents, lack of apertures, and immature grains are more likely to be destroyed, resulting in low taxonomic resolution, thereby reducing the degree of representation of vegetation communities (Goring et al. 2013; Vasil'chuk, 2005)

Preservation is acknowledged to depend on the grain characteristics such as grain size, exine thickness, and sporopollenin concentrations. Pollen grains with high sporopollenin concentrations are usually well-preserved compared to those with low concentrations. Moreover, thin and smooth exines are more vulnerable to damage in comparison to thick exines (Xu *et al.* 2016; Havinga, 1967; Bunting, 2010).

To a certain extent, almost all vegetation assemblages involve preservation issues, since grains are commonly subjected to chemical, mechanical, and biological degradation in the environment. Other than preservation, the absence of taxa in pollen records is also attributed to (1) few or scattered individuals in the region, (2) differences in pollen production between species, and (3) the climate conditions are unfavorable for pollen production (Hicks, 2006).

3. The number of pollen grains does not linearly correlate with the vegetation abundance, considering that pollen diagrams reflect the proportion of the total pollen extracted from the sediment, rather than the amount of pollen deposited at the time (Davis, 1963). This is partly influenced by pollen production and dispersal. Pollen is produced in different amounts depending on the type of plant, and dispersal depends on the morphological characteristics, as well as atmospheric and water circulation.

As an example, pollen that possesses air sacks such as pines (*Pinus*), spruce (*Picea*) and fir (*Abies*) can disperse long distances before deposition and their appearance can blur the presence of local taxon occurrence in the records. Since grains can be dispersed far beyond the normal ranges, their presence cannot be always construed as evidence that the plant was established or grew nearby the site (Bunting *et al*. 2004; Broström *et al*. 2016; Hicks, 2001; Davis, 2000; Xu *et al.* 2016; Davis, 1978).

4. Unfavorable climate conditions can affect pollen production, hence certain taxa may not be reflected in the soil samples. For example, the production and maturation of cones in conifers can be interfered by climatic factors such as relative available moisture (Faegri and Iversen, 1975; Hevly, 1981).

Moreover, climate change may have an adverse effect on pollen preservation due to changes in soil temperature and humidity. Strongly oxidizing or alkaline environments cause severely damage pollen, especially grains that have a low resistance to oxidation due to the characteristics of their exine (Campbell and Campbell, 1994; Xu *et al.* 2016).

5. Potential loss of information in the fossil record can be possible due to deposition and redeposition processes. These processes have been studied in great detail,

especially in lakes, since they are generally characterized by uninterrupted sediment stratigraphies and abundant preserved grains, which makes them a suitable environment for pollen analysis. Additionally, some authors have argued that pollen assemblages in lake sediments are consistent for a particular time, because grains are mixed evenly in the water body before falling on the bottom (Xu et al. 2016; Davis and Brubaker, 1973; Lynch, 1996). However, this is not always the case because lakes are not exempt from reworking and redeposition as a consequence of wind and water movements (Sun and Wu, 1987).

Sediments obtained from these environments can contain a high proportion of soil-derived palynomorphs of considerable age mixed with contemporaneous pollen spectra, which can influence the character of the pollen spectra and determination of pollen zones (Davis, 1984). This will highly depend on the dispersal and transport routes of palynomorphs to lake sediment, as well as the configuration of the basin (Irwin, 1978; Delcourt and Delcourt, 1980).

Loss of information is also related to the level of preservation. Poor preservation and severe deterioration of the pollen grains affect their taxonomic identity, therefore, these grains are classified as “indeterminable” (Delcourt and Delcourt, 1980). In the case of lakes, the configuration of the basin may affect the preservation of grains, and difficult identification.

Usually, the deeper portions of closed basins continuously accumulate homogeneous sediments for long periods of time and contain sedimentary sequences with excellent pollen preservation; this would be the case of lakes with slow and continuous infilling of sloughs and oxbows.

In contrast, pollen grains from river-fed lakes present high levels of deterioration due to mechanical damage and low water levels (e.g., Goshen Springs) (Cushing, 1967; Delcourt and Delcourt, 1978, 1979, 1980).

2.6 Palynology in the Southeastern United States

The first documented palynological study in the southeastern United States was published by I. Lewis and E. Cocke in 1929, in which they described the vegetation history of the Dismal Swamp of Virginia. Following this, Paul B. Sears reconstructed the paleoenvironment of late Holocene climates in different areas of the southeastern U.S. (Sears, 1932; Sears, 1937).

Until then, the use of pollen to reconstruct the Quaternary vegetation history of this particular region was generally restricted to qualitative description and tentative mapping, with no evidence of radiocarbon dating confirming the paleobotanical evidence (Delcourt & Delcourt, 1979). This was further solved by J. Arnold and W. Libby in 1950, with the introduction of radiocarbon dates together with empirical pollen-based data (Fairbridge, 1961).

In subsequent years, studies in Europe were focused on tracing the distribution and composition of deciduous forests during the Quaternary Period, however, evidence of this in the United States was sparse. Paul and Hazel Delcourt's (1979, 1980, 1985) research represent a good example of documented vegetation change in the southeastern part of the U.S., related to the constantly changing climatic conditions during the late Quaternary period.

According to Delcourt and Delcourt (1985) and Watts (1980), the palynological focus in studying past environments in the southeastern United States followed these lines of investigation:

1. Improved understanding of how plant communities respond to climate change. For example, the current vegetation assemblages of the southeastern United States may not have existed in the past due to different climatic conditions.
2. The calibration of fossil and modern pollen production with quantitative vegetation composition, along with climatological data, to derive climate-vegetation transfer functions.
3. As a result of the development of ocean-core studies (late 1970s), evidence for reconstructed interglacial and older Pleistocene floras in the southeastern U.S. can be provided by inference. Climate can be also inferred from pollen analysis of ocean, lake and bog sites.
4. A keen interest in where and how the remarkable biota of the southeast U.S. survived during the Quaternary, particularly in cases where plant communities had very limited ranges.

Reconstructing Quaternary environments remains the focus of palynological research to this day. Recent advances in microbiology and molecular phylogeny have enabled the estimation of ancestral palynological characters and their evolution processes (Wortley *et al.* 2015). Oak-hickory forest dynamics and past diversity were studied in the southeast U.S. using this approach (Liu and Quan, 2020).

Moreover, prediction models and algorithms are developed by considering relevant aspects of reconstruction, including pollen productivity, dispersal, spatial heterogeneity, preservation, and taphonomic modification of the assemblages. Modern pollen vegetation models (PVMs) in the northeast and southeast United States are utilized to estimate vegetation based on pollen counts. These models with calibration-prediction features reproduce fully spatial reconstructions that include individual taxon pollen production and dispersal functions, topographic complexity and proximity of adjacent pollen sources on a regional and continental scale (Trachsel *et al.* 2020).

It is important to note that dating methods are continually improving to provide reliable reconstructions of paleoenvironments. Since its invention, AMS (Accelerator Mass Spectrometry) has been widely used for recording the last ~35,000 years in sediment cores (Brown *et al.* 1989), however, the separation of pollen from other carbon-bearing material and the separation of sufficient pollen for dating have been challenging aspects for this method (Long *et al*. 1992).

A flow cytometry-based method for extracting, purifying, and dating pollen concentrates from widely varying sediments has been developed for the AMS technique, representing an important advance that is capable of successfully addressing analytical uncertainties in this technique, as well as minimizing the time required for producing the cleanest possible pollen extract possible (Tunno *et al.* 2021).

Another dating method known as OSL (Optically Stimulated Luminescence) (previously mentioned in Chapter I), is a tool that estimates the time since the last exposure of sediments to daylight. By using this method, it has been possible to determine the timing of expansion and retreat of the Laurentide Ice sheet in loess-paleosols of the Mississippi and Missouri river valleys during the Late Pleistocene (Khare, 2021; Brown and Forman, 2012; Leigh *et al.* 2004).

IIn addition, it has also been used to date sediments present in 16DF cores taken in the current study area to interpret the site's chronology (Gonzalez *et al*. 2017; Reese *et al.* 2018). It should be noted, however, that this method has some uncertainties due to sunlight exposure received in the cores, which could have influenced the OSL dates (DeLong *et al.* 2020). Yet, this tool offers high-resolution dating and continues to improve despite some of its common challenges, including limited practical applicability, time consumption, and uncertainties regarding overestimations (Stevens *et al.* 2007).

2.7 Paleovegetation in the Southeastern United States

In general, studies about paleovegetation before the Marine Isotope Stage 2 (MIS 2, 29,000 yBP - ~14,000 yBP) are sparse and poorly documented. During the Wisconsin Glacial episode (75,000 yBP-11,000 yBP), the predominant vegetation in the northern areas of the Gulf of Mexico (not including the exposed continental shelf) was composed of jack pine (*Pinus banksiana*) and red pine (*P. resinosa*); while oak (*Quercus*), hickory (*Carya*) and magnolia trees were present along the G.O.M's shores (Bonnicksen, 2000)

Spruce forests (*Picea*), pines, and firs (*Abies*) were dominant in the East along the Mississippi Valley reaching into Louisiana. Above the lower reaches of the Mississippi River, trees like oak, hickory, beech (*Fagus*) and walnut (*Juglans*) bordered the spruce forest, while black tupelo (*Nyssa*) and yew (*Taxus*) had a restricted distribution at the eastern part of the river (Royal *et al.* 1991; Martin and Harrell, 1957).

The most thorough description of the vegetation distribution during the past 20,000 years has been documented by Delcourt and Delcourt (1987). In their research, paleoecological evidence from 162 pollen sites described the response of temperate forest ecosystems to the Late Pleistocene and Holocene environmental changes. These ecosystems included forests mainly composed of *Picea*, *Pinus*, Populus, *Fraxinus*, *Quercus* and *Carya*, along with their distributional ranges at different time intervals (20, 16, 12, 8, 4 ka BP and 500 yr BP) (Delcourt and Delcourt, 1987).

As an example, during the Last Glacial Maximum (circa 20,000 yBP) the Atlantic Coastal Plain was surrounded by mostly northern pines (*Diploxylon* and

Haploxylon Pinus) which constituted more than 60% of the forest composition; while on the west of the Mississippi Valley, their dominance was lower than 20% (Figure 2.3).

Between 16.5 ka BP and 12.5 ka BP, warming continued and began to melt the Laurentide ice sheet, exposing new land in the north. This warming event maintained the dominance of southern *Pinus* between 20 and 40% in the southern Coastal Plain of Florida, Georgia and South Carolina, however, these populations began to advance northeastward along the Atlantic Coastal Plain and southern New England (Delcourt and Delcourt, 1987 By the end of the late-glacial interval (12 ka BP), the dominant northern pines which had almost completely vacated the Atlantic Coastal Plain, now constituted less than 20% of the forest composition.

Following the postglacial retreat of the Laurentide Ice Sheet during the mid-Holocene interval (8 to 4 ka BP), the southern pines, which spent the glacial period on the exposed continental shelf, kept advancing northward along the Atlantic and Gulf Coastal Plain, while northern pines extended from central Ontario northwestward across Manitoba, botch reaching between 40% and 60% of the forest composition in these areas. By the end of the glacial period (500 ka BP) the southern pines expanded to the west of the Mississippi Alluvial Valley and increased the area of major dominance in most of the Gulf Coastal Plain (>60%).

Aided by this research, Delcourt and Delcourt (1987) demonstrate that southeastern forest species responded to late Pleistocene and Holocene environmental changes. Forest composition and location adjusted to the warming trend that followed the glacial maximum at the end of the Pleistocene. Each taxa migrate differently as a reflection of their species' characteristics, competitive abilities, barriers and environmental tolerances.

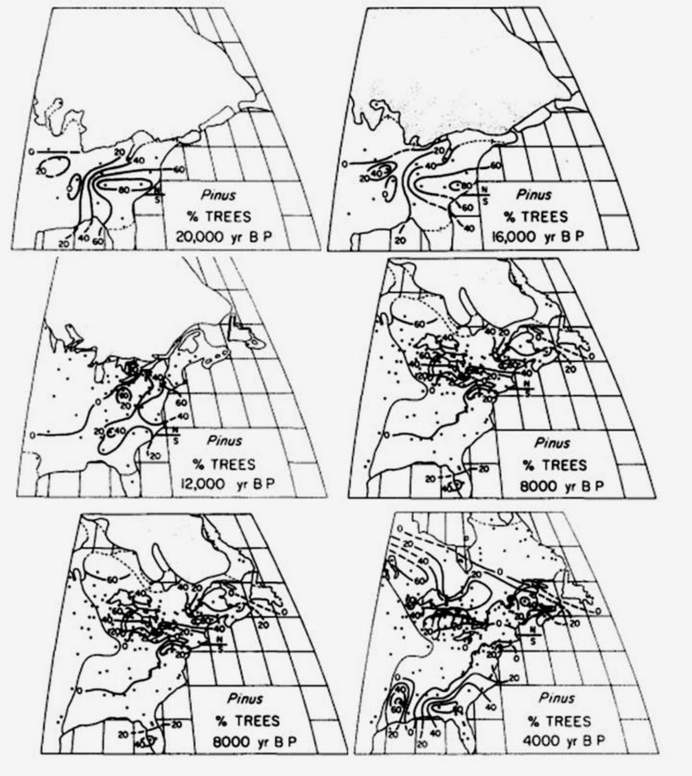


Figure 2.1. *Paleo-dominance maps of Pinus reconstructed for 20ka, 16ka, 8ka, and 4 kaBP* (Delcourt and Delcourt, 1987).

2.8 Drowned forests around the world

Cases involving terrestrial forest sediments that have been preserved in the offshore environment have been documented in several places around the world. In prehistoric times there was a land corridor linking mainland Europe with the British Isles, specifically between present-day Britain and Denmark. The Doggerland forest remains below the seabed surface covered by more than 100m of sediments, and to this day its age remains uncertain. Nevertheless, a sediment core recovered to 13 m below the present seafloor revealed that the youngest transition from the glacio-lacustrine to marine sediments was dated to ~14,000 cal BP, corresponding to the Older Dryas event (Glørstad *et al.* 2017).

The same area was later investigated by Fjeldskaar and Bondevik (2020) for paleovegetation purposes. A new core taken from this forest revealed a date of 27,000-23,000 yBP. Scots pine *(P. sylvestris*) and hazel trees (*C. avellana*) dominated the deciduous woodland, along with minor components including elm (*Ulmus*), wild grasses (Poaceae, *Sparganium*) and sedges (Cyperaceae). Sediment analysis determined that the channel aggradation occurred around 8-10 kaBP, indicating the direct effect of sea level rise during the Early-Mid Holocene transgression due to the postglacial rebound (Gearey *et al.* 2017; Fjeldskaar and Bondevik, 2020).

Borth-Ynyslas in Wales is another forest site drowned by rapid Holocene sea level rise. The sediment samples collected from a core at this site indicated a date of about 4,500 years BP; pollen analysis of the 40cm peat section indicated an initial dominance of alder (*Alnus*) followed by a phase of birch (*Betula*); in the uppermost section, both *Alnus* and *Betula* are dominant as well as *Pinus*. As a result of marine transgression, this forest was buried in less than 50 years in an environment clearly post-Boreal and preceded by the Younger Dryas (Heyworth, 1978; Kavanagh and Bates, 2019; Godwin and Newton, 1938; Clapham, 1999).

Other underwater forests have been found in Europe and Asia such as the ones buried beneath the lakes Bezid (Romania), Periyar (India), Kaindy (Kazakhstan), Kampong Phluk (Cambodia) and Volta (Ghana). A few others are located in the United States like Clear Lake (Oregon), Lake Huron (Michigan) and Caddo (Texas), however, the underwater forest discussed in this thesis represents the only example of a glacial forest that was once-exposed in the Gulf of Mexico.

CHAPTER III– STUDY AREA

3.1 Location

The well-preserved remnants of a bald cypress forest are located roughly 13 km offshore of Gulf Shores, Alabama, United States. This area encompasses 30,000 m^2 of the Northeastern Gulf of Mexico continental shelf. The cypress stumps are buried at a depth of ~18 m below the present sea level and remain exposed in a trough that is 1.5 m below the ambient sea floor (Gonzalez-Rodriguez, 2018; DeLong *et al*. 2021).

The study site is specifically located within the Mississippi-Alabama-Florida (MAFLA) province of the northern Gulf of Mexico, bounded on the north by the Alabama shoreline, to the west by St. Bernard Shoals in the Mississippi River Delta, and to the southeast by De Soto Canyon (see Figure 3.1). The MAFLA sand sheet exhibits a relief of 5 m and it is thought that its deposition occurred sometime during the Holocene Epoch (McBride *et al*. 1999; DeLong *et al*. 2020). Below this sand sheet lies the Last Glacial Maximum (LGM) lowstand valley which is carved out by the Mobile-Tensaw river system, which originated before the Wisconsinan glaciation (Anderson *et al*. 2004; Bartek *et al*. 2004; Kindinger *et al*. 1994).

From seafloor mapping, a series of locations with buried cypress stumps have been identified (Gonzalez *et al*. 2017). The location of the cores analyzed in this study is found on the bathymetric map in Figure 3.2. The distance between these new analyzed cores varies between 0 and 0.5 km, while the depth ranges between 16.1 and 19.1 m (DeLong *et al*. 2021).

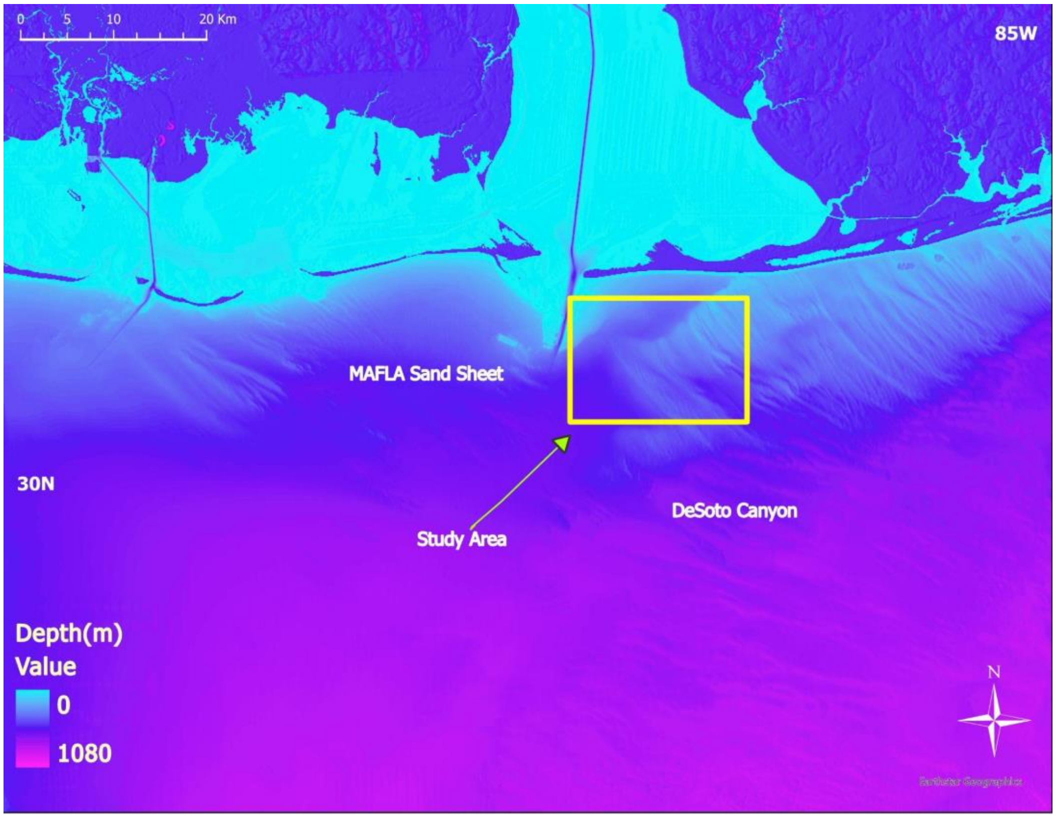


Figure 3.1. Approximate location of the underwater forest (yellow box) in the northern Gulf of Mexico.

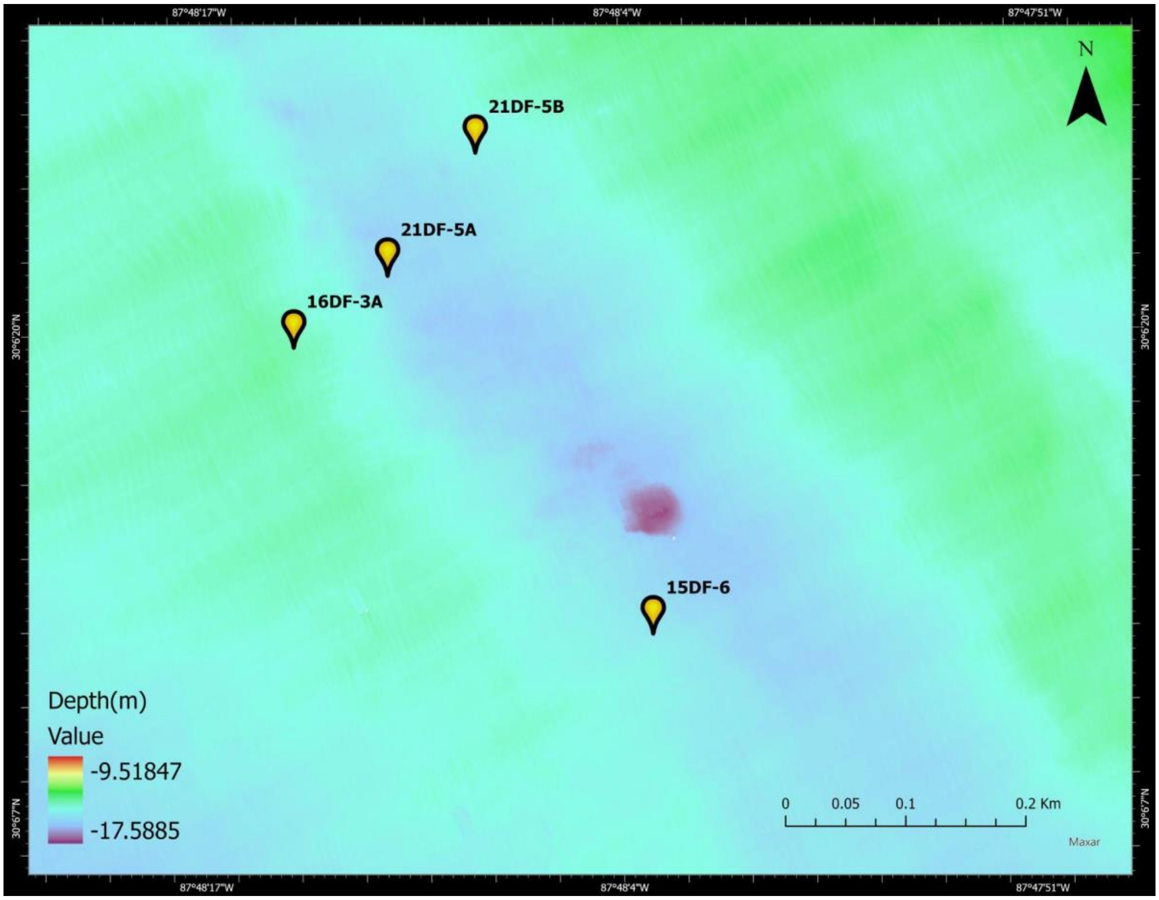


Figure 3.2. Approximate location of the core sites (~13 km offshore Orange Beach, Alabama).

3.2 Geologic settings: The Gulf of Mexico during the Late-Pleistocene

The Optically Stimulated Luminescence (OSL) dating method, applied to the core 16DF-3A, suggested that the underwater forest has a date of ~72,000±8 yBP, corresponding to the Late Pleistocene period during the Marine Isotope Stage (MIS) 4 (Figure 3.3) (Truong, 2018). During this time, the Gulf of Mexico was characterized to have constant changes in sea level driven by glacio-eustatic signals (Figure 3.3), which overall caused a global sea level drop between -100m and -120m below the present level (Waelbroeck *et al.* 2002; Kolla *et al.* 2000).

The Northern Gulf of Mexico, specifically the Lagniappe Delta (which extends east of the Mississippi Delta from mid-shelf to the continental slope) presented an estimated sea level of –30 m and -40 m below present levels during MIS 3 (Kindinger, 1989; Sydow *et al.* 1994). It is speculated that these fluctuations were influenced by the glacial discharge and sediment load in the lower area of Mississippi, which affected the eustatic sea level in the northern Gulf of Mexico (Rittenour *et al.* 2005).

After this period, changes in stratigraphy and sea level during the Pleistocene-Holocene transition (MIS 3-2) for the Mississippi-Alabama-Florida (MAFLA) sand sheet, where the forest was once exposed, remains uncertain. However, global sea level variations during this period oscillated between -80m and -40m below the present level (Figure 3.3) (Waelbroeck *et al.* 2002). Since the beginning of the Holocene, the Gulf of Mexico has experienced a progressive rise in sea level, mainly associated with global sea level changes (Donoghue, 2011). In some specific locations like southern Louisiana, these changes are also influenced by local processes such as subsidence due to sediment loading in the Mississippi River Delta (Törnqvist *et al.* 2004; Törnqvist *et al.* 2008).

Recently, sea level records have shown that for the past century, the Gulf of Mexico has experienced a rise of about 2 mm/year, less high than the Late Pleistocene and early Holocene rates (Donoghue, 2011). This started approximately 6,000 years ago after the rapid sea level rise caused by the Last Glacial Maximum happening during the Marine Isotope Stages 2 (29-14,000 yBP) and MIS 1 (14,000-0 yBP) (Lisiecki & Raymo, 2005). Since that slowdown in sea level rates, which allowed coastal land development in the area, the shoreline position has been relatively stable (Donoghue, 2011).

A rapid sea level rise is expected to have contributed to the burial of this forest around 46,690 – 43,625 yBP, either at the end of Marine Isotope Stage 3 (MIS 3) or at the end of MIS 4 72,000±8 yBP (OSL), when grasses and sedges dominated the forest. However, these dates correspond to two samples from core 15DF-1 (Reese *et al.* 2018) that were successfully dated with the conventional ^{14}C method; six other samples from this core returned radiocarbon ‘dead’, possibly due to the limits of radiocarbon detection. The oldest date of burial (72±8 kaBP) corresponds to the Late Pleistocene interbedded mud and peat (LPIMP) section of core 16DF3A dated with the OSL method (DeLong *et al.* 2020).

Because of its rapid burial, the wood in this forest was preserved in oxygen-free sediments for thousands of years, and its remains are still in excellent condition (DeLong *et al.* 2020).

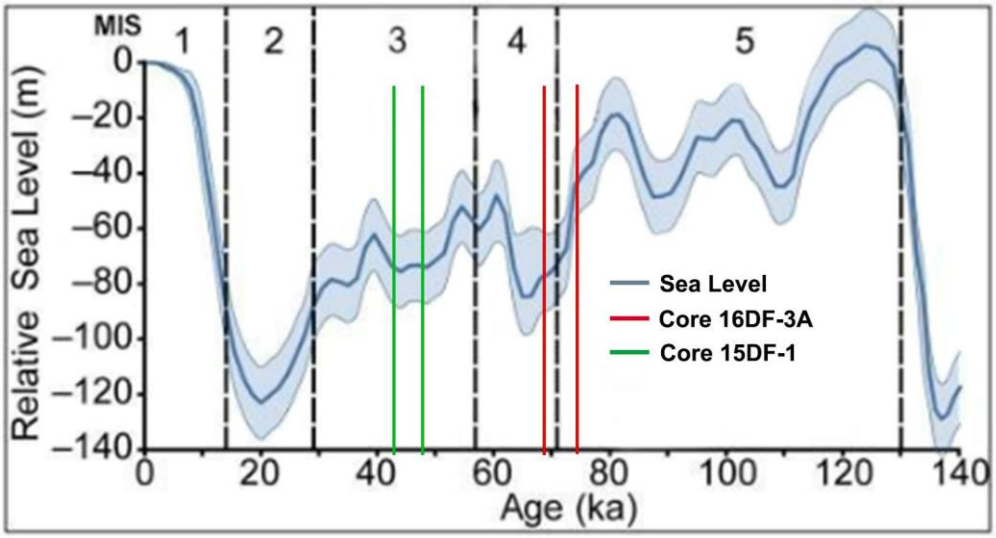


Figure 3.3. Global sea level variations during the last 140,000 years. Cores 16DF-3A and 15DF-1 (Reese *et al.* 2018) time period is denoted in red and green. Blue lines represent the maximum and minimum sea levels from Waelbroeck *et al.* (2002).

3.3 Regional Geology: Sediment description

Information about sedimentation and stratigraphy characteristics of the study site have been obtained from cores retrieved approximately at 18 m depth. These were composed of five different lithofacies, whose characteristics are consistent in all of the cores. From top to bottom, the cores have a first section of light Holocene sand (0-310 cm) containing shell fragments and foraminifera assemblages, consistent with a shallow marine environment (Gonzalez *et al.* 2015). The following section consists of a Holocene interbedded sand/mud layer (310-405 cm), with intervals where mud is more abundant than sand. Marine shell fragments are also common in this facies. Then, a Late Pleistocene interbedded mud/peat section is present (405-478 cm), darker in color than the previous facies. This section is distinguished by visible and thick wood fragments, as well as abundant organic material, where pollen analysis has been performed (Gonzalez, 2017). The next facies is described as Late Pleistocene interbedded sand/mud Late Pleistocene paleosol unit (10-62 and 80 cm), characterized by low organic content readings and no presence of macro or microfossils (Figure 3.4) (Gonzalez-Rodriguez, 2017).

This study's samples analyzed for pollen purposes have the following characteristics. The core 15DF-6 has two sections, the first interval from 0-47cm consists of a Holocene sand layer, and the second one ranges from 47-93 cm with late Pleistocene interbedded mud and peat facies; this last section is characterized by dark gray, tan to dark brown muds, and peats or peaty mud (Fig. 3.5) (DeLong *et al.* 2020).

Core 16DF-3A has three distinctive facies, the first one ranging from 0–62cm with Holocene sand, the second one between 62–177 cm has Holocene interbedded sand and mud layer, and the deepest section 177–220 cm consisting of a late Pleistocene interbedded mud and peat sediment, with a medium-dark gray color and fine-grained sub-bioclastic sand. Additionally, this last layer has the highest water content (20-28%) due to the presence of high organic material and wood debris (Figure 3.6) (Gonzalez, 2017).

Core 21DF-5A consists of one top layer containing well-sorted rounded quartz sand with shell fragments (9-20 cm), a middle layer with rip-up clasts (22-27 cm), and a lowermost section where brown/black clay is present (29-53 cm). Core 21DF-5B has a similar composition, having the uppermost layer composed of quartz sand (12-22 cm), transitioning to muddy sand with some wood fragments (22-35 cm) to reach dark brown clay sediment with larger wood fragments (35-50 cm) (Figure 3.7).

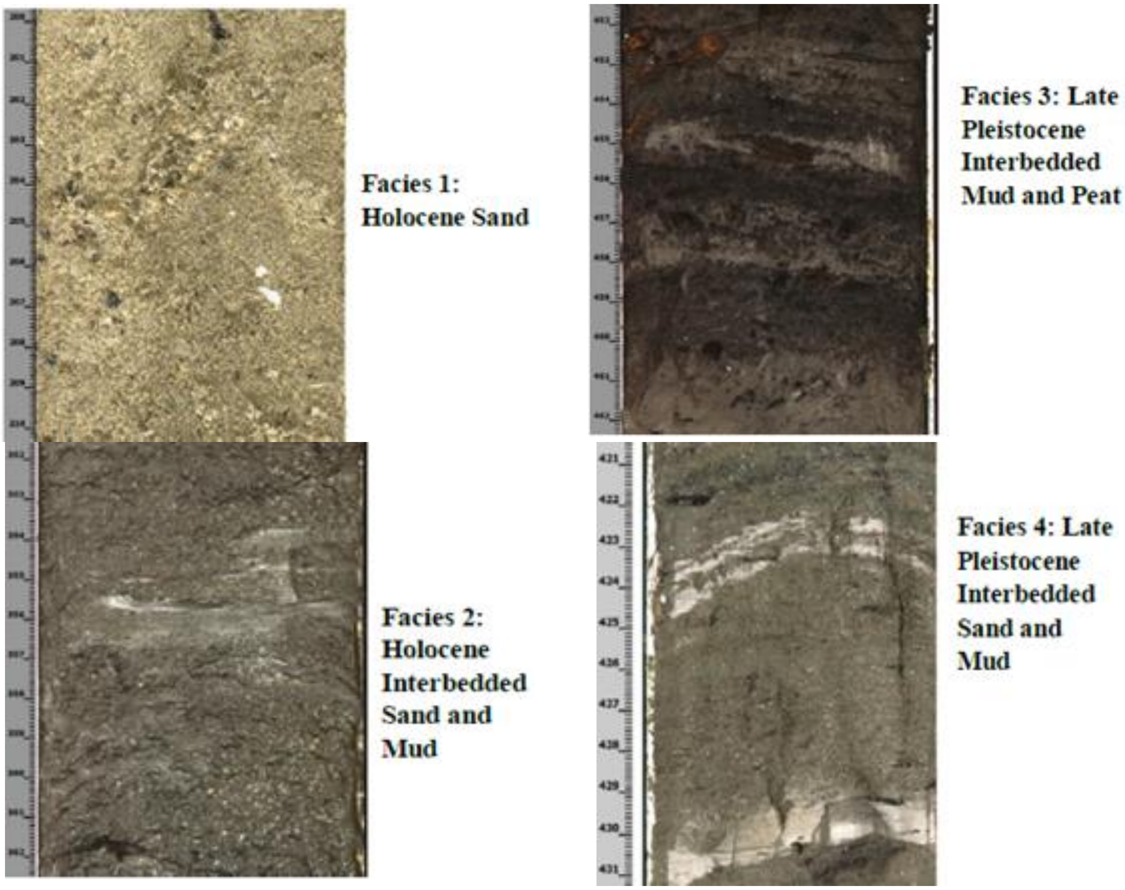


Figure 3.4. High-resolution imagery of the lithofacies found in the study cores.

(Figure adapted from Gonzalez *et al.* 2017).

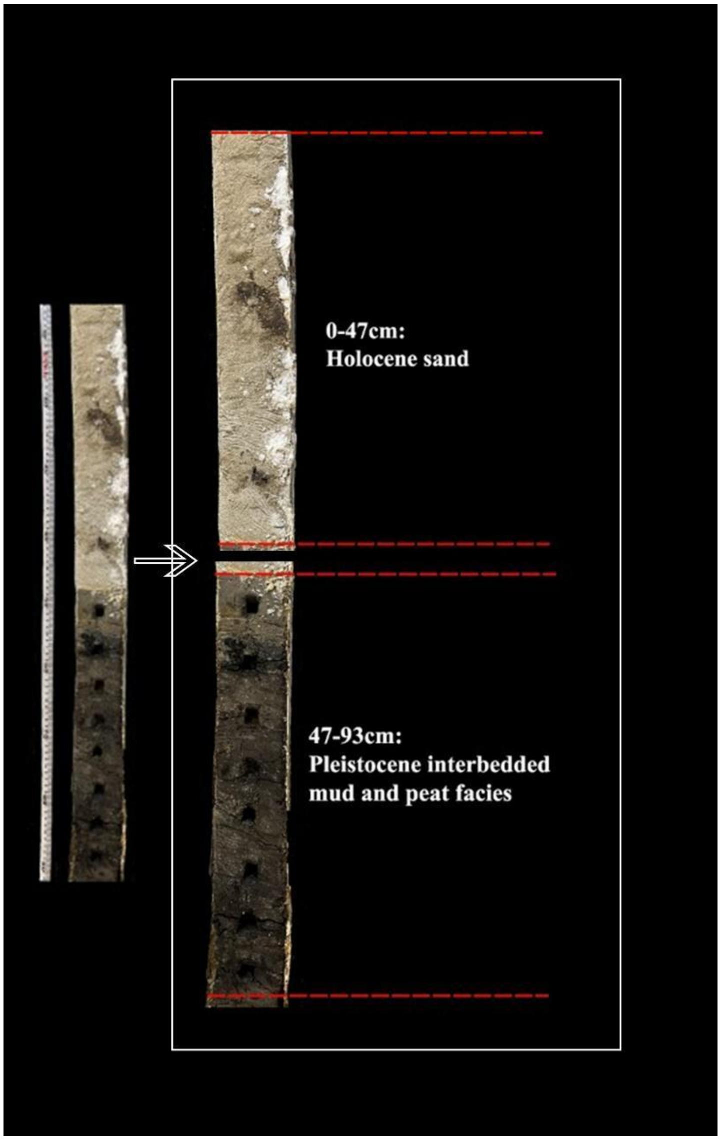


Figure 3.5. Imagery of the lithofacies found in the core 15DF-6.

Figure 3.6. Imagery of the lithofacies found in the core 16DF-3A.

(Figure adapted from DeLong *et al.* 2021).

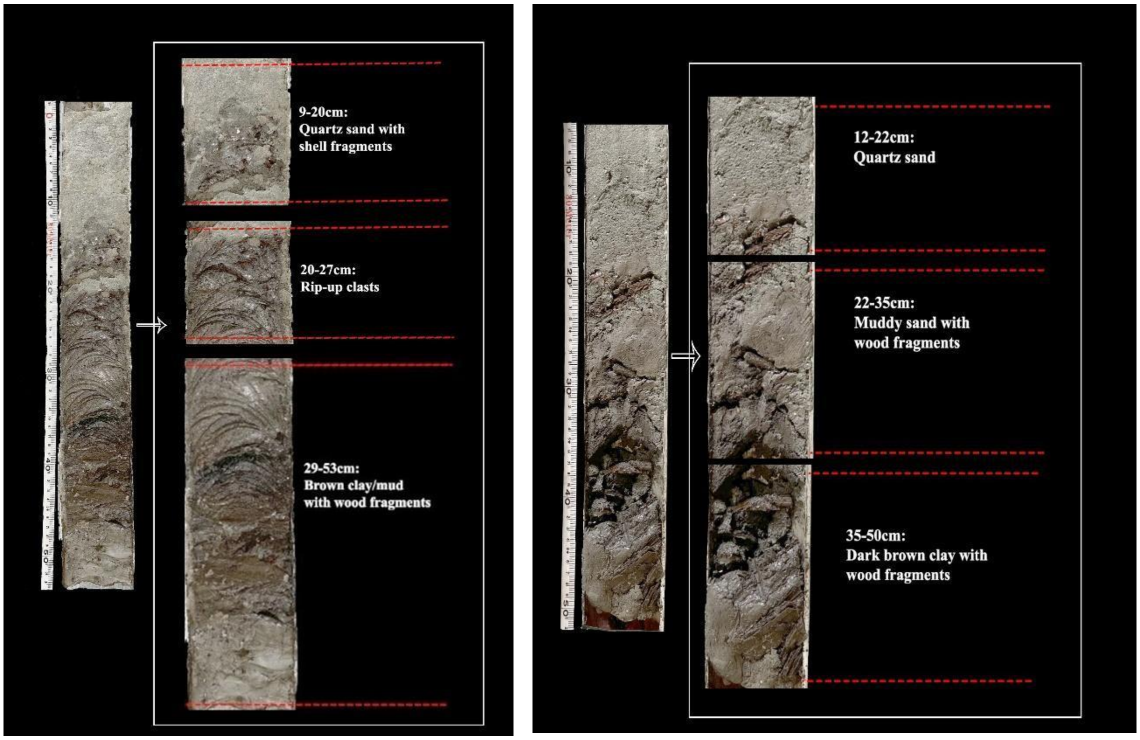


Figure 3.7. Imagery of the lithofacies found in the core 21DF-5A (left) and 21DF-5B (right*)*.

3.4 Vegetation

The sea floor bottom in the study site contains bald cypress stumps (*Taxodium*) that are generally found in floodplain environments at altitudes between 30-50 m (Doyle *et al*. 2015; Little, 1971). According to DeLong *et al.* 2020, global sea levels during the Holocene and Pleistocene fell below the present depth of the study site (~18 m) during the interval from ~115 ka to 82 ka and ~80 ka to 10 ka, therefore, based on the preferred conditions for bald cypress, the possible time frame where this forest may have grown is between 10,000 and 110,000 yBP.

Additional information about the vegetation of this forest has been obtained by analyzing pollen grains from cores retrieved in 2015 (15DF-1 and 15DF-3B) (Figures 3.8 and 3.9). Along with the bald cypresses, tupelo (*Nyssa*) trees and sedges (Cyperaceae) represented this environment, with other minor components such as oak (*Quercus*), hickory (*Carya*), birch (*Betula*), elm (*Ulmus*), ash (*Fraxinus*) and sweetgum (*Liquidambar*). Vegetation assemblages remained in constant change, probably due to the impacts of a marine transgression that occurred in late MIS 3, switching to a different composition of the forest dominated by grasses (Poaceae) and trees like cattail (*Typha*) and alder (*Alnus*) (Reese *et al*. 2018).

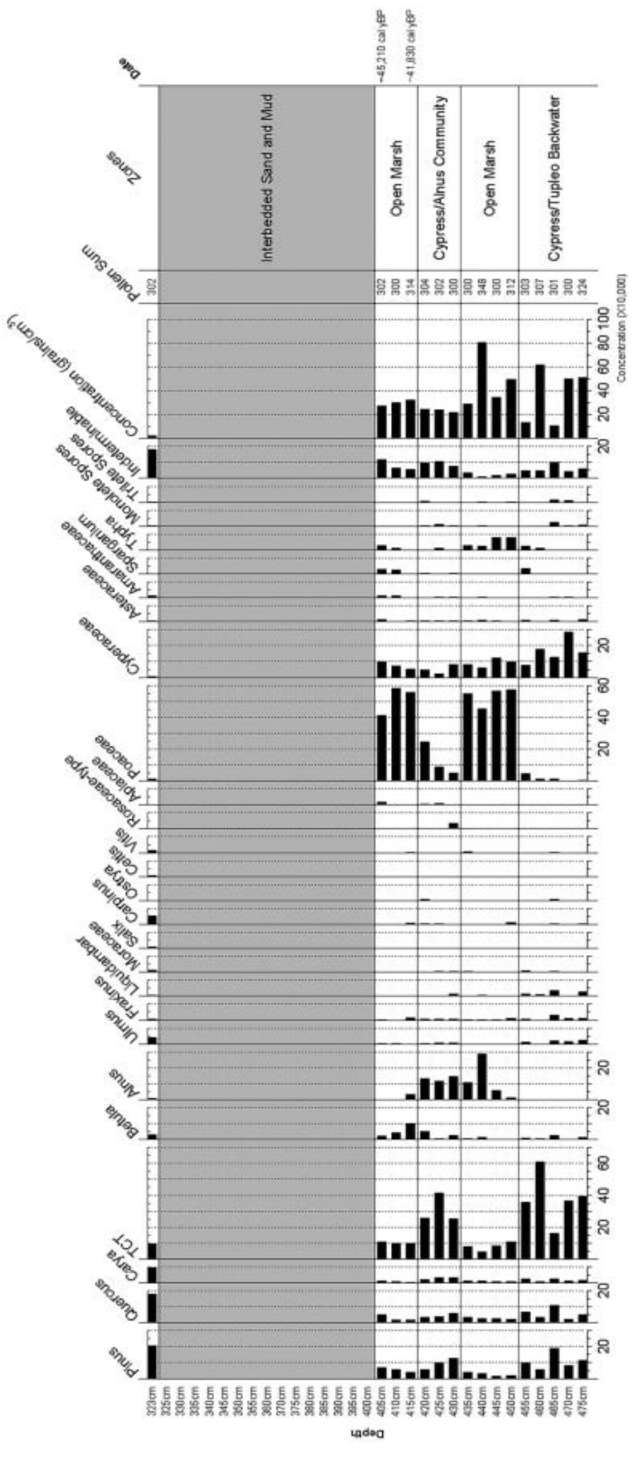


Figure 3.8. Pollen assemblages from the core 15DF1 (Reese et al. 2018).

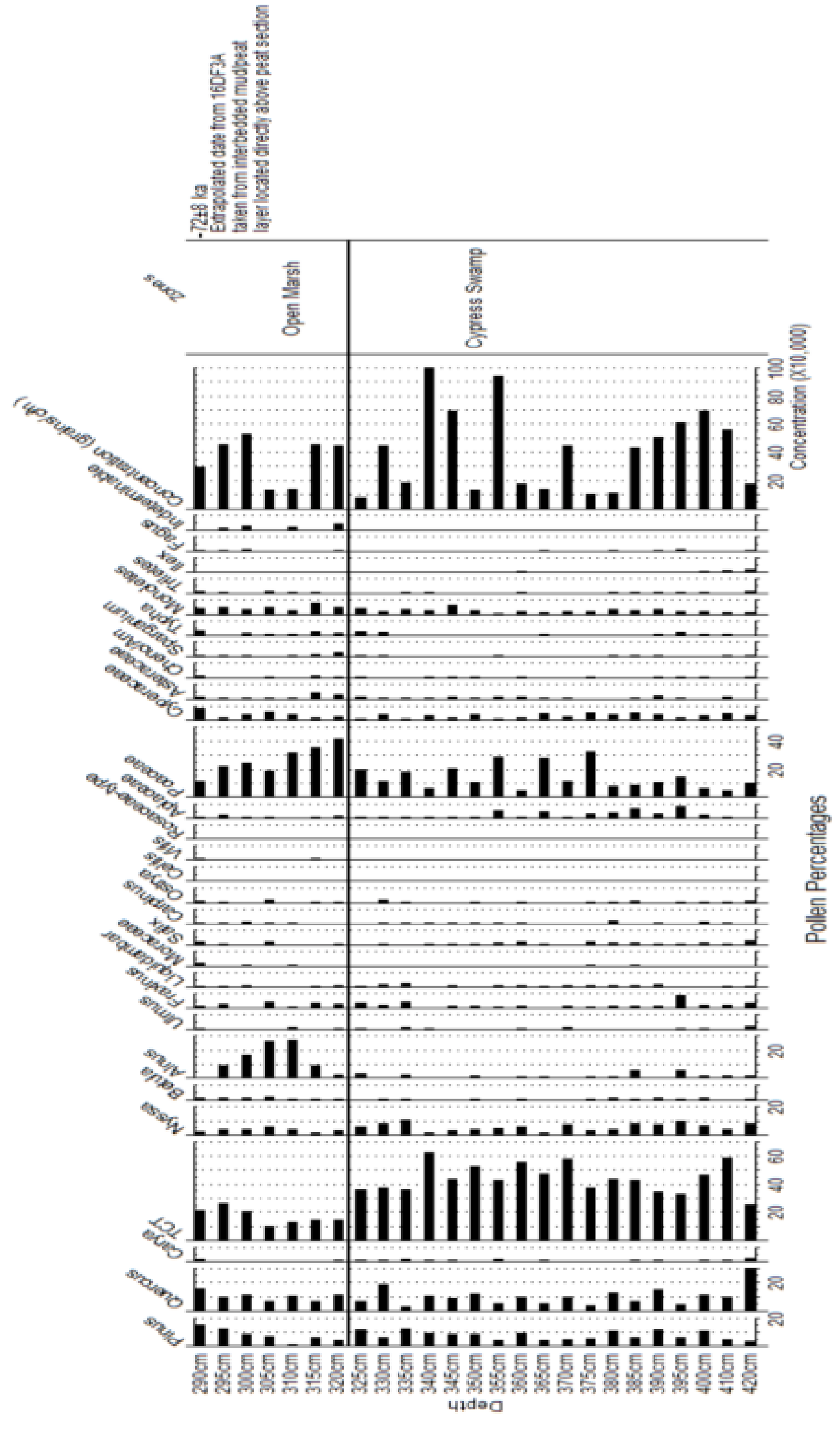


Figure 3.9. Pollen assemblages from the core 15DF-3B (Garretson, 2022).

CHAPTER IV– METHODS

4.1 Fieldwork

From August 2015 to July 2016, eighteen vibracores were retrieved from the study site, including 15DF-3B and 16DF-3A analyzed in this study. These were obtained on board the R/V Coastal Profiler (LSU Coastal Studies Institute) at approximately 15-20 m water depth. To obtain these cores, a 6 m long submersible vibracorer was used, these were cut into 1.5m and stored in a refrigeration room located in the Geography and Anthropology Department at Louisiana State University (Gonzalez, 2017).

Cores 15DF-3B and 16DF-3A were sampled at LSU in October 2020. Samples were collected every 5 cm through all the cores for our pollen analysis, and were retrieved by extracting 1 cm3 of organic mud every 5 cm using a sampling spatula. Each one was labeled according to the core section and placed in sampling bags (Faegri *et al.* 1989). These remain stored in the Biogeography laboratory (WSB 130) at the University of Southern Mississippi (USM).

Recently, cores 21DF-5A and 21DF-5B were recovered from the study site aboard the R/V Point Sur (USM) (Figure 4.1); these remain stored in the Geography and Anthropology Department (LSU). Samples from these cores were taken on April 15th, 2022 and transferred to the Biogeography laboratory at the USM, applying the methodology mentioned above for cores 15DF-3B and 15DF-3A.

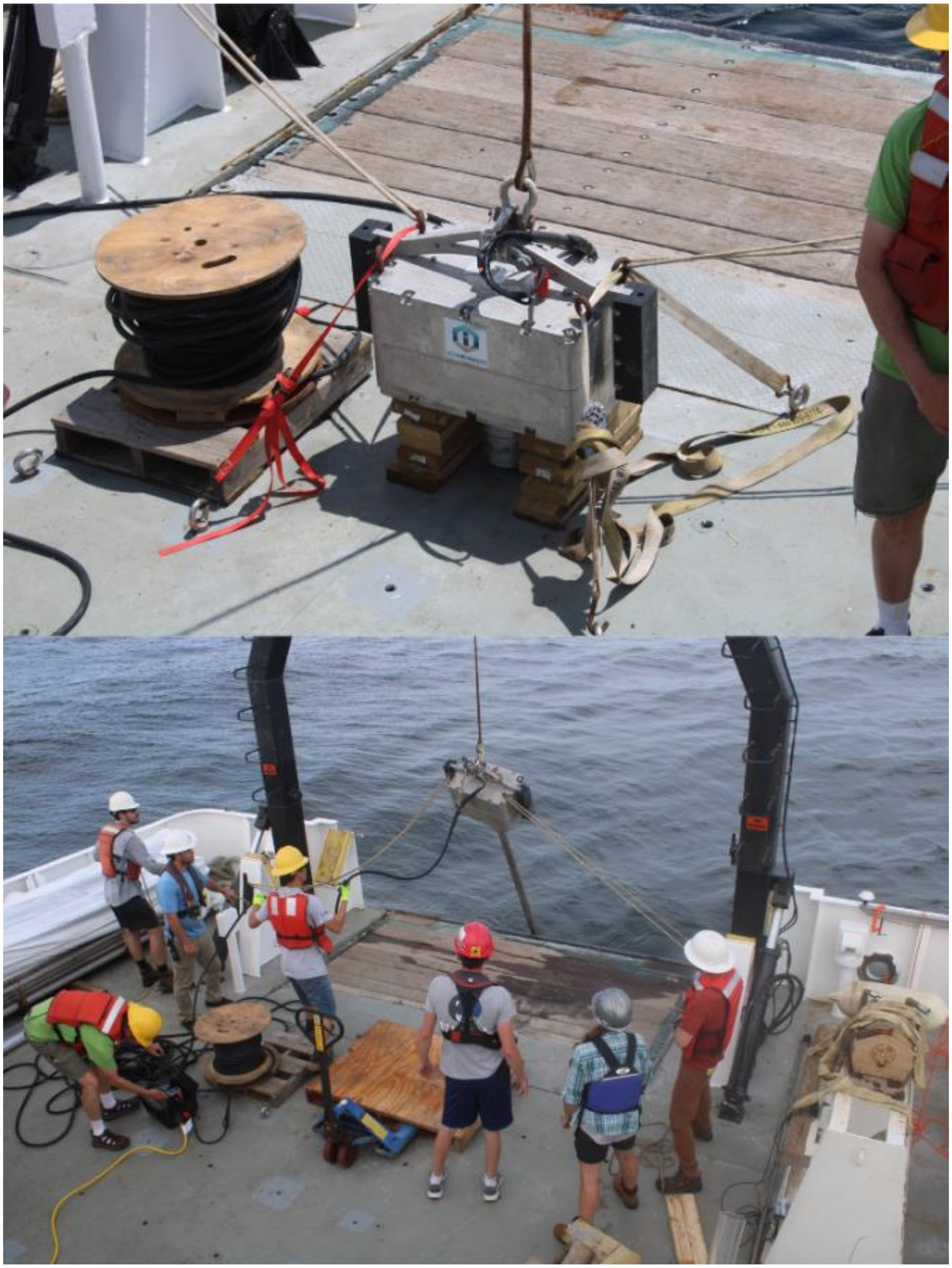
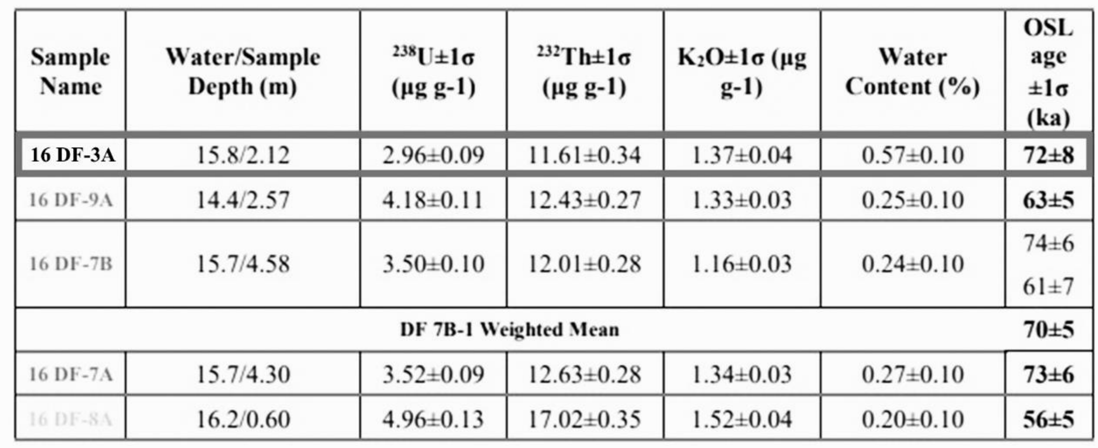


Figure 4.1. The Ocean Instruments RIC 5000 vibracoring system (DeLong et al. 2021).

4.2 Dating control

Eight samples taken from the peat section of core 15DF-1 were dated under the radiocarbon method (14C), the section 4.05 to 4.14 m revealed a date between ~41,830-45,210 cal yBP corresponding to the Marine Isotope Stages 3-4 (MIS 3-4). Six of these samples returned radiocarbon 'dead' possibly due to the radiocarbon reliable detection limits and bioturbation in the sediment (Gonzalez *et al.* 2017; Reese *et al*. 2018).

In November 2016, the deepest portion of the core 16DF-3A (177-220 cm, Pleistocene interbedded mud and peat) and the other four cores were sent to Coastal Carolina University and dated using Optically Stimulated Luminescence (OSL) technique. According to Shen *et al.* 2007 and Shen & Mauz 2012, this analysis uses a silt-sized fraction for dating, therefore the section of the core dated consisted in choosing the portion where coarse sediments overlaid the swamp facies (Gonzalez, 2017).
This technique revealed a date of ~72±8 ka for the interbedded mud and peat section of the core 16DF-3A (Gonzalez, 2017) (Table l). No dating technique was performed for cores 15DF-3B, 21DF-5A and 5B.



Sample Name	Water/Sample Depth (m)	^{238}U±1σ (μg g-1)	^{232}Th±1σ (μg g-1)	K$_2$O±1σ (μg g-1)	Water Content (%)	OSL age ±1σ (ka)
16 DF-3A	15.8/2.12	2.96±0.09	11.61±0.34	1.37±0.04	0.57±0.10	**72±8**
16 DF-9A	14.4/2.57	4.18±0.11	12.43±0.27	1.33±0.03	0.25±0.10	**63±5**
16 DF-7B	15.7/4.58	3.50±0.10	12.01±0.28	1.16±0.03	0.24±0.10	74±6 61±7
DF 7B-1 Weighted Mean						**70±5**
16 DF-7A	15.7/4.30	3.52±0.09	12.63±0.28	1.34±0.03	0.27±0.10	**73±6**
16 DF-8A	16.2/0.60	4.96±0.13	17.02±0.35	1.52±0.04	0.20±0.10	**56±5**

Table l. OSL dates of the analyzed sub-sections from five distinct cores. Core 16DF-3A is remarked. Coastal Carolina University, data from Dr. Zhixiong Shen (Table adapted from Gonzalez, 2017).

4.3 Laboratory analysis

Pollen processing procedures for cores 15DF-6, 16DF-3A, 21DF-5A and 5B were followed as stated in Reese *et al.* (2018) and Faegri *et al.* (1989). First, each 1/8 tbsp of the retrieved sample was placed in labeled testing tubes and two *Lycopodium* tablets (Lund University, batch 483216, count 18 583) were added to each one. Afterward, each sample was treated for carbonate removal with 12 ml HCl (10%, hydrochloric acid). Organic matter breakdown with 10% KOH (12 ml, potassium hydroxide) was the next step, with samples placed in a boiling water bath for five minutes. This procedure deflocculates the sediment and breaks down organics.

For clay removal, HF (10 %, hydrofluoric acid) was added and the tubes were placed in a boiling water bath for five minutes. For the next step, cellulose removal by adding acetolysis solution was needed, this consists of nine parts of Ac2O (acetic anhydride) to one part of H_2SO_4 (sulfuric acid). Before obtaining the final residue, tertiary butyl alcohol (TBA) was added to dehydrate pollen grains present in the samples. The final residue was stained with safranin, transferred into labeled vials and suspended in silicone oil.

For proceeding with grain identification, the previously obtained residue was mounted onto multiple labeled slides under a light microscope (400x magnification), and pollen grains were counted until reaching a minimum of 300 grains. Charcoal fragments, as well as fern spores were counted independently of the pollen grains.

Families and genera of pollen grains were identified using the North American pollen references (McAndrews *et al.* 1973; McAndrews & King, 1976). Once grains were counted, percentages and concentrations of indeterminable and undeterminable pollen grains were calculated with Tilia IT software (v2.6.1). With the same software, the results obtained from these calculations were presented graphically as shown in Chapter V.

CHAPTER V – RESULTS

5. 1 Core 15DF-6

The following sections of this chapter are the results of pollen analyses for each of the four cores. These results are presented as pollen diagrams, showing the percentage of each taxon calculated at every level; this calculation was estimated by the sum of all pollen grains counted for that level except for spores and *Lycopodium*.

Core 15DF-6 is divided into four different pollen assemblage zones based on the pollen percentage data. Overall, the dominating genera and families are *Taxodium*, Poaceae, *Quercus*, *Alnus* and *Pinus*, with minor components such as *Nyssa*, *Liquidambar*, Asteraceae, *Ulmus* and *Salix* (Fig. 5.1).

The lowermost zone of this core (90-85 cm) is mainly dominated by *Taxodium* (cypress) and *Pinus*, however, *Taxodium* prevails throughout this core at a fairly high percentage (~20%). After this interval, there is a notable transition that resembles an open marsh community (80 to 70cm); here *Taxodium* percentages drop under 20%, while *Alnus* trees and Poaceae (grass) start to increase, reaching 35% and >40%, respectively.

Still, in this open marsh environment (65 to 60cm), a noticeable decrease in *Alnus* is observed, while grasses reach >45%. Nevertheless, towards the end of this transition, there is a sudden drop in Poaceae (~25%) and an increase in *Taxodium* (~35%), leading to the core's uppermost section. This section (90 to 82.5 cm), is presented as a cypress/swamp environment, with *Taxodium* dominating and reaching more than 40%.

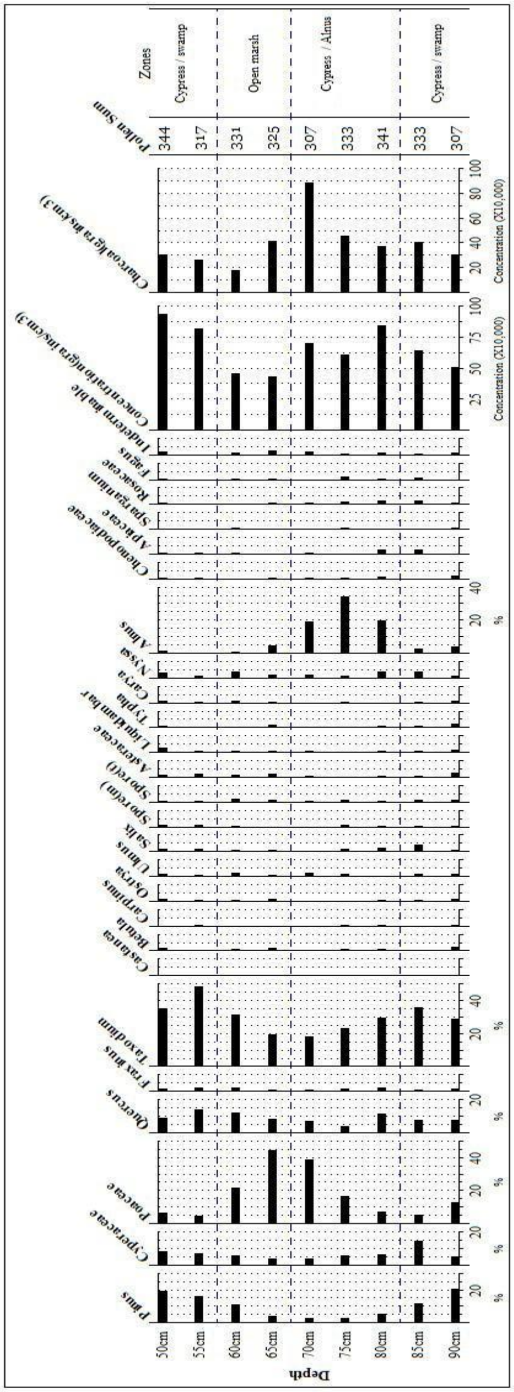


Figure 5.1. Pollen percentages of core 15DF-6.

5.2 Core 16DF-3A

The dominant vegetation through this core mainly consists of *Taxodium*, Poaceae, *Quercus*, Cyperaceae and *Pinus*; minor components were found such as *Alnus*, *Nyssa*, *Carya*, Asteraceae, *Betula* and *Liquidambar*. According to DeLong *et al.* (2020), a section of this core corresponding to a late Pleistocene interbedded mud and peat facies (1.77-2.20m), was OSL dated to 72±8 kaBP (Fig. 5.2).

The lowermost part of the core (220-180 cm) represents a cypress/swamp zone, where *Taxodium* is prevalent at a percentage of 40%, Poaceae concentration is relatively low with less than 10%, with *Quercus* and *Pinus* ranging between 10% and 22% through this zone. Low percentages of *Castanea* (chestnut) were also observed in this section. Towards the end of the zone, a decrease in *Taxodium* is observed (between 10-20%) and Poaceae percentages begin to increase.

This increase in grasses is accompanied by an increment in *Alnus* reaching approximately 10% at depths 170-175cm, this zone is denoted as an open marsh and *Alnus* transition. The top of this core at 165-170cm is distinguished by a high percentage of Poaceae (>40%) and a decrease in *Alnus*, which resembles an open marsh environment.

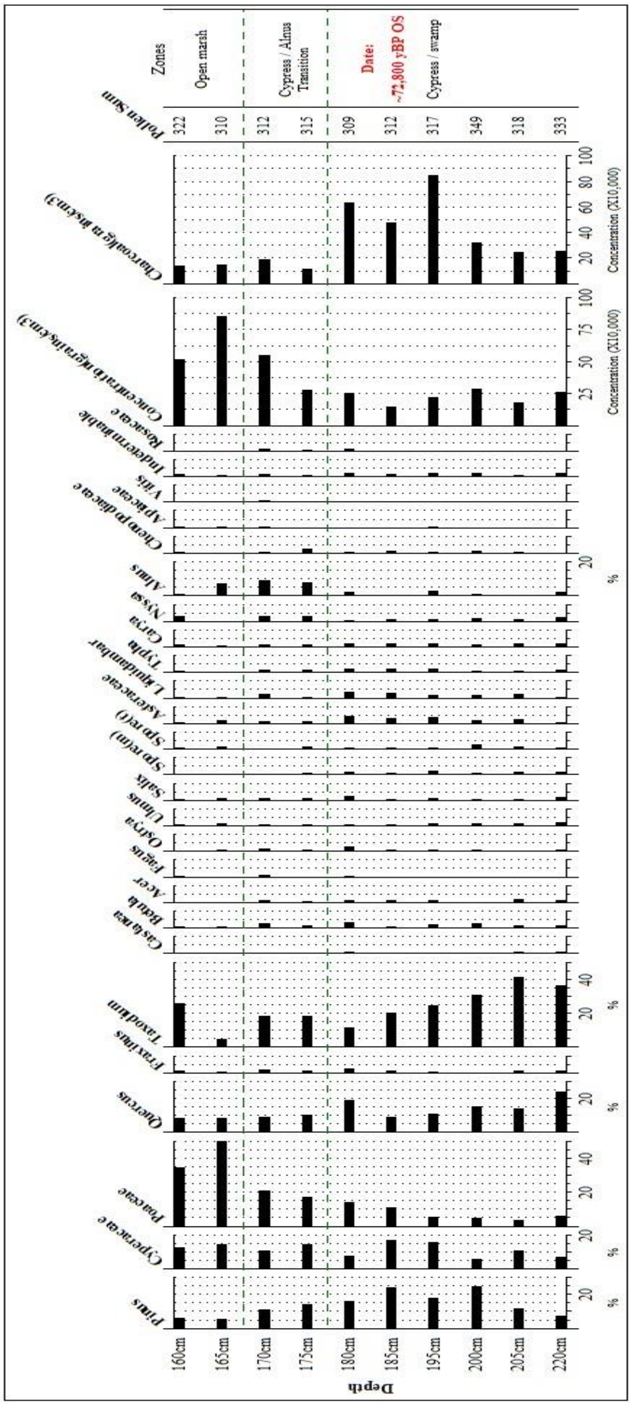


Figure 5.2. Pollen percentages of core 16DF-3A.

5.3 Core 21DF-5A and 21DF-5B

Core 21DF5-A is distinguished by three different zones (Fig. 5.3). The first zone in the lowermost section (50-40cm) represents a cypress and swamp environment, where Pinus is present at an average of 10% and Quercus percentages range between 10 and 15%. *Taxodium* mainly dominates this zone with a high percentage (60%), which starts decreasing towards the middle section of the core; subsequently, with this decline, an increase in Poaceae is observed.

The second zone is described as an open marsh environment (30-25cm), containing high percentages of Poaceae (~49%) with relatively low concentrations of *Pinus* (below 10%) and *Taxodium* (~20%). At the end of this zone, *Alnus* emerges reaching approximately 16%. The uppermost zone maintains a high percentage of Poaceae (30%) and a low concentration of *Taxodium* below 10%, however, *Alnus* reaches up to 35% and transforms this zone into an *Alnus*/open marsh community. Overall, *Quercus* concentrations never drop below 10% in this core; other minor components were found through all the zones including *Ulmus*, *Betula*, *Ostrya*, *Nyssa* and *Liquidambar*.

Core 21DF-5B is divided into two major zones presenting a transition from a cypress/swamp to an open marsh environment. The first zone (49-25cm) resembles the end of a cypress community with high percentages of *Taxodium* and Poaceae (~25%). Pinus percentages are at their highest in this zone at 10% but will decrease after the transition. The open marsh environment (40-30cm) contains high concentrations of Poaceae, reaching approximately 60% and *Taxodium* drops below 10%.

Minor components such as *Quercus* do not change through all this core, maintaining between 10 and 15%, respectively. Overall, *Alnus* percentages are low, however, a slight increase is observed in the uppermost section (30cm); *Nyssa*, *Betula* and *Ulmus* are other minor components with concentrations of ~5%.

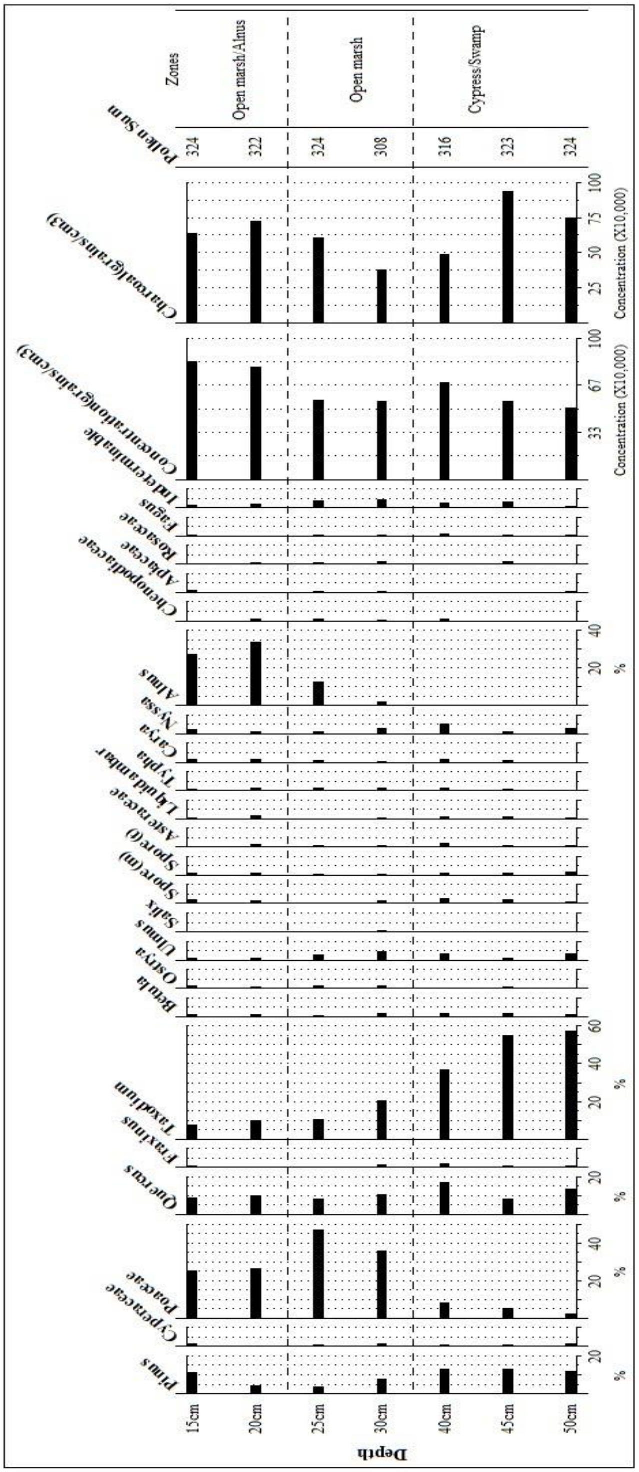


Figure 5.3. Pollen percentages of core 21DF-5A.

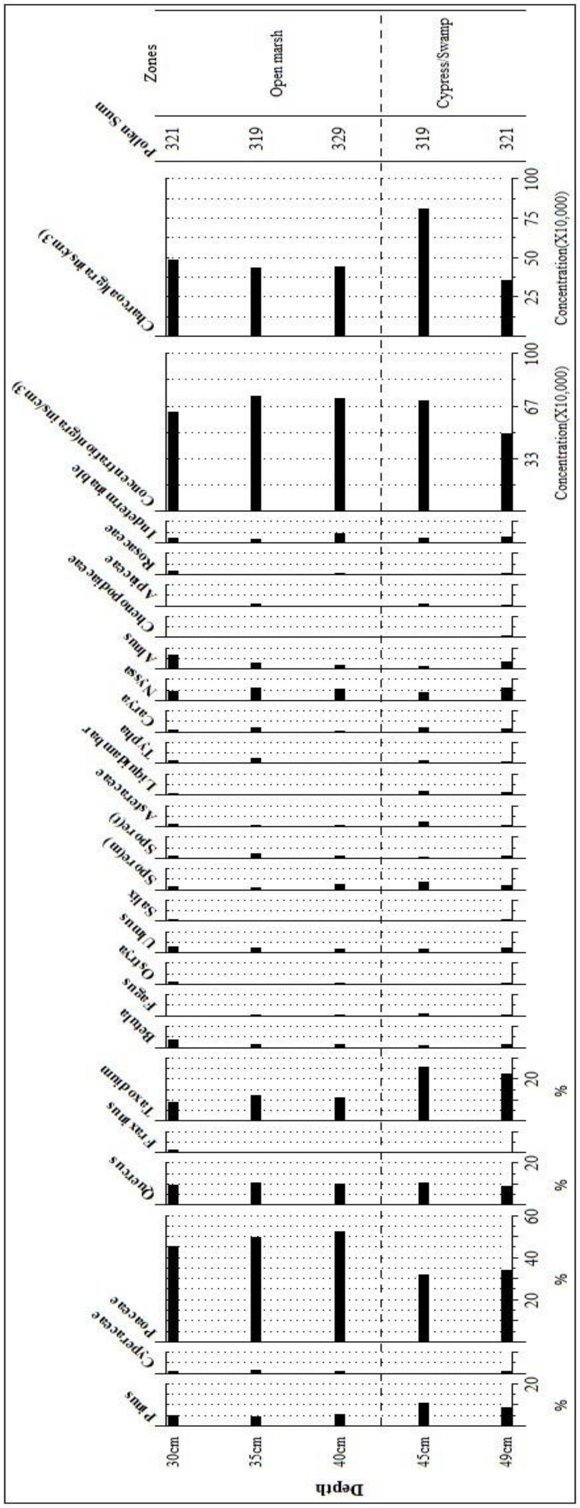


Figure 5.4. Pollen percentages of core 21DF-5B.

CHAPTER VI – DISCUSSION

The evidence found in these terrestrial sediments revealed possible vegetation assemblages for the Late Pleistocene on the formerly exposed continental shelf. This chapter describes the similarities between the newly analyzed cores and the one published by Reese *et al.* (2018), and Garretson (2022).

To establish a comparison between the new cores, 15DF-1 and 15DF-3B, *Alnus*, *Taxodium*, and Poaceae were selected due to their noticeable and similar patterns in taxonomic percentages. The comparison diagrams in this chapter also include *Quercus*, *Pinus* and Cyperaceae as minor components, since their presence and percentages are consistent across all cores (Figures 6.1 to 6.4).

6.1 Differences between cores 15DF-6, 16DF-3A and 15DF1

In order to establish a comparison between these cores, *Alnus*, *Taxodium* and Poaceae were selected due to their similarities. *Quercus* and *Pinus* are also present in these comparison diagrams, and although these are minor components, their presence and percentages are consistent through the core.

Overall, cores 15DF-6 and 16DF-3A revealed an initial cypress and swamp environment, transitioning to two dominating open marsh landscapes which are only differentiated by the appearance of no modern-analog *Alnus* communities. Specifically, this pattern can be seen from 4.75 to 4.15m in core 15DF-1 (Reese *et al.* 2018), this could be possibly related to a sea level rise event associated with the MIS 4-3 transition, where sea level fell to ~-80 meters and rose rapidly to between ~-60 and -30 meters (Anderson *et al.* 2015) (Figure 6.1 and 6.2).

Discussing this pattern in depth, some differences in percentages can be seen between these two cores in comparison with 15DF-1 considering that the elevation between the sites is different, as seen previously in Figure 3.2. In both cores 15DF-6 and 16DF-3A, *Pinus* percentages were consistent at <20%, probably due to the regional pollen rain and their long-distance dispersion before deposition (Reese *et al.* 2018; Bunting *et al.* 2004). *Quercus* was also seen at <20%, which could be almost considered a minor component; however, its appearance was consistent through all of the core zones; the same was observed for sedges (Cyperaceae) which are further discussed in this section.

The response of *Quercus* species to constant sea level oscillations in this area during the Late Pleistocene is still unclear. However, fossil pollen records from Central Mexico have shown that this genus along with *Pinus*, *Alnus* and *Juniperus* were consistently present in small percentages at around 44,000-11,000 yBP (Watts and Bradbury, 1982); showing minor fluctuations in response to dry/warm and cool/moist conditions between 24,000 and 19,000 yBP (Metcalfe *et al.* 2000).

Regarding the minor components, *Carya*, *Liquidambar* and *Ulmus* were found through all of the zones at very low percentages (<10%). These trace amounts are typical in assemblages located in the Gulf of Mexico boundaries, specifically during the LGM (Delcourt *et al.* 1984; Givens and Givens, 1987; Jackson & Givens 1994). Genera of the family Betulaceae such as *Betula* and *Ostrya* were also consistently found in all of these cores at <10%, except for *Carpinus* which was only found in the open marsh zones of 15DF-6 (80 to 60 cm); a similar situation with this last one can be seen in the open marsh environments of 15DF-1. These taxa were frequent in the lower latitudes and warm temperate areas of the southeastern United States, and extended into the subtropical areas of the Gulf of Mexico Coastal Plain during the Late Pleistocene-Holocene (Thompson *et al.* 1999).

Other minor components included tupelo trees (*Nyssa*) that reached 10% or more in these cores; however, it is difficult to determine in which zones it was most dominant. According to Jones *et al.* (2017), a backswamp environment is normally characterized by *Nyssa*, consistently present *Taxodium*, and elevated grasses (Poaceae); moreover, 15DF-1 also reflected a relatively high percentage of *Nyssa* associated with *Taxodium* (Reese *et al.* 2018). It is known that this genus grew in moist areas, such as riparian floodplains, with increased groundwater levels in valleys and surrounding slopes during the Late Pleistocene, around the southeastern United States (LaMoreaux *et al.* 2019).

The final Pleistocene pollen spectra seen in 15DF-1 indicated an open environment dominated by grasses (Poaceae) and sedges (Cyperaceae) (Reese *et al.* 2018. Though it is hard to establish a difference, in both 15DF-6 and 16DF-3A the Cyperaceae family ranged between 10 and 20% through all the zones. During the late glacial period in the eastern United States, it was common to see an association of Cyperaceae–*Fraxinus*–*Ostrya* at high percentages, something nonexistent once the Holocene period was reached (Williams *et al.* 2004).

Nevertheless, most of the genera inside the Cyperaceae family were highly associated with Poaceae from the Late Pleistocene until the LGM (Paduano *et al.* 2003), possibly demonstrating that low temperatures and high sea levels during that time could not support trees like *Taxodium*.

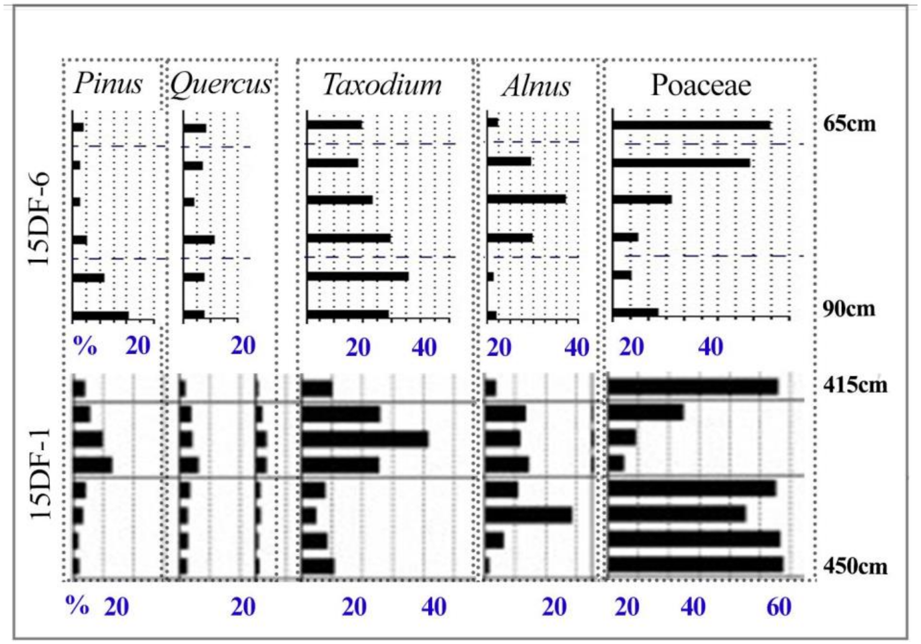


Figure 6.1. Comparison between core 15DF-6 and 15DF-1 (Reese et al. 2018). Evidence of vegetation assemblages between 65 and 90 cm.

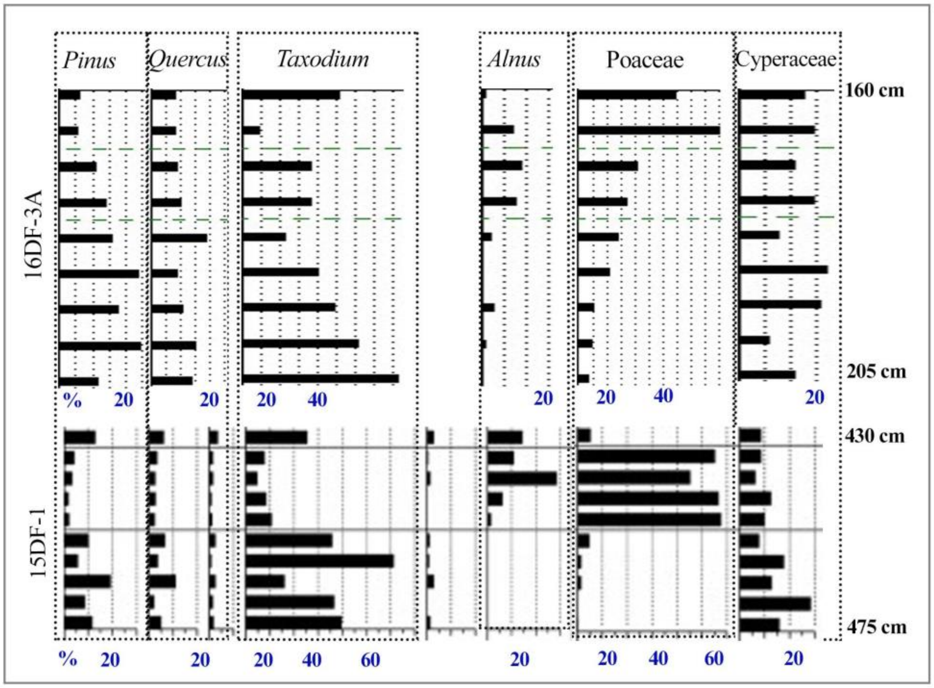


Figure 6.2. Comparison between core 16DF-3A and 15DF-1 (Reese et al. 2018).

Evidence of vegetation assemblages between 160 and 205 cm.

6.2 Differences between cores 21DF-5A/5B and 15DF-1

In general, 21DF-5A did not show major differences in comparison with 15DF-1, where the dominant taxa percentages ranged between 20 and 60%, as can be seen in Figure 6.3. It can be noted that *Alnus* in the uppermost section of 21DF-5A (20-15 cm) reflected percentages above 20%, which is considered common in the backswamp environments before the LGM episode (Jones *et al.* 2017); this is discussed further in Chapter 6.3.

The minor components in both 21DF-5A and 5B never exceeded 10%, similar to 15DF-1, however, the same case was observed for the family Cyperaceae (Figures 6.3 and 6.4). This family reached more than 20% (4.75-4.55 m) in core 15DF-1 (Reese *et al*. 2018). If we consider the length of the two new cores, 60 cm (21DF-5A) and 48 cm (21DF-5B), these may not represent enough material to adequately inform about the vegetation assemblages. Despite their short lengths, it is possible to establish a comparison because small fragments of these cores are similar to segments in 15DF-1. The assemblages in core 21DF-5A are similar to those in the lowermost section of 15DF-1B (435-475 cm) which transitions from cypress to grass dominant environments. A similar case is noted for 21DF-5B with a slight difference in *Alnus* percentages, which resembles the uppermost section in 15DF-1B(405-420 cm) (Figures 6.3 and 6.4).

In addition to the length of the cores, the number of zones present differs as well. In Core 21DF-5A, there are three zones, beginning with a cypress and swamp environment, transitioning to two open marshes distinguished by the presence of Alnus communities. There are just two zones in 21DF-5B, similar to the first two zones in 5A, where Alnus is almost absent until the uppermost section.

Furthermore, the active hurricane season during 2020-2021 in the northern Gulf of Mexico, specifically Hurricane Sally which passed over the study area, possibly affected the zone, since areas of the main study site were partially buried and exposed (DeLong *et al*. 2021). Considering this, it is known that the sampling process can be affected by topographical changes, causing differences in pollen concentrations and complicating the identification process (Rull, 2012; Alba-Sánchez *et al.* 2010).

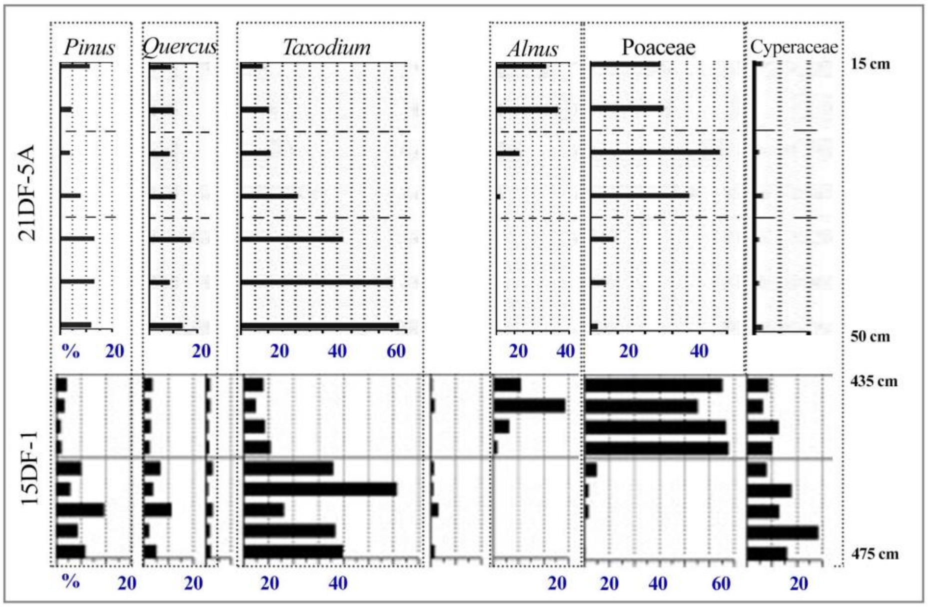


Figure 6.3. Comparison between core 21DF-5A and 15DF-1 (Reese et al. 2018).

Evidence of vegetation assemblages between 50 to 16 cm.

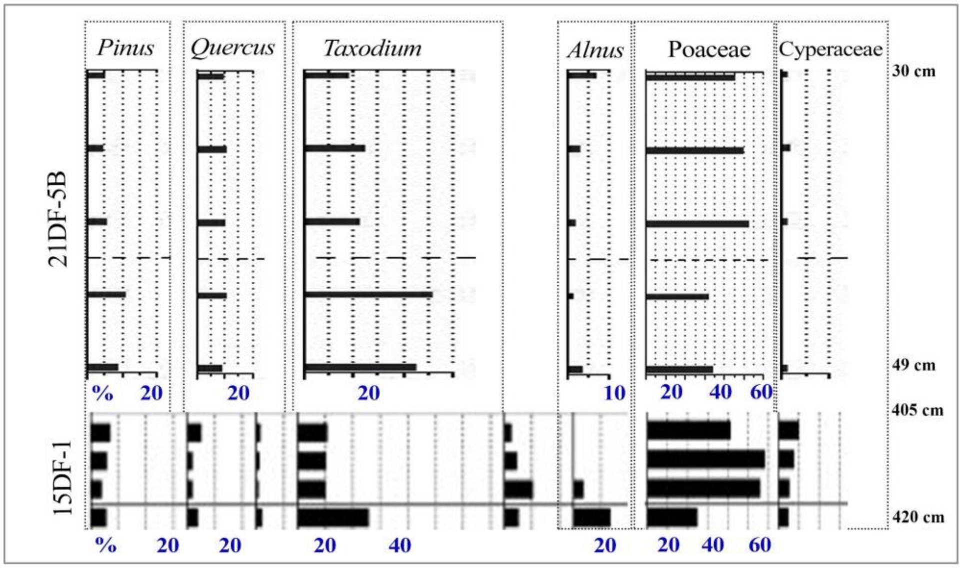


Figure 6.4. Comparison between core 21DF-5B and 15DF-1 (Reese et al. 2018).

Evidence of vegetation assemblages between 49 to 30 cm.

6.3. Environment-shifters: *Taxodium,* Poaceae and *Alnus*

In this narrative, Taxodium trees (along with Poaceae) show a unique and interesting variation throughout the cores. Their presence and absence could be considered evidence for paleovegetational changes and important taxa for zone designation. In the four new analyzed cores and 15DF-1 (Reese *et al.* 2018) this genus reached up to 40% of the sediment composition and it was accompanied briefly by a no-modern analog *Alnus* community with percentages of 20 to 40% (Figure 6.1-6.4).

The humid subtropics of the southeastern U.S. are known for their swamp and riverine environments that are one of the main habitats for bald cypress trees. In general, *Taxodium* represents an indicator genus for swamps and coastal wetlands (Doyle et al. 2015). Aside from saltwater intrusion, the constant rise in sea level caused additional water input, which resulted in permanent flooding of wetlands in the southeast coastal region of the United States (Lumibao *et al.* 2020; Anthoff *et al.* 2010), this is important for understanding the observed behavior of *Taxodium* in these cores.

As saltwater moves inland to freshwater swamps of the southeastern US, coastal forests transition to grass-dominant marshes (Krauss *et al.* 2009; Tanner *et al.* 2007). This transition is observed in the lowermost section of core 15DF-1 (475-455 cm) as well as 15DF-6, 16DF-3A, 21DF-5A and 21DF-5B analyzed in this study.

However, recent sediment studies near this site have shown that the majority of the swamp ecosystem transitioned into freshwater marsh rather than saltwater marsh (Brome, 2022). The geochemical characteristics of the sediment present in core 15DF-1 have been extensively examined by Brome (2022). The lowermost section of core 15DF-

1 (475-455 cm) which transitions from swamp to an open marsh environment, indicated near marine conditions due to the sulfur (SO_2) content present (Brome, 2022; Aharon and Fu, 2003). Nevertheless, these values do not necessarily represent true marine conditions, and could be attributed to general chemical changes in sulfur cycles (Brome, 2022).

Taxodium is considered one of the most salinity-tolerant species in the southeastern US and is also highly resistant to sulfur dioxide, therefore, neither the gradual increase in salinity induced by sea level nor the high sulfur content could have been detrimental (Krauss *et al.* 2007; Zhou *et al.* 2010; Shanklin and Kozlowski 1985).

The decline of cypress (*Taxodium*) and emergence of grasses (Poaceae) observed in the cores analyzed in this study, is possibly attributed to an altered flood regime that drove vegetation to change (Reese *et al.* 2018). Although Taxodium is widely rated as an extremely flood-tolerant tree, the growth of seedlings is reduced by flooding with stagnant water. This occurs because seeds cannot fully sprout when submerged, and must grow to a height sufficient to keep shoots above the water surface during the first growing season (Elcan and Pezeshki, 2002; Shanklin and Kozlowski, 1985; Loucks and Keen, 1973).

Unlike *Taxodium*, grasses of the Poaceae family are capable of tolerating waterlogging in flooded wetlands due to their root system structure and stomatal conductance, which facilitates oxygen to be captured and transported to submerged tissues (Kercher and Zedler, 2004; Colmer, 2003; Mollard *et al.* 2008). This can explain their emergence after the decline in *Taxodium*, which is observed at depths 80-60cm (15DF-6), 220-180 cm and 160-165 cm (16DF-3A), 30-15cm (21DF-5A) and 40-30cm

(21DF-5B), with percentages between 20 and 40%. These open marsh zones could also reflect the warm interglacial intervals that occurred during the Late Pleistocene, since seed germination in Poaceae is inhibited by low temperatures, having the ability to only grow in warm environments within a range of 20-30°C (Khan and Ungar, 2001).

Moving forward, spikes of *Alnus* and *Taxodium* can be observed at intervals 80-70cm (15DF-6), 175-170cm (16DF-3A) and 450-430 cm (15DF-1, Reese *et al.* 2018). This is common in warm temperate areas of the southeastern United States and is characteristic of backswamp environments before the LGM (>47,470 ^{14}C yBP) (Jones *et al*. 2017; Furlow, 1990; Rich *et al*. 2000).

It was previously hypothesized that this assemblage may represent a no-modern analog *Taxodium–Alnus* community because of the commonalities to the modern-day Atlantic Coastal Plain Blackwater Levee Forest, where the natural levees and young sand bars on blackwater streams allowed hosting such association (Schafale, 2009). Therefore, the formation of natural levees and sand bars as a result of floodplain aggradation in the underwater forest, possibly allowed the presence of this no-modern analog cypress-alder community (Gonzalez *et al.* 2017; Reese *et al.* 2018)

It is also important to consider that during the late-glacial period, *Alnus* species were widely dispersed in the eastern United States south of the ice sheet (Jackson and Williams, 2004), and abundant in the Atlantic Coastal Plain southeastern US between 23,000 and 16,500 yBP (Delcourt and Delcourt, 1979). Rather than being a result of bioturbation or long-distance transport, their presence on these assemblages is an indication of the paleovegetation community at the time.

6.4 Core 15DF-3B

Two major zones in core 15DF-3B previously analyzed by Garretson (2021) were observed. In the lowermost part of this core high percentages of *Taxodium* are evident, resembling a cypress backwater environment. The same pattern was observed in all of the cores analyzed in this study (15DF-6, 16DF-3A, 21DF-5A and 21DF-5B), however, transition zones on these core samples are more similar to those in 15DF-1 (Reese *et al*. 2018). The length of this zone in 15DF-3B is 95 cm while the analyzed cores range between 10 and 40 cm maximum.

It was also observed that 15DF-3B didn't show the no-modern analog cypress and alder communities, while this was evident in 15DF-1 and the other cores. Yet, high percentages of Alnus (<20%) were present on the uppermost section of this core corresponding to open marsh communities (290-320 cm), similar to what is observed in 21DF-5A (15-20 cm). However, this difference is unclear since 21DF-5A's length is too short (5cm). No noticeable differences were found regarding the minor components like Cyperaceae, *Nyssa*, *Fraxinus*, *Ulmus*, *Betula*, *Ostrya*, *Pinus*, among the others (Figures 3.10 and 5.3).

6.5 Differences between cores 15DF-3, 15DF-6 and 16DF-3A

The comparison between 15DF-6, 16DF-6 and 15DF-3B (Garretson, 2022) is shown in Figures 6.5 and 6.6. Because of the short length of these cores, only the cypress/swamp zone was selected for comparison. In 15DF-6 and 15DF-3B, Taxodium percentages ranged from 40 to 60%, while in Poaceae these were of ~20% throughout the zone. A marked increase was observed in Alnus, which was present in the cypress/swamp zone of 15DF-6 at 20%; however, only trace amounts are present in 15DF-3B, where it was more predominant in the uppermost section of the core that resembles the open marsh environment (Figures 6.5 and 6.7). There were no noticeable differences in the minor components (*Pinus* and *Quercus*), both of which kept their percentages below 20% (Figure 6.5).

Core 16DF-6 is possibly the one that shares most similarities with 15DF-3B. A consistent percentage of *Pinus* and *Quercus* was found throughout the whole cypress/swamp zone (20%). *Taxodium* is observed in 16DF-3A with percentages of <20% in the uppermost section of the core (170 cm); however, when advancing to the bottom section (220 cm) these increase to almost 60%, which is also observed in 15DF-3B. Similar results are seen with *Alnus*, whose percentages are approximately 10% in the upper section (170 cm), but decrease when reaching the bottom section of the core (220 cm). In both cores, most of the cypress/swamp zone contains *Alnus* in trace amounts, and percentages in the Poaceae family are consistently below 40% (Figure 6.6).

6.6 Differences between cores 15DF-3, 21DF-5A and 21DF-5B

In core 15F-3B (Garretson, 2022), the uppermost section resembles an open marsh with a transition to a cypress/swamp environment (290 to 335 cm), reflecting similar percentages to those in 21DF-5A and 5B. As can be seen in Figure 6.7, *Pinus* and *Quercus* maintain percentages of <20%, however, the most notable similarities can be observed in *Taxodium* whose percentages are no higher than 30% in the open marsh zone. Once the cypress/swamp transition is reached, Taxodium increases up to 40%.

An inverse pattern is observed in Poaceae, this family reaches up to 40% in the first zone but decreases below 20% once the cypress/swamp environment is reached. Furthermore, *Alnus* in 15DF-3B shows up to 20% in the open marsh zone but a noticeable decline is present in the cypress swamp section. The same is also observed in 21DF cores, but with a slight difference. *Alnus* in 21DF-5A initially reaches 20%, but disappears when transitioning to cypress/swamp; in 21DF-5B, however, the genus is consistent in both zones at 20%, never reaching 0% (Figure 6.7).

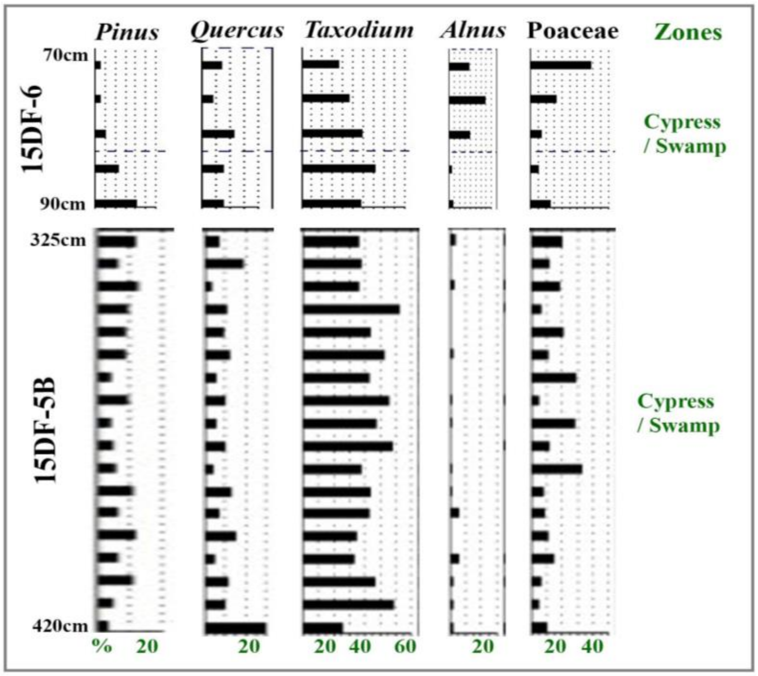


Figure 6.5. Comparison between core 15DF-6 and 15DF-3B (Garretson et al. 2022).

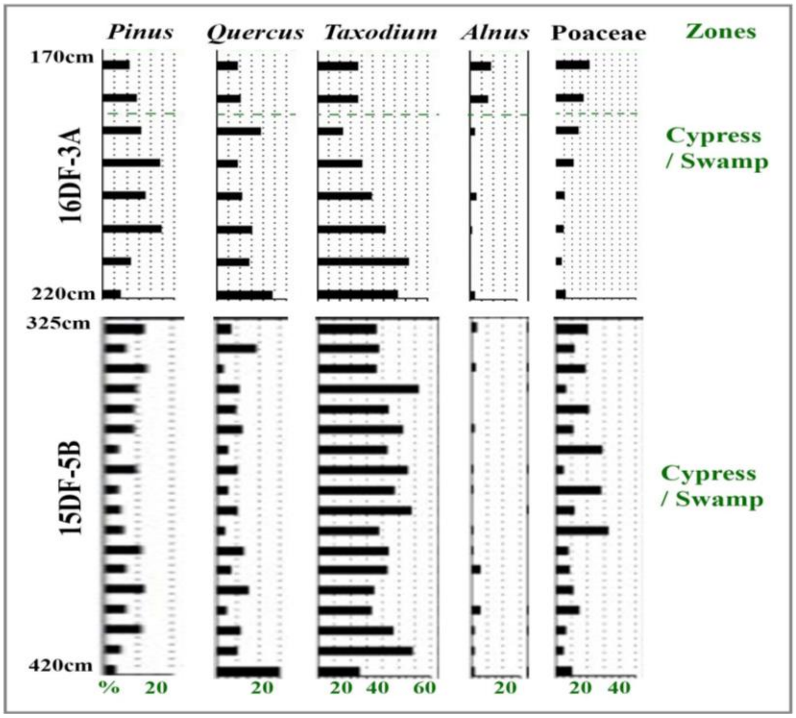


Figure 6.6. Comparison between core 16DF-3A and 15DF-3B (Garretson et al. 2022).

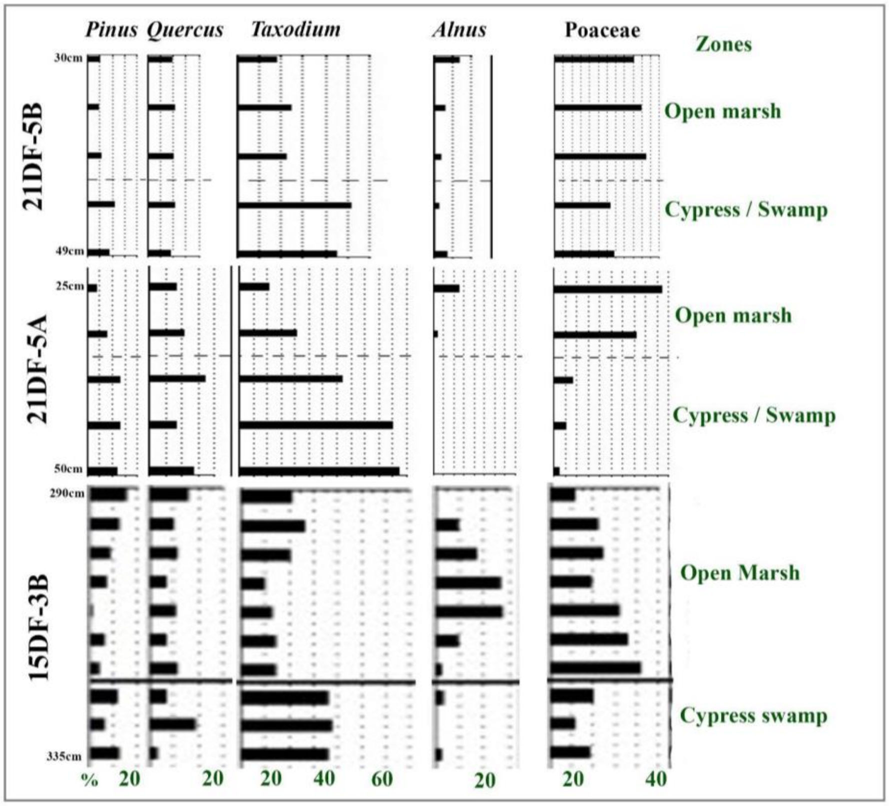


Figure 6.7. Comparison between core 21DF-5A, 21DF-B and 15DF-3B (Garretson et al. 2022).

6.7. About OSL dating method uncertainty

Radiocarbon analysis in core 15DF-1 (Reese *et al.* 2018) specifically the 4.05m section, presented a radiocarbon date of ~45,000 cal years, but other sections were radiocarbon dead and thus older than 45,000 years. This led to additional dating using the OSL method, which revealed a date of 72,000 ±8,000 (±1σ) yBP in the Late Pleistocene interbedded mud and peat section (LPIMP) of core 16DF-3A (DeLong *et al.* 2021).

In some cases, radiocarbon dates can often be overestimated depending on the amount of carbon present in the study site. The influence of reworked organic material and dissolved inorganic carbon in the ocean are considered to be the main causes of overestimating radiocarbon ages (Lee *et al.* 2011). On the other hand, the OSL dating method can be affected by the depletion of the OSL signal due to light exposure during core retrieval and storage, incorporation of sediment that was not exposed to sufficient sunlight prior to deposition, and the reworking of older material into sediments during deposition (Berger, 2006; Armitage, 2015, 2017).

Assuming the radiocarbon dates are accurate, this forest was rapidly buried around 40 ka or 62 ka as a result of floodplain aggradation caused by sea level rise. It is possible that the floodplain was adjacent to a tributary river that fed into the Mobile River, and the rapid rise of sea level of 15 m over 3000 years could have promoted aggradation (DeLong *et al.* 2020).

Aggradation can occur when coastal stream channels respond to forcing mechanisms such as sea level rise or changes in sediment supply (Blum and Törnqvist, 2000). The present site is located near the area encompassed by two incised valleys south of Mobile Bay. When sea level rose, these valleys were filled with sediment prior to the Last Glacial Maximum between 34.5 and 21.6 kaBP (Carson *et al.* 2019; Gonzalez *et al.* 2017). However, floodplain aggradation could have occurred for different reasons at varying times, for example, changes in the sediment load, or changes in the graded profile of the stream. (DeLong *et al.* 2021; Simon and Rinaldi, 2006).

If the OSL dates in core 16DF-3A are correct, the forest existed well above sea level (~-20 to -85 m) and the interbedded mud and peat facies (LPIMP) were deposited from approximately 80 ka to 60 kaBP. Due to the elevation of the site, even at the pulse of sea level rise at ~60ka, floodplain aggradation is unlikely but cannot be ruled out as a possible mechanism (DeLong *et al.* 2020, 2021). Moreover, the LPIMP section present this core is similar to those observed in 15DF-1 (430-475 cm) and 15DF-3B (325-420 cm). Considering that core 15DF-1 contains the longest peat section of 0.70 m, the sections observed in 16DF-3A and 15DF-3B might not represent the entire peat present at this site, and may extend further if longer cores are retrieved in the future.

As previously discussed, the assemblages in the four analyzed cores showed minor differences in comparison with 15DF-1. Similar percentages and vegetation transitions between the cores suggest that these sediments were deposited at the same time. Since some ^{14}C dates were radiocarbon dead, and there are large uncertainties regarding the OSL method, additional dating is necessary to adequately explain the story of this site.

CHAPTER VII - CONCLUSION

Unraveling the vegetational composition of paleoenvironments is always a daunting task. The study of fossil pollen grains has made it possible to provide information that aids in reconstructing the vegetational patterns of this ancient landscape, and infer the paleoclimatic conditions. The pollen results also helped to address my three original hypotheses.

1. Results from cores 15DF-6, 16DF-3A, 21DF-5A and 21DF-5B share strong similarities in pollen composition and display the same general transitions between prominent pollen zones. The minor differences found are possibly due to the changes in depth, the physical location and/or the length of cores. We can conclude that these share strong similarities when compared with core 15DF-1 (Reese *et al.* 2018) and 15DF-3B (Garretson, 2022) and likely represent the same event.

2. The no-modern analog cypress–alder community that was observed in core 15DF-1, is present in 16DF-3A and 15DF-6. It was previously stated that such association was possible due to the formation of bars and natural levees, as a consequence of the floodplain aggradation possibly driven by the rapid sea level rise.

3. The high percentages of *Alnus* found in cores 21DF-5A and 21DF-5B may indicate that this genus is a representative of the paleovegetation community, rather than indicative of bioturbation or long-distance transport. Moreover, *Alnus* was widely distributed south of the ice sheet during the Late Glacial Period, including the Gulf and Atlantic Coastal Plains in the southeast.

Finally I would like to address the uncertainty surrounding the date of earliest possible existence and final burial of this forest. The peat section of core 16DF-3A has an average date of 72 ±8 kaBP (OSL) corresponding to the MIS 5-4 period. These dates were taken from the entirety of the peat section in the core. On the other hand, 15DF-1 which was radiocarbon dated revealed a period between 45-41 kaBP during MIS 3-4. This date from core 15DF-1 was taken from the very top of the peat section and may indicate the time of burial. Undoubtedly, sea-levels were considerably different in these two periods, but there is a possibility that both dates are correct.

Considering the similar pollen assemblages between this study's sediments and 15DF-1, we can conclude that the sediments from the cores belong to the same period. Yet, stratigraphic connections can’t be confirmed due to the uncertainty of the OSL dating method. The peat section in core 16DF-3A may reflect the earliest possible period for the development of this forest. Also, it is possible that the radiocarbon dates in 15DF-1 are correct and represent the final burial. There is a need for additional dates using both methods in future cores to confirm these statements.

While the pollen analysis in this study provided additional information regarding vegetation dynamics at this site, I would like to emphasize the importance of considering the biological and evolutionary patterns in vegetation at a regional scale. Climate change and sea level were aspects that affected the forest composition and abundance across the southeastern United States, since more adapted species replaced others and modified the forest composition.

A deeper understanding of the biology and adaptation of life over time can help us better understand how vegetation responds to fluctuating climatic conditions. After all, the shifting in vegetation assemblages we have seen in this story was driven by the biological response to climate change.

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