

Spring 5-12-2022

## **Analysis of Fossil Pollen from a Pleistocene Cypress Forest Preserved on the Northern Gulf of Mexico Continental Shelf**

Kathryn Joyce Garretson

Follow this and additional works at: [https://aquila.usm.edu/masters\\_theses](https://aquila.usm.edu/masters_theses)



Part of the [Climate Commons](#), [Glaciology Commons](#), [Oceanography Commons](#), and the [Paleontology Commons](#)

---

### **Recommended Citation**

Garretson, Kathryn Joyce, "Analysis of Fossil Pollen from a Pleistocene Cypress Forest Preserved on the Northern Gulf of Mexico Continental Shelf" (2022). *Master's Theses*. 893.  
[https://aquila.usm.edu/masters\\_theses/893](https://aquila.usm.edu/masters_theses/893)

This Masters Thesis is brought to you for free and open access by The Aquila Digital Community. It has been accepted for inclusion in Master's Theses by an authorized administrator of The Aquila Digital Community. For more information, please contact [Joshua.Cromwell@usm.edu](mailto:Joshua.Cromwell@usm.edu).

ANALYSIS OF FOSSIL POLLEN FROM A PLEISTOCENE CYPRESS FOREST  
PRESERVED ON THE NORTHERN GULF OF MEXICO CONTINENTAL SHELF

by

Kathryn Joyce Garretson

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

Approved by:

Dr. Andy Reese, Committee Chair  
Dr. David Cochran  
Dr. Thomas Patterson

May 2022

COPYRIGHT BY

Kathryn Joyce Garretson

2022

*Published by the Graduate School*



THE UNIVERSITY OF  
**SOUTHERN**  
**MISSISSIPPI®**

## ABSTRACT

This study presents the findings of fossil pollen analysis performed on terrestrial sediments preserved on the northern Gulf of Mexico continental shelf (site hereafter known as the Underwater Forest or DF). This research aims to establish vegetation composition on a continental shelf glacial refuge and provide a better understanding of vegetation response to sea-level rise. Two cores (15DF1 and 15DF3B) located at different locations within the forest were recovered and analyzed. Pollen results from both cores were similar, with high percentages of *Taxodium* and *Nyssa* pollen in the lowermost sections reflecting an assemblage typical of contemporary baldcypress swamps. Pollen assemblages then shift in both cores, as Poaceae becomes dominant in the upper sections. I interpret this as a transition from a baldcypress swamp to more open coastal marsh as marine transgression occurs. During the marsh period in both cores, *Alnus* becomes a major taxon. This rise in *Alnus* occurs with high percentages of *Taxodium* in Core 15DF1, but occurs with high percentages of *Poaceae* in Core 15DF3B, possibly indicating localized differences. Radiocarbon dates of 15DF1 revealed an age of 45,210 cal a BP placing the core in Marine Isotopic Stage (MIS) 3. An extrapolated optically-stimulated luminescence (OSL) date from a sister core to 15DF3B, revealed an age of 72,000 years (early MIS 4 or 5). However, the pollen results from both cores indicate that the peat sections have recorded the same event in the paleoenvironment, making additional dates necessary to establish more reliable time control.

## ACKNOWLEDGMENTS

I would first like to acknowledge and thank my advisor and mentor, Dr. Andy Reese, for his continued support, guidance, and patience throughout this project. This thesis would not be what it is today without Dr. Reese's guidance, suggestions, and encouragement. Dr. Reese has shown me that hard work and effort are key components that make a good scientist. With his assistance I have become a better researcher, writer, and student.

I would also like to thank the additional members of my committee, Dr. David Cochran, and Dr. Thomas Patterson. Both Dr. Cochran and Dr. Patterson have been very supportive and provided helpful comments and guidance throughout my time as a master's student, and throughout the completion of this thesis.

This project would not have been possible without the help of several other people. The Underwater Forest team, Dr. Kristine DeLong, Dr. Kevin Xu, Dr. Samuel Bentley, Dr. Grant Harley, Dr. Andy Reese, Jeff Obelcz, Kelli Moran, and Kendall Brome, have all been very helpful during the course of this project. Dr. Alicia Caporaso and Mr. Doug Jones of the Bureau of Ocean Energy Management (BOEM) have been very supportive and provided helpful feedback for presentations that have been given on the pollen aspect of this project. To the entire team, I sincerely thank you all for allowing me to be a part of this exciting endeavor, and for your continued enthusiasm regarding my pollen results.

In addition, I would like to thank my family for their continued support, patience, and for keeping me grounded and focused while finishing this thesis. I am truly proud of the finished project and am infinitely grateful to those listed above.

## TABLE OF CONTENTS

ABSTRACT .....	ii
ACKNOWLEDGMENTS .....	iii
LIST OF TABLES .....	vi
LIST OF ILLUSTRATIONS .....	vii
LIST OF ABBREVIATIONS .....	viii
CHAPTER I - INTRODUCTION .....	1
1.1 Background .....	1
CHAPTER II – LITERATURE REVIEW .....	5
2.1 Overview .....	5
2.2 Using Fossil Pollen for Environmental Reconstruction.....	7
2.3 The Start of Palynology and Its Growth in Europe.....	9
2.4 North American Glacial Age Pollen .....	13
2.4.1 <i>Important Considerations for Pollen Studies from a Glacial Refuge</i> .....	19
2.5 Offshore Pollen Studies .....	21
2.6 Quaternary Dendrochronology and Baldcypress Reconstruction.....	25
CHAPTER III – STUDY AREA .....	31
3.1 Geologic Setting.....	31
3.2 Core Analyses .....	35
3.2.1 <i>Sediment Composition</i> .....	35

3.2.2 Pollen .....	38
3.2.3 Wood and Dendrochronology.....	41
3.2.4 Foraminifera .....	43
3.2.5 Seeds .....	44
CHAPTER IV – METHODOLOGY .....	45
4.1 Field Work .....	45
4.1.1 Vibracoring .....	45
4.2 Laboratory Methods.....	47
4.2.1 Pollen Processing .....	47
CHAPTER V – RESULTS .....	50
5.1 Core 15DF1.....	50
5.2 Core 15DF3B .....	52
5.3 Comparison of Core 15DF1 and 15DF3B .....	54
CHAPTER VI – DISCUSSION.....	55
6.1 Justification of Classification of Transitional Communities in Cores .....	56
6.1.1 Uncertainty of Radiocarbon Dates .....	60
CHAPTER VII – CONCLUSION .....	63
REFERENCES .....	65

## LIST OF TABLES

Table 4.1 Radiocarbon dating results from core DF1 .....	49
Table 4.2 Optically Stimulated Luminescence Date (OSL) of 16DF3A .....	49



## LIST OF ILLUSTRATIONS

Figure 1.1 Map of the Gulf of Mexico region where the study site is located .....	2
Figure 1.2 3D elevation map of the forest site with the trough encircled in red dashed lines .....	3
Figure 2.1 Images of paleo-reconstruction maps of Pinus.....	17
Figure 3.1 Global sea level variations for the last glacial interval.....	32
Figure 3.2 A 3D digital elevation model representing bathymetric data from 2015 and 2016.....	34
Figure 3.3 The three lithofacies found from sediment analysis.....	37
Figure 3.4 Sample locations of micropaleontological and <sup>14</sup> C analysis and view of lithofacies in core 15DF1.....	38
Figure 3.5 Image of core 15DF3B lithofacies .....	39
Figure 3.6 Bathymetric map of core locations.....	39
Figure 3.7 3D subsurface model of the study site.....	40
Figure 3.8 Twenty-three wood specimens collected in 2013 by divers.....	41
Figure 3.9 Analysis of foraminifera in core 15DF1 .....	43
Figure 3.10 Seeds from core 15DF1 found preserved in the peat section .....	44
Figure 4.1 (A) map of the study with all cores taken from 2015 and 2016 shown. (B) the vibracoring system used for sample collection in 2015 and 2016.....	46
Figure 5.1 Pollen analysis of core 15DF1 .....	51
Figure 5.2 Pollen analysis of core 15DF3B .....	53
Figure 6.1 Sea level estimates for the last 140 ka.....	61

## LIST OF ABBREVIATIONS

<i>DF</i>	Drowned Forest
<i>LIS</i>	Laurentide Ice Sheet
<i>LGM</i>	Last Glacial Maximum
<i>MIS</i>	Marine Isotopic Stage
<i>cal ka</i>	calibrated thousand years
<i>cal yr BP</i>	calibrated years before present
<i>ka</i>	Kiloannum (thousand years ago)
<i>ka B.P.</i>	thousand years Before Present
<i>cal yr A.D.</i>	calibrated years Anno Domini
<i>MAFLA</i>	Mississippi-Alabama-Florida
<i>OSL</i>	Optically Stimulated Luminescence
$^{14}\text{C}$	Radiocarbon
<i>LSU</i>	Louisiana State University
<i>HS</i>	Holocene sand
<i>HISM</i>	Holocene interbedded sand and mud
<i>LPIMP</i>	Late Pleistocene interbedded mud and peat
<i>SFC</i>	Submerged Forest tree-ring chronology
<i>HCL</i>	Hydrochloric acid
<i>KOH</i>	Potassium hydroxide
<i>HF</i>	Hydrofluoric acid

## CHAPTER I - INTRODUCTION

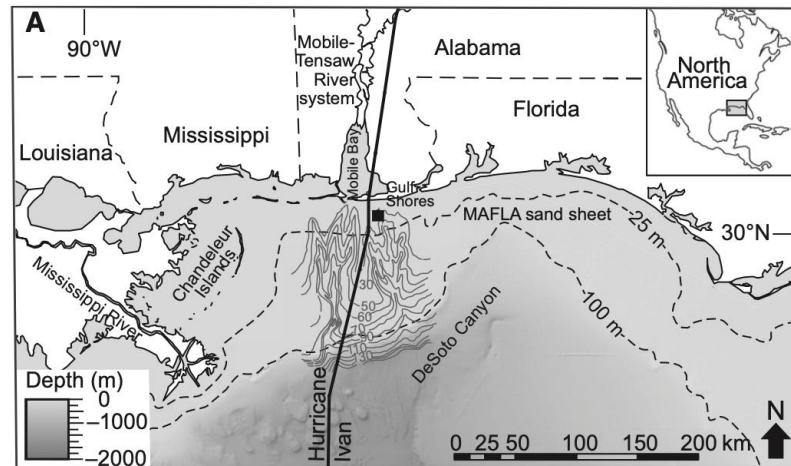
### 1.1 Background

Numerous studies have been conducted using fossil pollen to track migration of vegetation as it moves northward following the retreat of major ice sheets after glacial events (Whitehead, 1964; Davis, 1983; Bryant Jr. and Holloway, 1985; Delcourt and Delcourt, 1987; Connor and Kvavadze, 2008; Ülker et al., 2018; Harbert and Nixon, 2018). Archives for these fossil pollen studies have mainly consisted of sediments taken from lakes, bogs, and swamps to analyze the change in vegetation dynamics during glacial transitions within North America (Brugam, 1978; Delcourt and Delcourt, 1987; Davis, 1983; Gavin et al., 2001; Breen et al., 2012). Recently, studies of fossil pollen have moved to the ocean to focus specifically on tracking vegetation on the glacial refugia on the former continental shelf (Reese et al., 2018; DeLong et al., 2021; Gonzalez et al., 2017).

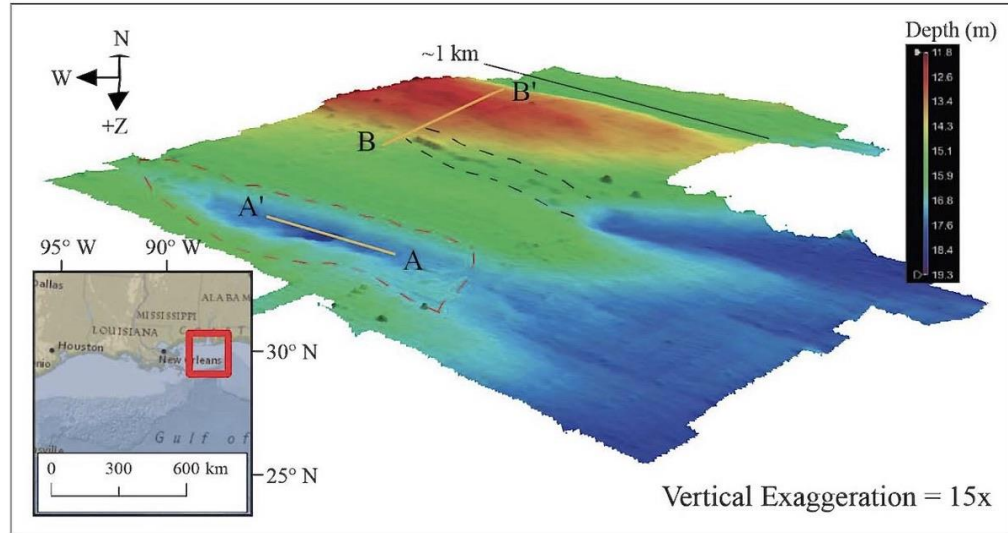
These glacial refugia, geographic regions where both flora and fauna migrated to survive glacial events, are used to map the degree of suitable habitat available for vegetation, observe changes in genetic diversity, and act as protected areas to monitor species mortality rate as ice sheets advanced and sea levels dropped due to climate change (Shafer et al., 2010; Selwood and Zimmer, 2020). Climate change and post glacial events have played a major role in the fluctuation of sea level increase and decrease. Many tree taxa migrated equatorial during these periods and became buried as post-glacial sea levels rose. With rising sea levels, most terrestrial sediments would have been completely erased or disturbed due to wave action and rising seas. If these sediments were preserved, they would had to have undergone some sort of rapid burial to escape erosion. Such a site has

been discovered, and ancient terrestrial peat has been recovered from the continental shelf in the Gulf of Mexico (Reese et al., 2018; DeLong et al., 2021; Gonzalez et al., 2017). This archived paleoenvironmental data from the once exposed continental shelf site is extremely valuable, and rare, as it can provide information regarding vegetation response to sea level rise, having recorded a transgressive marine event.

The Underwater Forest was first discovered in 2010 by divers approximately 13 km off the coast of Gulf Shores, Alabama, and is located along the western edge of the paleo-Mobile River valley located along the eastern branch covering  $\sim 2 \text{ km}^2$  of the northern Gulf of Mexico continental shelf (Figure 1.1) (Reese et al., 2018; DeLong et al., 2021). Today, it lies in approximately 18-20 m of water and the exposed cypress stumps were found in growth position rooted in the terrestrial sediment in a  $\sim 0.5 \text{ m}$  deep trough believed to have once been covered by a Holocene sand sheet (Figure 1.2) (Reese et al., 2018; DeLong et al., 2021).



*Figure 1.1 Map of the Gulf of Mexico region where the study site is located (DeLong et al., 2020).*



*Figure 1.2 3D elevation map of the forest site with the trough encircled in red dashed lines (DeLong et al., 2020).*

The area in which the site resides in the Gulf of Mexico is, today, characteristically described as a complex and dynamic system of open ocean circulation and freshwater discharge due to sea level changes and an abundance of tropical storms (Gonzalez et al., 2017). Before the forest was overtaken by marine conditions it represented an assemblage of vegetation typically found in a cypress-tupelo backwater environment, and the forest likely transitioned to a more open marsh environment after flooding occurred (Reese et al., 2018). Though it is not clear how the underwater forest came to be preserved, the mostly likely explanation for the burial of the forest is rapid floodplain aggradation due to sea-level rise, or overbank flooding, which is independent of sea level change, during glacial age climate fluctuations (DeLong et al. 2021; Gonzalez et al., 2017; Reese et al., 2018).

This underwater forest is the first of its kind to have been studied, making it extremely important in establishing vegetation dynamics on a continental shelf glacial

refuge. The research from this study will build upon existing pollen studies by adding data points on the exposed continental shelf. In this thesis, pollen will be analyzed from a new core from the Underwater Forest (core 15DF3B). The results will be compared to the already published pollen data from core 15DF1 (Reese et al., 2018). The cores are located roughly 560 m apart with core 15DF3B located at ~0.5 m lower bathymetry on the opposite side of the trough that contains the bulk of the preserved cypress stumps. From this study, I aim to provide additional information concerning the vegetation composition and dynamics of the site. This information will lay the groundwork for helping us to understand vegetation response to sea level change in this particular area and establish vegetation dynamics on a continental shelf glacial refuge. In addition to this, I aim to use this palynological information to address dating discrepancies between the two cores. To accomplish these objectives, the results from this thesis will address the following research hypotheses:

1. There is transition from an older cypress marsh to more open-water community in core 15DF3B, similar to the results seen in core 15DF1.
2. During this transition, the pollen in DF3B will show evidence of a similar no-modern analog (cypress-alder) community.
3. There is a difference in the age of the peat in core 15DF1, and core 15DF3B (using the extrapolated OSL date from 16DF3A), but similarities in pollen assemblages between the two cores will suggest that these events are coeval, and that a better dating control is needed.

## CHAPTER II – LITERATURE REVIEW

### 2.1 Overview

Fossil pollen has been of great interest to scientists reconstructing past vegetation assemblages and tracking the migration of certain species as the climate has varied (Delcourt and Delcourt, 1987; Davis 1983; Bryant and Holloway, 1985; Connor and Kvavadaze, 2008; Dupont and Wyputta, 2003; Harbert and Nixon, 2018; Reese et al., 2018; DeLong et al., 2021). Sediments from swamps, lakes, and bogs are typically selected for fossil pollen studies, but palynologists have also studied fossil pollen preserved in marine sediments to reconstruct past vegetation and determine site specific changes occurring due to sea level change (Dimichele and Falcon-Lang, 2011; Brown and Pasternack, 2005; Tarasov et al., 2005; Sheldon and Tabor, 2009; Reese et al., 2018; DeLong et al., 2021). Due to its unique composition and morphology, fossil pollen is found preserved in a variety of environments where sediments are undisturbed and anoxic (Grimm and Jacobson Jr., 1991; Jahren, 2004; Denk and Tekleva, 2006). If conditions within an environment are right, pollen can be recovered and identified down to a significantly low taxonomic level, even after millions of years (Nielsen and Odgaard, 2004).

Because of this, pollen has been used worldwide to reconstruct and investigate vegetation response to glacial and interglacial transitions (Davis, 1983; Anderson et al., 1989; Grimm and Jacobson Jr., 1992; Gavin et al., 2001; Gugger and Sugita, 2010; Shafer et al., 2010; Breen et al., 2012; Harbert and Nixon, 2018; Reese et al., 2018). From these studies, scientists have determined vegetation patterns and migration paths of plants as they retreated from an advancing ice sheet, and then reclaim the land these

glaciers once occupied (Delcourt and Delcourt, 1987; Aharon 2003; Flower et al., 2015). Though studies regarding fossil pollen are plentiful across most of North America and Europe the same cannot be said for the southern portion of the United States. During the last glaciation, the Laurentide Ice Sheet (LIS) only extended as far south as 40° N in the United States (Delcourt and Delcourt, 1987; Sugden, 1977). Therefore, the deep lakes and depressions carved out by ice that create ideal archives for pollen are hard to find across the southern United States. The southeast contains an abundance of oxbow lakes which are the results of river cutoffs making them very short-lived temporally, and do not contain pollen useful for reconstructing glacial-age plants (Bhattacharya et al. 2016; Shen et al. 2021). Fossil pollen assemblages that do exist in the southeastern United States dating back to the last glaciation are highly deteriorated due to the varying composition or type of rocks, transport via wind or water, deposition environment, and microbial attacks within the sediment (Delcourt and Delcourt, 1980).

The recent discovery of the Underwater Forest on the Gulf of Mexico continental shelf is a unique site that could possibly aid in establishing the vegetation assemblage of a continental shelf glacial refuge, as well reconstruct vegetation migration of the southeastern U.S. during the last glacial period. However, a thorough review of the use of pollen as a paleoenvironmental proxy, and a literature review of past pollen studies is needed in order to put our study site and palynological findings in perspective.



## **2.2 Using Fossil Pollen for Environmental Reconstruction**

The term ‘fossil pollen’ is quite misleading because fossil pollen actually has nothing to do with being fossilized. Fossil pollen simply refers to an important type of proxy data that is used for reconstruction of past environments. Fossil pollen is removed from the sediments in which they are embedded in by a series of chemical processes that remove any organics, clays, minerals, and other substances surrounding the actual pollen grain (Faegri and Iversen, 1964). The pollen grain is quite resilient as it is made up of a thick layer of sporopollenin, which can only be broken down by microbial action, and repeated wet-dry events (Denk and Tekleva, 2006; May and Lacourse, 2012). This makes pollen an ideal paleoenvironmental proxy that can be found in various locations to reconstruct vegetation across a wide temporal range.

When pollen is deposited in an environment where it is not subject to external stressors, it can remain intact and identifiable for millions of years. Ideal environments for fossil pollen include environments that contain anoxic sediments. Anoxic sediments usually contain high amounts of organic matter and low amounts of oxygen. When fossil pollen is embedded in these anoxic sediments it becomes well-preserved due to the low amount of biological disturbance occurring within the sediment, and the continuous accumulation of organic matter settling on top (Parducci et al., 2017). If no physical or biological disturbance occurs during the interment period, the sediment will show a stratigraphy that accurately reflects the surrounding depositional environment (Brush, 1989). Should biological or physical disturbances occur, then the sediment will likely be disturbed and will not reflect an accurate representation of the surrounding area, making interpretation of changes occurring within the environment difficult to observe (Brush,

1989). Therefore, good archives are an essential component to any successful palynological reconstruction.

Suitable archives may be found anywhere but are most commonly found in deep, natural lakes as well as bogs, swamps, ice caps, and glaciers (Parducci et al., 2017). Naturally occurring lakes and the size of their catchment areas are crucial in the representation of pollen species from the surrounding area. Lakes that are more open have larger catchment areas, which allows pollen to collect from regional and/or extraregional sources (Parducci et al., 2017). Smaller catchment areas, or more enclosed catchment areas, typically contain local species (Parducci et al., 2017). For successful reconstructions to occur it is essential to understand and identify suitable archives.

## **2.3 The Start of Palynology and Its Growth in Europe**

Modern Quaternary pollen analysis began in Europe with geologist Lennart von Post in 1916 (Gaillard et al., 2018; Edwards, 2018). Von Post conducted many of his studies across his native Sweden after seeing the stratigraphical importance of pollen within peat bogs (Gaillard et al., 2018; Edwards, 2018; von Post, 1910). He eventually developed his idea of expressing pollen counts as percentages and presenting these percentages in diagrams (Gaillard et al., 2018; Edwards, 2018). Since the first presentation of his pollen diagrams in 1916, von Post's research has outlined the principles, and methodology of modern day pollen analysis which largely influenced scientists to utilize peatlands and interglacial-glacial sediments worldwide (Birks and Berglund, 2018; von Post and Granlund, 1926; von Post 1926a; Granlund, 1932) Von Post's research paved the way for modern day studies which focus on fossil pollen existing during glacial and interglacial periods across the United States to determine how vegetation responded to the advance and retreat of ice sheets, and the fluctuations in global temperature and atmospheric conditions.

Early palynology continued in Europe by scientists analyzing peat and bog sediments for paleoenvironmental reconstruction across various regions of the continent. Scientists have inferred long-term dynamics of forest composition relating to the reduction and extinction of species in southern Europe from fossil pollen assemblages located in marine and terrestrial sediments (Magri et al., 2017). Throughout the Pleistocene, forest vegetation decreased as herbaceous steppe environments increased (Magri et al., 2017; Cheddadi and Bar-Hen, 2009). Results revealed that the decrease in forest vegetation began in the early Pleistocene (Magri et al., 2017; Cheddadi and Bar-

Hen, 2009). Since the beginning of the Pleistocene, the cycle of glacial and interglacial periods led to an alteration in forest steppe vegetation in the Mediterranean (Magri et al., 2017). The cyclicity of the climate strongly reduced sub-tropical forests, which required high temperatures and precipitation and led to an increase in oak-dominated vegetation and coniferous forests at high altitudes (Magri et al., 2017). Pollen results showed that forests continued to decrease, and steppe conditions increased during the Mid-Pleistocene Revolution between 1.2 – 0.5 Ma (Magri et al., 2017; Cheddadi and Bar-Hen, 2009). While most of these results focus on sites across southern Europe, other studies have focused on paleoenvironmental reconstruction of southwest Europe.

Mountainous regions of southwest Europe, specifically the Picos de Europa, have long since been a source of studies pertaining to Quaternary glaciations (Serrano et al., 2012). Sediments from Campo Mayor Lake, located in between the Central and Eastern massifs of the Picos de Europa, which received high amounts of proglacial meltwater, and sedimentary load from the Las Salgardas glacier were used to provide high resolution records of environmental changes occurring during the Quaternary glaciation (Serrano et al., 2012). Glacial lake deposits reflected periods of infilling due to increasing and decreasing glacial activity (Serrano et al., 2012). From these glacial deposits, sediments dated back to Marine Isotopic Stage (MIS) 3 occurring between 60 and 25 ka B.P. (Serrano et al., 2012). Many paleoenvironmental reconstructions are successful because when sediment loads are undisturbed, they provide a clear stratigraphical record of environmental changes.

Results have shown that past biome distribution across Europe from the LGM differs greatly from the modern-day pattern (Peyron et al., 1998). *Poaceae* and *Artemisia*

shows past landscapes in northwest Europe consisted of cool steppe vegetation found in very cold, dry conditions throughout the year (Peyron et al., 1998). Past Mediterranean Sea records revealed much higher levels than at present in very cold, wet conditions (Peyron et al., 1998). *Pinus* percentages were higher in the Mediterranean region than the northwest (Peyron et al., 1998). Regions of the Mediterranean were found to have higher temperatures which explains the abundance of temperate summergreen and coniferous species (Peyron et al., 1998). Past and present climates have been shown to differ greatly, but evidence of differentiation in regions containing similar vegetation existing in the same climate have also been proven.

Other studies have shown that discrepancies can occur between regions that are characterized by similar vegetation during the LGM (Broström et al., 2008). *Picea*, *Fagus*, and *Plantago* pollen obtained from moss polsters along the Jura Mountains were found in significantly higher percentages than the same species of pollen collected from lake sediments on the Swiss Plateau (Broström et al., 2008). The difference in the percentages is likely due to the type of site in which pollen was collected from (moss polster vs. lake sediment), and environmental factors effecting the sites such as climate change, species composition, and vegetation structure (Broström et al., 2008). Fossil pollen has been used to reconstruct past vegetation and climate gradients for the LGM, and more recently the Holocene.

The Holocene epoch, beginning ~ 11, 650 cal yr B.P., provides many aspects that are essential in establishing chronologies of past climates (Mauri et al., 2015). Evidence from fossil pollen sequences across Europe reveal a warming climate which later stabilized by a balanced cooling over southern Europe mid-Holocene (Davis et al., 2003).

This warming strongly influenced vegetation migration. Pollen spectra from two lake basins revealed a highly diverse ecosystem consisting of steppe and tundra (Berglund et al., 2008). Unstable soils favored Arctic tundra species such as *Alnus*, and southern steppe species like Poaceae (Berglund et al., 2008). With increasing temperatures and humidity, shrubs and trees immigrated before vegetation decreased around 13,000 cal yr BP (Berglund et al., 2008). The rapid climate change at 12,700 cal yr BP replaced sub-Arctic woodlands with Arctic tundra ecosystems which inevitably led to a highly diverse ecosystem (Berglund et al., 2008).

Similar to the climate change event at 12,700 cal yr BP, the cooling event at 8.2 ka BP strongly effected the migration patterns of temperate broadleaved summer green, Boreal needle evergreen, and temperate broadleaved evergreen trees across Europe (Li et al., 2019). Pollen records show temperate summer green trees and grasses immediately responded to cooling temperatures while temperate evergreen trees lagged behind in western Europe (Li et al., 2019). Temperate summer green decreased in northern Europe at the start of the cooling before disappearing and dominating the southern regions (Li et al., 2019). Conversely, grasses expand and dominate areas that were once previously occupied by temperate summer green species (Li et al., 2019). Broadleaved evergreen trees slightly increase after cooling occurs, but northwestern broadleaved evergreens decreased as grass expanded and invaded southward (Li et al., 2019). These European studies laid the groundwork for palynology, and as the study continued to evolve it was quickly utilized in regions outside of Europe and spread to North America where the first studies were conducted on bogs in southeastern Canada (Auer, 1927; Birks and Berglund, 2018).

## **2.4 North American Glacial Age Pollen**

Pollen records from the LGM, which began ~20 ka in North America have proven to be particularly useful as they record abrupt changes occurring within the climate such as alternating warming and cooling events (Wang et al., 2019). Fossil pollen sequences from glacial deposits located along the Illinois and Mississippi river valleys, have analyzed sediments believed to be deposited during the Pleistocene, beginning ~2.4 million years ago, and Holocene, beginning ~11.6 ka, epochs (Curry and Follmer, 1992; Muhs et al., 2001). As the climate warmed after the LGM, glaciers slowly retreated across the surface of the Earth creating pockets and basins in which glacial sediments containing fossil pollen were deposited (Lawson, 1982). Glacial deposits found within river valleys and floodways in previously glaciated regions of North America have provided insight to the flow patterns of subglacial till deposited by glacier meltwater as it flowed southward toward previously unglaciated land (Dalton et al., 2018). Scientists have been able to infer the direction in which glacial deposits traveled as ice sheets receded and melted, and the migration patterns of vegetation as they responded to the warming climate.

Certain regions of the United States have provided useful pollen evidence to reconstruct vegetation assemblages in areas that were not previously glaciated. Fossil pollen evidence from Texas suggests that certain areas in the region were once covered by large, wooded areas while other regions consisted of savannas (Bryant Jr. and Holloway, 1985). The same pollen evidence from Texas suggests a north-south temperature gradient change existed during glacial and interglacial periods which likely effected the range and distribution of both plants and animals (Bryant Jr. and Holloway,

1985). Research has shown that the vegetation of high-latitude regions in Alaska were especially sensitive to climate warming (Muhs et al., 2001). Stratigraphic analysis of fossil pollen sequences reveals boreal species of *Picea* and *Betula* are found along these high latitudes and are representative of the present day Alaskan boreal forest (Muhs et al., 2001).

Paleorecords have reconstructed past climate and vegetation assemblages by analyzing dominant species in glacial pollen records and comparing the average temperature at which those species occur at today (Dalton et al., 2018). Pollen studies have also indicated that plant taxa respond individualistically to climate change rather than shifting as a whole community of species (Wang et al., 2019; Prentice et al., 1991). Focusing on species-specific response to climate change has provided an improved resolution of pollen taxonomy and interpretation of post-glacial forest dynamics (Finkelstein et al., 2006; Delcourt and Delcourt, 1987). Studies have focused on certain fossil pollen species by comparing them to modern day distributions to track their migration due to environmental changes during glacial and interglacial periods (Finkelstein et al., 2006; Delcourt and Delcourt, 1987; Gugger and Sugita, 2010). Fossil pollen records of *Abies* have been synthesized to estimate the location of tree populations at the LGM, and their post-glacial range shifts (Gugger and Sugita, 2010). Other species such as *Picea*, *Quercus*, *Fraxinus*, and *Pinus* have provided great insight to tree taxa migration as major glacial margins were shifting between 10,000 and 8,000 cal yr BP (Delcourt and Delcourt, 1987).

In their landmark synthesis study, the Delcourt's produced fossil pollen sequences from 162 different sites for *Picea*, *Pinus*, *Fraxinus*, *Quercus*, *Carya*, and *Populus* pollen



recovered from bogs and swamps (Delcourt and Delcourt, 1987). These sequences were used to reconstruct paleoenvironmental maps at 4000-year intervals illustrating the shifting glacial margin of the LIS in North America (see Figure 2.1 for *Pinus* example) (Delcourt and Delcourt, 1987).

Their results showed that tree taxa migrated and expanded their range northward toward newly deglaciated land as the southern margin of the LIS receded (Delcourt and Delcourt, 1987). Much of the vegetation that existed in the unglaciated region south of the LIS consisted of boreal forest-tundra species like *Picea* (Jacobson Jr. et al., 1987; Webb III, 1987; Jackson et al., 2000; Yansa, 2006). Boreal forest-tundra species were widespread along the southern margin of the LIS and migrated northeastward with the exception of *Pinus* which migrated in an east-west band south of the retreating ice, eventually expanding into the south where it occurs today (Jacobson Jr. et al., 1987; Delcourt and Delcourt, 1987).

From 20 ka BP to 16.5 ka BP northern Diploxylon *Pinus* species composed >60% of forest compositions within the central Atlantic Coastal Plain, and southern Appalachian Mountains, while minor constituents appeared in full-glacial forests within the Mississippi Alluvial Valley (Figure 3) (Delcourt and Delcourt, 1987). During this same time period, southern Haploxylon *Pinus* were primarily found in the southern Atlantic Coastal Plain before species percentages diminished to <20% west of the lower Mississippi Alluvial Valley (Delcourt and Delcourt, 1987). It is hypothesized that the southern pines sought refuge on the exposed continental shelf in areas that have now been consumed by the Gulf of Mexico and southern Atlantic (Schmidtling and Hipkins, 1998). These pines are ‘missing’ from the Delcourt’s study as there were no cores recovered

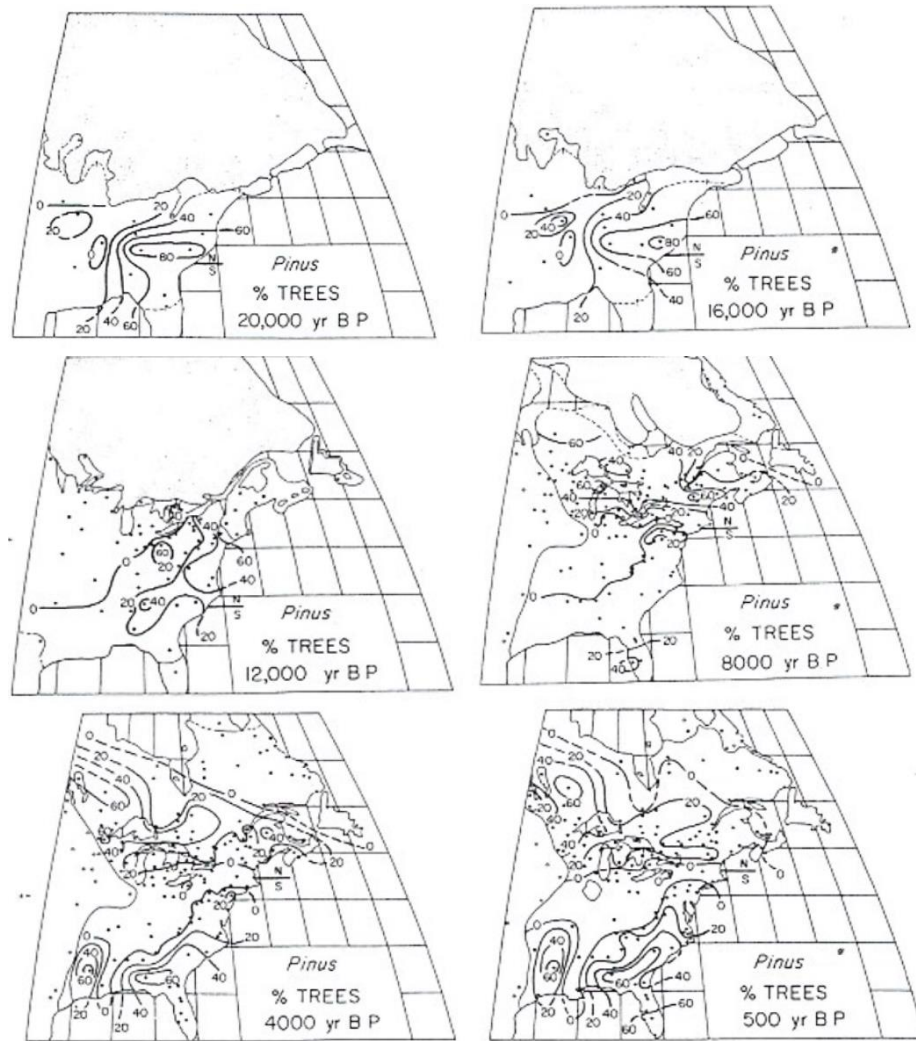
from these coastal refuges. This thesis adds additional information to the gap in the literature by providing a first look at these former glacial refuges on the exposed continental plain.

As the climate warmed from 16.5 ka BP to 12.5 ka BP, northern pines began to diminish in areas it previously dominated and became locally extinct by 16 ka BP in the continental interior while southern pine species remained on the exposed, southern Coastal Plain (Delcourt and Delcourt, 1987).

As the late Pleistocene transitioned to early Holocene at 12 ka BP, northern Diploxylon pines migrated northeastward and into southern New England by 12 ka BP, while the southern Haploxylon pines still had not made a significant appearance at the Delcourt's sites during this time, and still lingered on the exposed coastal plain (Delcourt and Delcourt, 1987). By 8 ka BP, Northern Diploxylon pines extended their range to 53°N where pine now composed as much as 60% of forest species (Delcourt and Delcourt, 1987). Southern Haploxylon pines migrated northward along the Atlantic Coastal Plain to southern Florida reaching >40% dominance as they emerged from their coastal refuge (Delcourt and Delcourt, 1987).

During the mid-Holocene interval at 4 ka BP, areas where northern Diploxylon pine once dominated extended northwestward from central Ontario across Manitoba, with the southern limit of northern Diploxylon pine extending from Minnesota and Wisconsin eastward across the Great Lakes and into New England (Delcourt and Delcourt, 1987). During this same interval, southern Haploxylon pines increased in dominance now comprising 40-60% of forests across the Gulf and Atlantic Coastal Plains (Delcourt and Delcourt, 1987). By pre-settlement times at 500 BP, northern Diploxylon pines

dominated the western Great Lakes region and central Canada, while southern Haploxylon pines expanded their ranges northward west of the Mississippi Alluvial Valley and increased in dominance across the Gulf and Atlantic Coastal Plains along with the Florida peninsula (Delcourt and Delcourt, 1987).



*Figure 2.1 Images of paleo-reconstruction maps of Pinus found within forests from 20 ka BP to 500 BP borrowed from the Delcourt's study (Delcourt and Delcourt, 1987).*

Research has also shown that as the LIS retreated, summer monsoons intensified, depositing fossil pollen from glacial refuges into lake basins causing their levels to rise (Shuman et al., 2002). Of importance in the Delcourt's study is the scarcity of sites and pollen evidence from the extreme southern regions of the U.S., and the lack of sites from the once exposed continental shelf during the LGM. Before the discovery of the Underwater Forest, there were no known methods of reconstruction for this environment on this glacial refuge. Questions regarding the timing and migration of certain taxa into the refuge, and out of the refuge as sea levels rose again, and their newly formed communities, still remain unaddressed.

### ***2.4.1 Important Considerations for Pollen Studies from a Glacial Refuge***

Several factors need to be considered when studying fossilized pollen from a glacial refuge. The Quaternary Period began ~2.6 million years ago and extends to present day. Throughout this period, the Earth has experienced repeated glacial and interglacial events, during which glaciers covered large landmasses of the world (the LIS of North America, and the Eurasian Ice Sheet of Europe), and warm periods when the glaciers melted. The latest glacial-interglacial cycle to occur was the Wisconsin glaciation. Approximately 100,000 years ago the Earth transitioned into a glacial period which reached its maximum extent, the Last Glacial Maximum (LGM), ~20,000 years ago (Baker et al., 1989; Clark and Mix, 2002). As these continental sized glaciers grew thicker and denser, due to an accumulation of snowfall, they began to advance across the planet, lowering sea levels by as much as 120-135 m (Fowler, 1997; Clark and Mix, 2002).

During this period, the LIS covered most of North America and expanded into Wisconsin and further south marking the beginning of the Wisconsin glaciation ~31,500 years ago (Baker et al., 1989). As the glacier expanded across North America, vegetation migrated southward (Delcourt and Delcourt, 1987). When the climate began to warm during the transition out of the stadial period, from 20 ka to 16.5 ka BP, the LIS, which extended south to ~40°N began, to recede causing sea levels to rise from glacial meltwater runoff (Delcourt and Delcourt, 1987). Glacial deposits containing loess, sediment from rocks finely ground due to glaciers moving across the Earth's surface, began to melt, and were deposited into surrounding waterways and drainage basins, such

as the Mississippi River, leading to the Gulf of Mexico (Delcourt and Delcourt 1987; Flower et al. 2004).

Plant assemblages existing close to the edge of the ice sheet migrated onto the newly deglaciated land and slowly extended their ranges northward with the warmer climatic conditions. Vegetation that existed in the southern part of unglaciated North America began to extend northward following the retreat of the ice sheet. During this period of warming as vegetation migrated northward with the retreating ice sheet, meltwater from surrounding ice caps discharged into the ocean, causing sea levels to rise significantly (Aharon 2003). As sea levels rose due to the influx of meltwater, flooding rapidly occurred burying, or erasing and washing away sediments containing fossilized pollen and plant macrofossils that were once above sea level.

## 2.5 Offshore Pollen Studies

Terrestrial pollen sequences archived in marine sediments were once thought to be difficult to use in paleoenvironmental reconstructions because they contain pollen from large scale mixing from diverse sources (Scott et al., 2012). However, due to the advancements in paleoenvironmental reconstruction scientists have been able to infer from marine sediment cores how vegetation responded to sea level changes along shorelines, and the continental shelf during glacial periods (Yu et al., 2017). Pollen recovered from cores in the South China Sea show vegetation radically changed during the LGM to the post-glacial period as sea levels rose (Yu et al., 2017; Shu and Wang, 2013). Herbaceous taxa increased dramatically due to changes in precipitation during glacial periods while non-arboreal pollen species were shown to indicate a forest-steppe environment existing under precipitation levels less than half of the modern-day regime (Yu et al., 2017).

Deep sea cores also revealed that wind transport of highly productive pollen species, such as *Pinus*, were found to have high percentages in sediments that were farther from the shoreline and buried under higher sea levels (Yu et al., 2017; Shu and Wang, 2013). These results indicate that wind transported species played an important role despite their transport limitation of river input into the deep ocean during periods when sea levels were high (Yu et al., 2017). Sediment cores recovered from the Bohai Sea in north China show high percentages of *Pinus* along with *Quercus*, *Carya*, *Liquidambar*, and *Betula* indicating a highly diverse forest composition that received pollen from the surrounding region before being overtaken by rising sea levels and expanding water bodies (Shu and Wang, 2013). Other regions of Asia have identified

TCT (Taxodiaceae-Cupressaceae-Taxaceae) pollen in marine sediments along the southern coastline of South Korea with deciduous angiosperms, along with *Pinus*, in upland areas (Yi et al., 2012). This assemblage implies that coastal areas of Korea were likely dominated by swamp vegetation whereas upland areas consisted of mixed deciduous-conifer forests during the Pliocene (Yi et al., 2012).

Marine pollen records from southwestern Africa show a change in vegetation distribution across various latitudes over the last 30,000 years (Dupont et al., 2007; Scott et al., 2012). These varying latitudes represent the vegetational shift of open forest, savanna, montane, and desert fringe (Dupont et al., 2007; Scott et al., 2012). Sediments dating to the last glacial period from the River Congo contained high percentages of *Cyperaceae* pollen that indicates the presence of swamps rather than savanna within the basin (Dupont et al., 2007). Pollen percentages are highest in sediments deposited at the river mouth and suggest that this influx is linked to continental shelf erosion, and rising sea levels (Dupont et al., 2007). Pollen samples dating to the early Miocene from the Niger Delta Basin in west Africa show an abundance of rain forest and freshwater swamp species indicating tropical paleoclimate conditions (Ogbahon, 2019). Distribution patterns of grass and mangrove pollen suggest climate conditions fluctuated between dry and wet periods (Ogbahon, 2019).

Marine sediments located in the Canary Islands have revealed vegetation changes over the last 9600 years in response to the changing climate (Nascimento et al., 2015). Pollen sequences representing hygrophilous trees were replaced by Monteverde forest taxa approximately 5500 years ago suggesting the climate was shifting towards drier conditions (Nascimento et al., 2015). Forest composition shifted on Tenerife around



2000 years ago, eliminating species of *Quercus* and *Carpinus* from pollen records as a result of the appearance of the first human colonists (Nascimento et al., 2015).

In addition to this, offshore pollen studies from South America have provided an extensive record of vegetation changes during glacial and interglacial periods. A 50,000 year-long record containing pollen embedded in sediments from the Amazon deep-sea fan, and the continental shelf, has been used to reconstruct past vegetation within the Amazon Basin (Haberle and Maslin, 1999). Evidence revealed that tropical forests still dominated the Amazon during the last glacial period (Haberle and Maslin, 1999; Colinvaux et al., 1996). However, forest composition varied due to reduced precipitation, atmospheric carbon dioxide, and considerable cooling of the climate (Haberle and Maslin, 1999). Pollen analysis of the Amazon Basin shows forest assemblages appear to be characterized by continuous resorting of structure and composition throughout the LGM (Haberle and Maslin, 1999). Andean taxa, which are now separated by altitude and temperature, were later incorporated into lowland communities (Haberle and Maslin, 1999).

In other regions of South America, pollen sequences collected from swamp forest sediments along the coast of Chile indicate a humid phase occurred between ~9900 and 8700 cal yr BP due to the presence of dense swamp forest taxa (Maldonado and Villagrán, 2006). Pollen starved sediments containing little evidence pointing to semiarid vegetation assemblages imply that a period of extreme aridity occurred until approximately 5700 cal yr BP (Maldonado and Villagrán, 2006). Pollen analysis shows that swamp vegetation recovered slowly due to a prominent moisture increase at ~4200 cal yr BP, before a slightly less intense drought period occurred between ~3000 and 2200

cal yr BP (Maldonado and Villagrán, 2006). Climate was highly variable at ~2200 cal yr BP, but swamp forest taxa successfully expanded while changes were occurring during the Holocene (Maldonado and Villagrán, 2006).

## **2.6 Quaternary Dendrochronology and Baldcypress Reconstruction**

While pollen analysis is a commonly used method for reconstructing past environments, it is not the only method available. Since glaciation did not occur in the southeastern United States, there is a lack of long-lived suitable archives containing well-preserved fossil pollen, due to the high amount of deterioration, and lithological changes occurring within basins located in the southeast (Delcourt and Delcourt, 1980). Many paleoenvironmental archives, such as lakes, that exist in the southern United States consist of meandering river floodplain ecosystems that lead into oxbow lakes which act as catchment areas of sediments and nutrients (Bhattacharya et al., 2016; Shen et al., in press). Though oxbow lake sediments are effective palaeoecological archives, no oxbow lakes exist extending back to the LGM (Bhattacharya et al., 2016; Shen et al., in press; Bryant, 1985). Therefore, dendrochronology is often used in conjunction with pollen analysis due to its reliability of using annual growth tree-ring dates to observe how vegetation has responded to changing climatic, and atmospheric conditions over an extended period of time.

Andrew Douglass was the first to observe crosscut sections of trees deeming ‘sensitive rings’ within the wood in 1904, and later publishing his idea in 1909 (McGraw, 2003). At first, tree ring chronologies were limited to about 4,000 years ago, but combined oak and pine chronologies from Hohenheim University have extended dates as far as 10,429 BP, and have become the backbone for Holocene radiocarbon calibration (Friedrich et al., 2004; McGraw, 2003; Mackay et al., 2003). Evidence of dendrochronology studies has shown that casting a wide net over broad geographical distributions is essential because spatial reconstructions demand suitable networks of tree

ring dates across the world (Martinelli, 2003). Well preserved tree-ring samples were obtained from oaks and pines in exposed gravel pits in southern Germany (Friedrich et al., 2004). These species are made up of resistant heartwood making them preservable under anaerobic conditions over thousands of years (Friedrich et al., 2004; Becker and Kromer, 1986). Tree-ring dates revealed that the trees died and were quickly buried in sediments by fluvial activity (Friedrich et al., 2004). Chronologies also showed that large annual growth rings were prevalent due to the improved growing conditions on the floodplains after the mid-Holocene (Friedrich et al., 2004; Becker and Kromer, 1986).

Other studies have shown many forested regions of the subarctic, subantarctic, and the tropics have proven particularly useful in dendrochronological reconstructions due to the high sensitivity of the tree species responding to climatic changes (Martinelli, 2003; Mancini, 2002; Garibotti and Villalba, 2017; Mamet, 2012; Payette et al., 2002; Caetano-Andrade et al., 2020; Giraldo et al., 2020). Dendrochronologic analysis of tree logs and stumps preserved in anoxic peat, mud, and lake sediments show that much of the Eurasia Arctic region was ice-free and partly forested (Eronen and Jasinski, 2002). As the Eurasian ice sheet melted, vegetation of tundra, steppe, and forest resided south near the ice border (Eronen and Jasinski, 2002). These tree species were set to invade the newly deglaciated landscape 15-13 ka in Siberia, and 13.1 ka in Sweden (Eronen and Jasinski, 2002; Hantemirov and Shiyatov, 2002). Chronology studies of subantarctic species show that vegetation did not colonize until nearly a century after glaciers had retreated, and newly exposed surfaces for growth and colonization, such as moraines, had formed (Garibotti and Villalba, 2017). Other regions containing subantarctic species show

contrasting chronologies with vegetation rapidly colonizing previously barren landscape to a forested area dominated by trees (Garibotti and Villalba, 2017).

Certain regions of the tropics have also provided valuable insights to tree-ring chronologies due to their high sensitivity as the climate changes. Tropical species located within the Chocó region of Colombia experience hydric seasonality, dry or flooding periods (Giraldo et al., 2020). Even under these conditions tropical tree species can still experience growth periodicity showing visible growth rings that are useful in dendrochronology (Giraldo et al., 2020). Tree-rings revealed an annual rainfall >7200 mm dating 1000-670 y BP and indicate that tropical species are able to capture and record a span of historical overhauls embedded in the wood (Giraldo et al., 2020; Caetano-Andrade et al., 2020).

Studies have also been conducted extensively across North America. Dendrochronology analysis performed on fossil wood from a reservoir in Colorado was compared to modern trees revealing an age dating back to the Pleistocene era (Brown et al., 2014; Griggs et al., 2017). Results show fossil trees likely grew under similar environmental conditions as today (Brown et al., 2014). Fossil wood preserved in glacial deposits was found along the shoreline of Lake Michigan that became overrun by the LIS (Panyushkina and Leavitt, 2007). Preserved remains of wood provided high resolution tree rings from a period of 14,000-4,000 yBP occurring in moist lowland and cedar swamps (Panyushkina and Leavitt, 2007). Chronologies revealed that ring size changed and grew which is consistent with rising water levels due to the LIS (Panyushkina and Leavitt, 2007). Other tree-ring data have shed light on glacier movement in Alaska showing glacial activity is consistent with fluctuations of tidewater (Wiles et al., 1999;

Payette et al., 2002). Areas along the ice margin were overtaken by glacio-lacustrine and fluvial sediments that likely occurred during an ice advance before 500 cal yr A.D. (Wiles et al., 1999). Though different trees have different growing rates, growth rings from different trees of varying species have shown a re-population of forestation following the retreat of ice sheets as early as 7<sup>th</sup> century A.D. (Wiles et al., 1999).

Past dendrochronology studies from various regions of the world have proven to be useful. However, for this thesis study, dendrochronology studies along the coastal regions of the United States are, perhaps, the most important regarding reconstruction of changing ecosystems over time. Dendrochronology studies conducted in coastal forest ecosystems that were not previously glaciated across the world have provided groundbreaking information regarding sea level change, global temperature change, and storm intensity and frequency (Penland et al., 1990; Doody, 2004; Valiela, 2009; Tucker and Pearl, 2021). These coastal ecosystems record the adaptation and impacts of global phenomena as they affect tree growth (Tucker and Pearl, 2021). Many of these coastal ecosystems include baldcypress swamps, which are commonly found at edges of rivers and oxbow lakes in flood plains (Little, 1977). Baldcypress is a long-lived deciduous conifer that is highly responsive to precipitation, temperature changes, and produces clear, and simple growth rings that can be used to date the exact year over a wide temporal scale (Stahle et al., 2011; Stahle et al., 2012; Brandon, 2013; Therrell et al., 2020).

Existing bald cypress forests have been extended with data from subfossil bald cypress wood to develop these exact chronologies and reconstruct climate change over a certain period of time (Stahle and Cleaveland, 1992; Stahle et al., 2011). Reconstructions

made from precipitation, and drought index data derived from these long chronologies are commonly used to determine climate dynamics (Stahle et al., 2012). The majority of these reconstructions are made from living trees and/or dead logs that are collected from the surface, submerged in the water, or partially buried in the sediment (Stahle et al., 2012). Chronologies available from bald cypress wood of living trees, and buried logs shows potential for millennia-long chronologies dating back to the late-Holocene (Stahle et al., 2012). This chronology has been partially achieved in the southeastern United States in South Carolina, and recently in the Gulf of Mexico (Stahle et al., 2012; Reese et al., 2018; DeLong et al., 2021; Gonzalez et al., 2017). Very few bald cypress forests located in wetland environments exist in the southeastern United States, and even fewer ancient bald cypress forests exist anywhere in the region (Stahle et al., 2011; Dimichele and Falcon-Lang, 2011). However, the fossilized bald cypress stumps found in the Underwater Forest is the first ancient forest to exist in the southeast containing both bald cypress, and fossil pollen in an environment that was flooded due to sea level increase.

Taking all these studies into consideration, it is clear that fossil pollen has been utilized across the planet extensively. It has also been shown that dendrochronology has provided an excellent method of dating, and an additional source of information to aid in reconstructions of past environments. Pollen sequences and subfossil wood have been analyzed from terrestrial sediments, glacial deposits, and lacustrine sediments. Despite all this, there are still no studies focusing on sites located offshore on the once exposed continental shelf. If these sites do exist, they have not yet been discovered nor has any research about them been published. The first site to bring forth new information about

fossil pollen from a glacial refuge existing within a marine environment in the southeastern United States is the Underwater Forest.

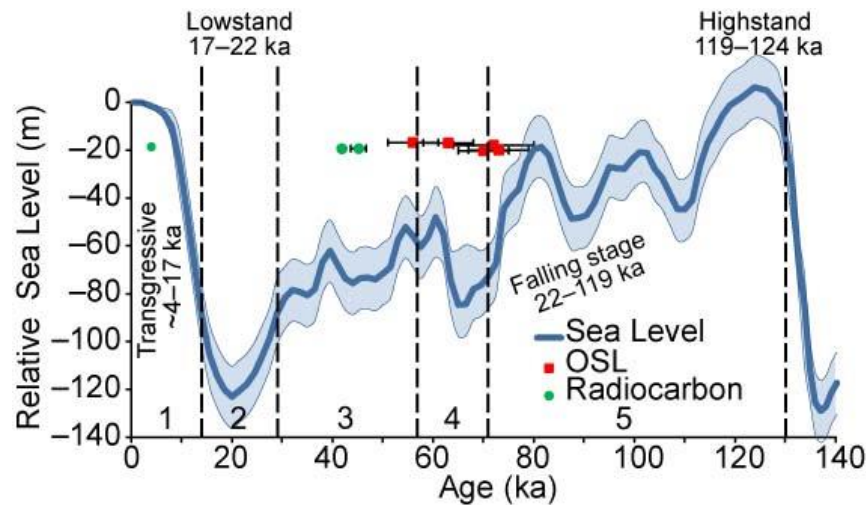


## CHAPTER III – STUDY AREA

### 3.1 Geologic Setting

The Underwater Forest resides in ~18 m of water within the Gulf of Mexico approximately 13 km off the coast of Gulf Shores, Alabama. It is situated along the western edge of the paleo-Mobile River valley located along the eastern branch, covering approximately 2 km<sup>2</sup> of the Northern Gulf of Mexico continental shelf (refer back to Figure 1.1) (Reese et al., 2018; DeLong et al., 2020; DeLong et al., 2021). No surficial expressions of the paleo-valleys exist today likely due to the fact that they were filled with a combination of estuarine, marine, and deltaic sediments during and after sea level transgression (DeLong et al., 2020).

The site is bordered to the north by the Alabama barrier islands, the St. Bernard Lobe of the Mississippi River Delta System, and Chandeleur Islands to the west, the carbonate-ramp platform of the Florida Peninsula to the east, and the DeSoto Canyon to the southeast (Figure 1.1) (DeLong et al., 2020). The site is occupied in the Mississippi-Alabama-Florida (MAFLA) sand sheet zone of the passive outer continental shelf northern Gulf of Mexico (Figure 1.1) (DeLong et al., 2021). Evolution of the MAFLA sand sheet is believed to be largely tied to sandy sediment discharge from small rivers (DeLong et al., 2021). Located below the sand sheet is a deep valley from the LGM carved out by the Mobile-Tensaw River System that was originally initiated before the Wisconsin Glaciation (DeLong et al., 2021). The LGM was encompassed by MIS 2, followed by MIS 1, which experienced a slowing in sea level rise during the Holocene, allowing for the formation of coastal landforms to develop in the Gulf of Mexico which have since stabilized (Figure 3.1) (Gonzalez et al., 2017).



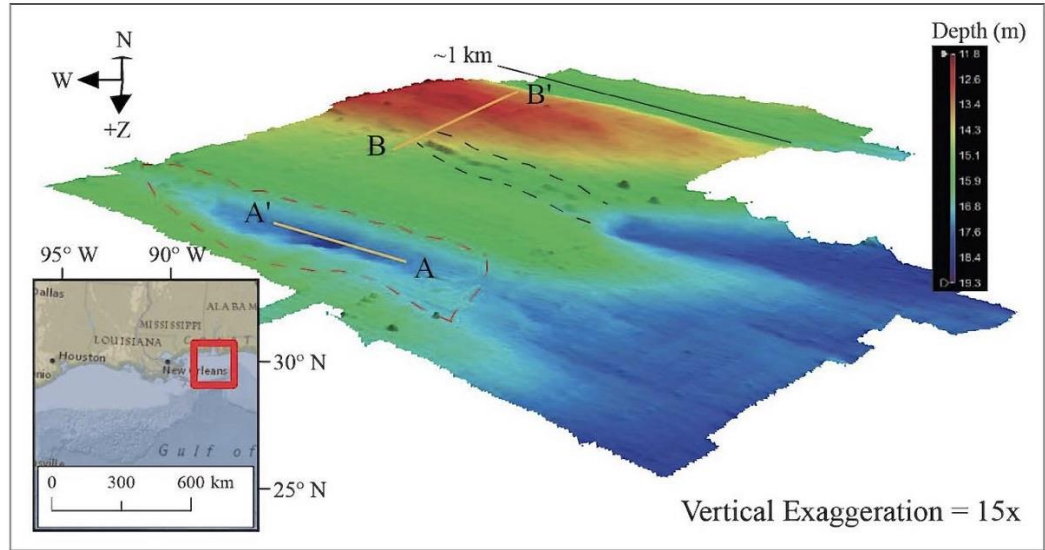
*Figure 3.1 Global sea level variations for the last glacial interval. Core 15DF1 depth range and radiocarbon age are plotted on eustatic sea level maximum and minimum range (Gonzalez et al., 2017).*

The sea level curves seen in Figure 3.1 have been used to approximate a time frame in which the forest may have grown (Gonzalez et al., 2017). At the 20 m depth level is an intersect of sea level near dates of ~10,000 ka, ~82,000 ka, ~115,000 ka, and ~125,000 ka (Gonzalez et al., 2017). Between ~80 ka to 10 ka global sea levels rose and fell below the modern water depth of the study site, and represent a period where the forest was likely alive, and the continental shelf was exposed as land which allowed for the establishment of terrestrial ecosystems (DeLong et al., 2020). The forest is estimated to have grown between 74-45 ka before experiencing burial during the deglacial interval (18-10 ka) (DeLong et al., 2020). However, it is also possible the forest site could have been buried by overbank flooding which occurred independently of sea level rise.

The width of the shelf thins from 200 km to 50 km beginning near the Chandeleur Islands of Louisiana to the Florida panhandle (DeLong et al., 2020). The portion of the

shelf located south of Alabama receives a generous amount of sediment mainly from the Mobile Bay, and barrier islands and spits (DeLong et al., 2020). The Underwater Forest is believed to have once been covered by the MAFLA Holocene sand sheet and indicates a northwest-southeast shore oblique-ridge with trough morphology relief up to 5 m (DeLong et al., 2020; DeLong et al., 2021). Figure 1.1 depicts the track of Hurricane Ivan in 2004, which caused extreme wave action that likely removed the sand sheet and resulted in substantial scouring of the seafloor, exposing the Underwater Forest site (DeLong et al., 2020; DeLong et al., 2021).

Today, the site is composed of exposed bald cypress stumps in growth position, and fossil pollen embedded in terrestrial peat sediment overlain with sand and interbedded mud and clays (Reese et al., 2018; DeLong et al., 2021). Other paleoenvironmental proxies found embedded in the terrestrial sediment include foraminifera and seeds (DeLong et al., 2020). The seafloor of the forest contains a series of troughs and ridges extending northwest and southeast with 2-5 m vertical relief, and ~0.5 km wavelength (Figure 3.2) (DeLong et al., 2021). These stumps reside within and around a ~0.5-1 m deep trough that runs ~100 m long with <10° walls (Figure 5) (DeLong et al., 2021).



*Figure 3.2 A 3D digital elevation model representing bathymetric data from 2015 and 2016. Red dashed lines represent the trough where tree stumps are exposed (DeLong et al., 2021).*

## 3.2 Core Analyses

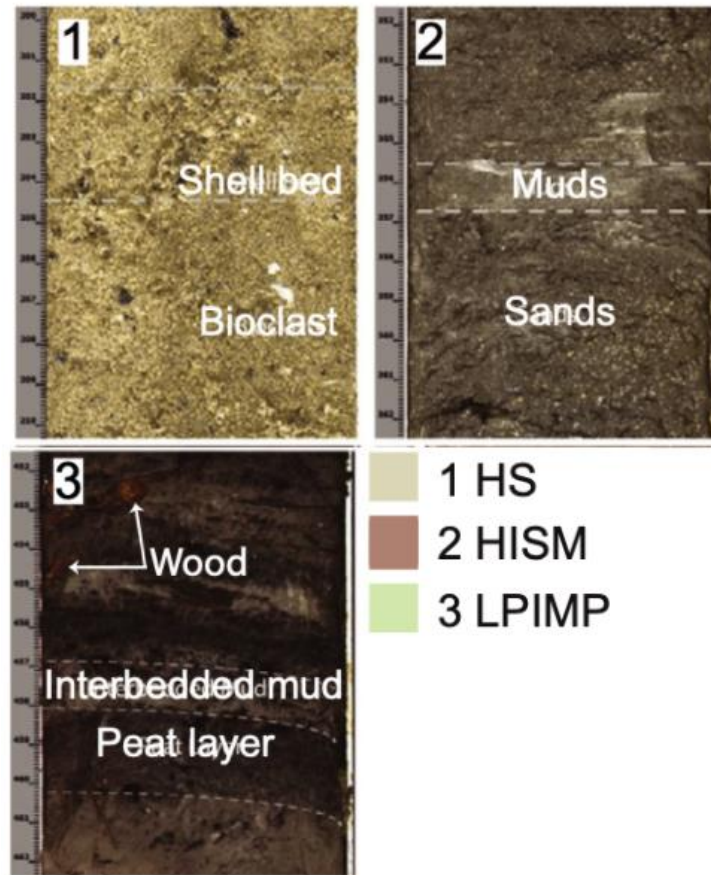
### 3.2.1 *Sediment Composition*

Previous studies have been conducted in the northern Gulf focusing on the Holocene evolution of Mobile Bay sediments (DeLong et al., 2020). These studies show seven environmental facies within the MAFLA area: lower shoreface, sand sheet, open bay or central estuary, lower bay shoreface, bay beach, and two Pleistocene soil horizons (DeLong et al., 2020). The MAFLA is largely composed of Quaternary sediments deposited by small rivers during glacial intervals and shifting depocenters (DeLong et al., 2020). Analysis shows that Holocene sands at the site were overlain by Pleistocene coastal and terrestrial deposits (DeLong et al., 2020). Cores collected from the forest contain multiple sediment types which allowed preservation of fossil pollen and wood in the peat sections (DeLong et al., 2020). Sediment analysis further revealed that preservation was made possible by anoxic sediments, such as the peat from the top of the cores, that are typically found in swamp environments (DeLong et al., 2020).

Sediment samples from all cores were found to be of Pleistocene age with river derived, back swamp, and deltaic plain interbedded mud and terrestrial peat along with woody remnants (Reese et al., 2018). Gonzalez and others (2017) show sediment analysis from the ancient forest is composed of five facies: Holocene sand, Holocene interbedded sand and mud, late Pleistocene interbedded mud and peat, late Pleistocene interbedded sand, and mud, and late Pleistocene paleosol (Figure 3.3). Facie 1 consisting of Holocene sand is characterized by light beige to gray, fine-medium grained quartz sand with an abundance of shell fragments (Gonzalez et al., 2017). Facie 2 contains Holocene interbedded sand and mud of light to medium dark gray mud containing fine

grained sand and some shell fragments (Gonzalez et al., 2017). Facie 3 of late Pleistocene interbedded mud and peat contains dark gray and tan to brown mud, peat, woody debris, microfossils, and seeds (Gonzalez et al., 2017; DeLong et al., 2020). Facie 4 is similar in pattern to facie 2, but contains more sand, is darker in color, has higher organic content, and contains no microfossils (DeLong et al., 2017). Facie 5 is characterized as having light gray to yellow-orange silt and clay due to oxidation (DeLong et al., 2020).

These Pleistocene deposits consist of the Citronelle Formation which is an extensive siliciclastic deltaic deposit found across the Gulf Coastal Plain (Gonzalez, 2018). Sediments can be frequently shifted on to the continental shelf due to the microtidal area of the Northern Gulf Coast, and are composed of silts, clays, and gravels that can be traced from Florida to Texas (Gonzalez, 2018; DeLong et al., 2020).



*Figure 3.3 The three lithofacies found from sediment analysis. Numbers indicate facies. Facies 1 Holocene sand (HS), facies 2 Holocene interbedded sand and mud (HISM), and facies 3 late Pleistocene interbedded mud and peat (LPIMP) (Gonzalez et al., 2017; DeLong et al., 2020).*

### 3.2.2 Pollen

Pollen analysis was performed on two cores, 15DF1 and 15DF3B (this thesis), and results for 15DF1 were published by Reese (2018). Figures 3.4 and 3.6 show core 15DF1, measuring at 4.9 m long, was taken at 15.3 meters below sea depth ~420 m northeast of the trough on a slightly elevated ridge (DeLong et al., 2020). Figure 3.7B depicts the elevation where 15DF1 is located on the ridge northeast of the trough. Core 15DF3B measuring at 4.53 m long, and located ~560 m southwest of 15DF1, was taken from within the trough at a slightly lower elevation 15.8 meters below sea level (Figures 3.5 and 3.6) (DeLong et al., 2020).

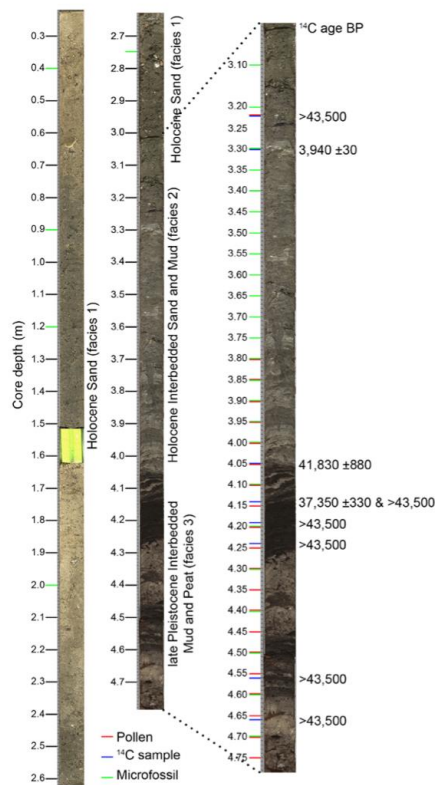
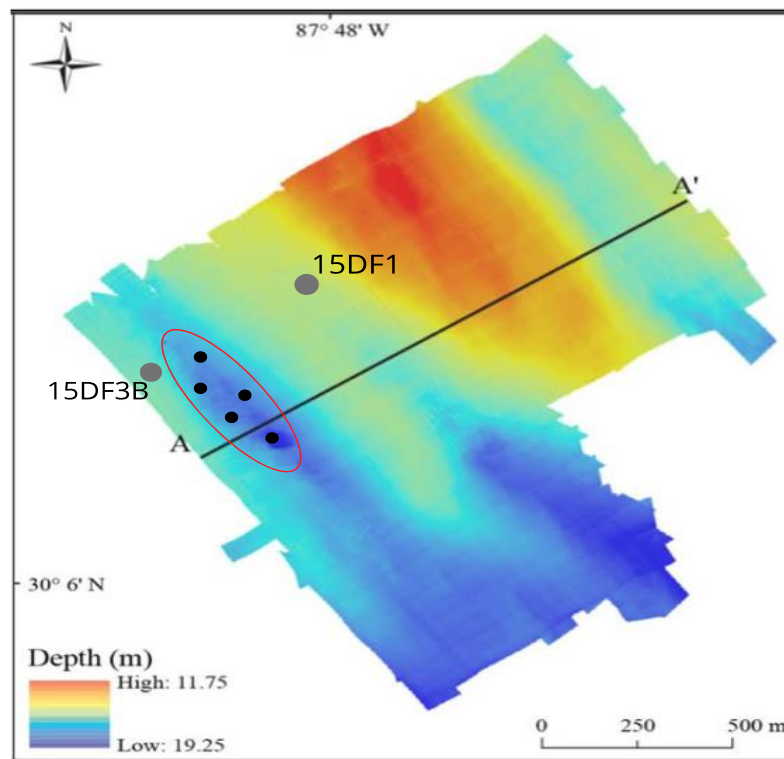


Figure 3.4 Sample locations of micropaleontological and  $^{14}\text{C}$  analysis and view of lithofacies in core 15DF1.

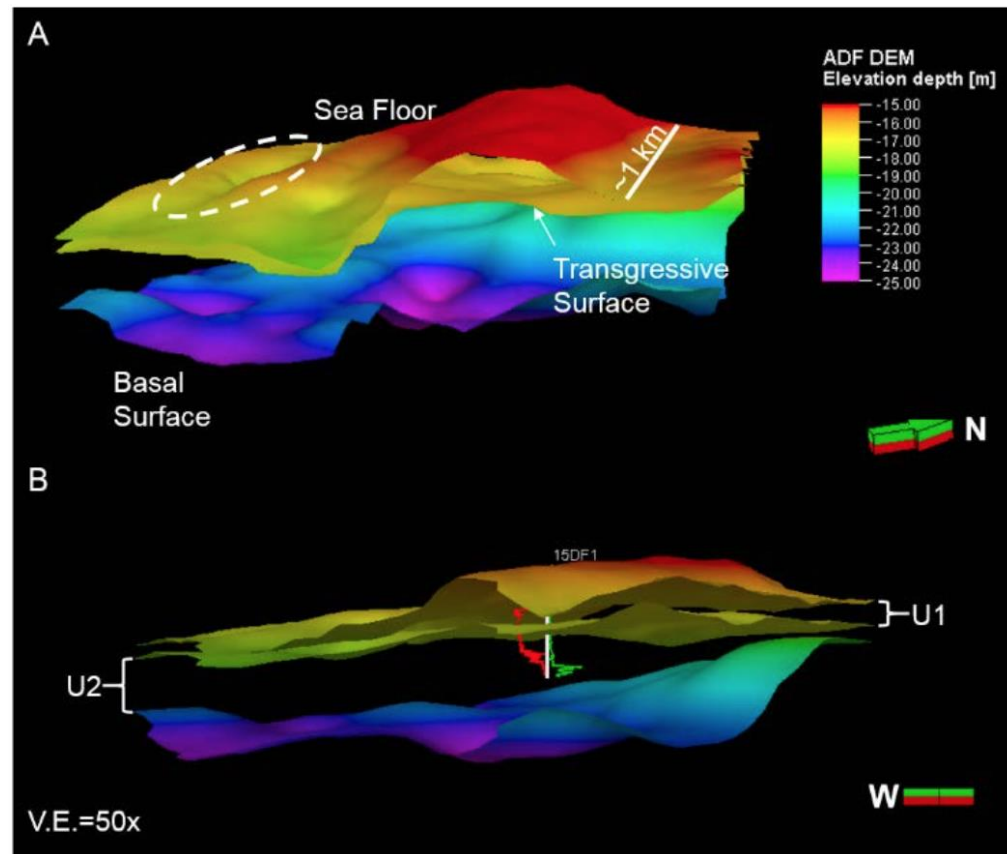




*Figure 3.5 Image of core 15DF3B lithofacies (Reese 2020).*



*Figure 3.6 Bathymetric map of core locations. The red circled area represents the trough containing the exposed stumps which are represented by the black dots (DeLong et al., 2020).*



*Figure 3.7 3D subsurface model of the study site. (A) white dashed circle represents trough where stumps are exposed. (B) core 15DF1 displayed on the elevated ridge (DeLong et al., 2020).*

### 3.2.3 Wood and Dendrochronology

Five of twenty-three wood specimens collected by divers were visually identified as bald cypress due to volume of sample size (Figure 3.8) (DeLong et al., 2020). One specimen of the twenty-three was identified as a palm but was very degraded, and therefore discarded as it could not be used for dendroclimatology (DeLong et al., 2020). Stumps were identified and confirmed as bald cypress due to a commonly found indicator of pinching rings and growth forms (DeLong et al., 2020). DeLong and others (2020) noted that stumps from the Underwater Forest are similar to modern day baldcypress from Pascagoula, Mississippi.



*Figure 3.8 Twenty-three wood specimens collected in 2013 by divers. The specimen identified as a palm (j-k) was discarded due to degradation (DeLong et al., 2020).*

Twelve of the twenty-three wood samples were retained for dendrochronology analysis, but two samples were unsuccessful due to dating issues and disturbance caused by wood-boring organisms (DeLong et al., 2020). The remaining ten samples were successfully cross dated against one another, developing a floating in time Submerged Forest tree-ring chronology (SFC) (DeLong et al., 2020). A reliable  $^{14}\text{C}$  date could not be established because this chronology is floating in time, therefore, bald cypress references from Pascagoula, beginning at 1466 CE, could not be used to cross date against due to the time series (DeLong et al., 2020). Radiocarbon and OSL results of wood specimens estimate the age of the forest is between 41.8 and 74 ka (DeLong et al., 2020).

### 3.2.4 Foraminifera

Foraminifera found within the sediment were identified to the genus and species level when possible and compared to specimens at the LSU Natural Science Museum's Collection of Fossil Protists and Invertebrates (DeLong et al., 2020). Foraminifera was only found in facies with sandy sediments and interbedded sand and mud (DeLong et al., 2020). Both 15DF1 and 15DF3B contained foraminifera such as the genus *Rosalina* and *Elphidium* (DeLong et al., 2020). Analysis of 15DF1 estimates foraminifera found within the core to be of Holocene age (Figure 3.9) (DeLong et al., 2020).

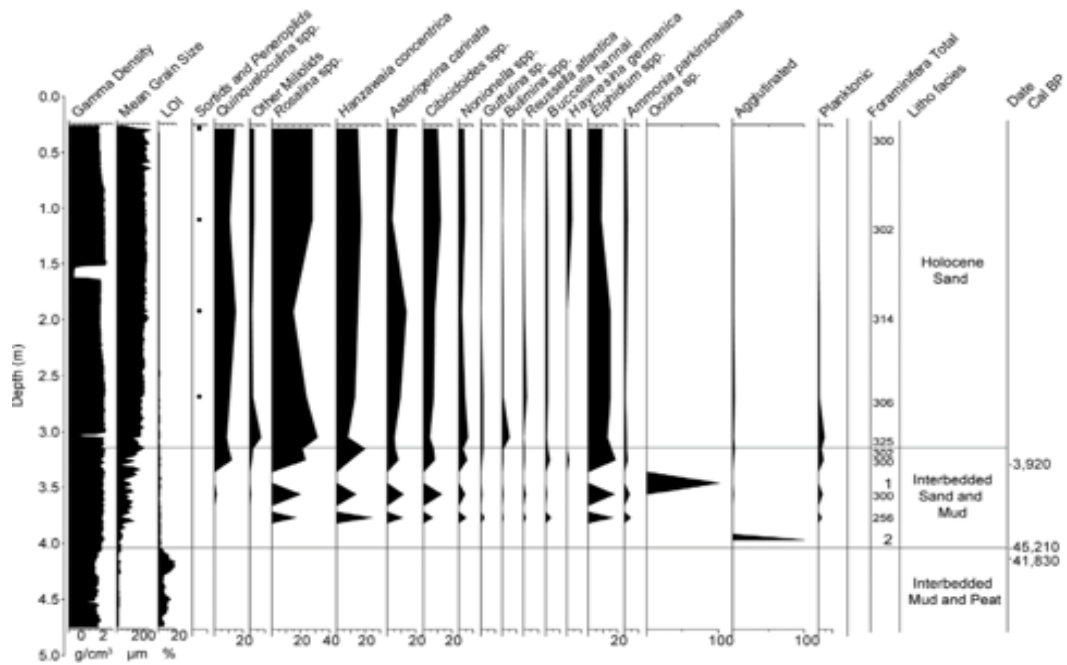


Figure 3.9 Analysis of foraminifera in core 15DF1 (DeLong et al., 2020).

### 3.2.5 Seeds

Figure 3.10 shows seeds that remained intact and were found preserved in mud and peat samples collected from core 15DF1 (DeLong et al., 2020). Notable species include *Taxodium*, *Liquidambar*, and *Nyssa* (DeLong et al., 2020). Only preliminary analysis of seed presence has been completed for core 15DF1, and seeds have been saved for future analysis (DeLong et al., 2020).

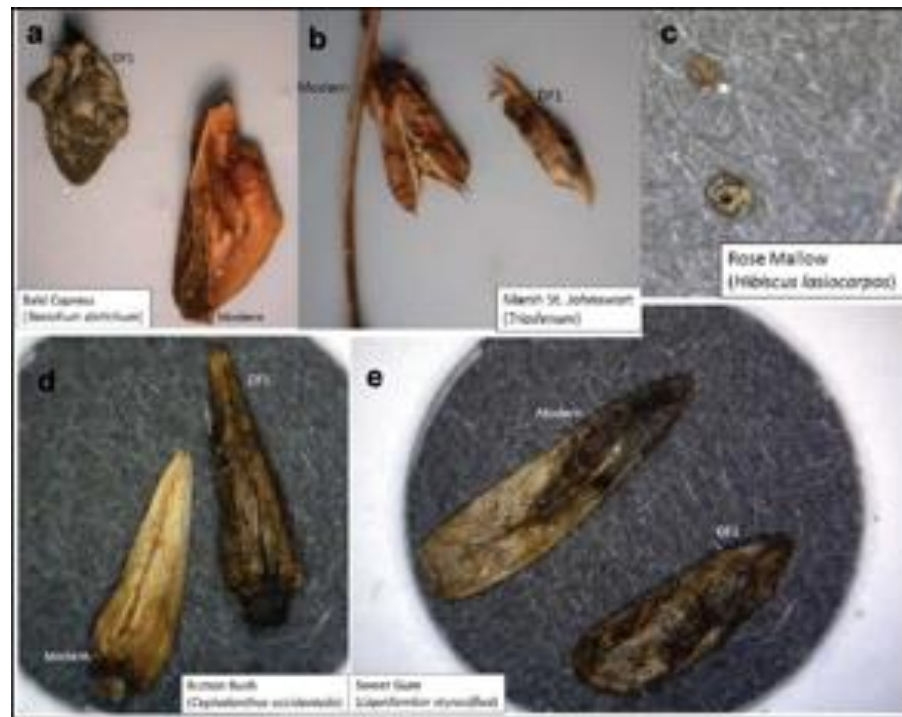


Figure 3.10 Seeds from core 15DF1 found preserved in the peat section (DeLong et al., 2020).

## CHAPTER IV – METHODOLOGY

### 4.1 Field Work

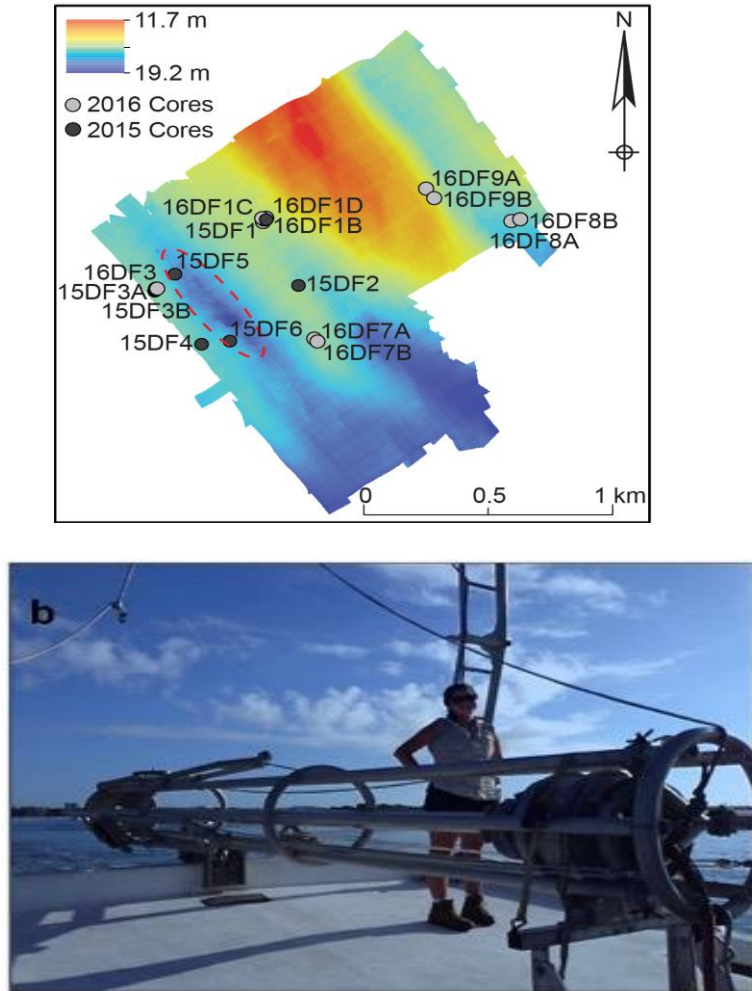
The forest was initially discovered by divers in 2010. In 2012, a survey was conducted revealing a 1.2 m deep depression and a 408 m long channel and was followed by diving operations in October of 2013 which recovered wood specimens (DeLong et al., 2020). More fieldwork was conducted in 2015 and 2016 via the R/V *Coastal Profiler* which is owned by Louisiana State University's (LSU) Coastal Studies Institute (DeLong et al., 2020). Vibracores were retrieved from the site to analyze terrestrial sediments (DeLong et al., 2020). A second collection was made in July 2021 via the *Point Sur* to retrieve more samples, but the expedition was largely unsuccessful.

#### 4.1.1 Vibracoring

The samples collected from 2015 and 2016 using a 6 m long, 75 mm diameter aluminum tube attached to a vibrating head held together by a steel tripod deployed from the *Coastal Profiler* (DeLong et al., 2020). Figure 4.1B depicts the vibracoring system during transit (DeLong et al., 2020). The vibracoring system was submerged into the water and lowered onto the seafloor in water ranging from 14-18 m in depth with operations ceasing once the vibracore could not penetrate further into the seafloor (DeLong et al., 2020). Cores were collected at various areas to target specific features of interest around the sediment ledge, in the depression, and where modern sediments were present in the east and south (Fig. 4.1A) (DeLong et al., 2020). Sediment cores were cut onboard into 1.5 m long sections, labeled, and sealed with tape for transport (DeLong et al., 2020). Cores were transported to LSU, cut in the vertical position in order to preserve core integrity, and placed in a refrigeration unit at 4°C (DeLong et al., 2020). In 2016, a



total of five locations were sampled with two cores taken from each site with one core to be used for optically stimulated luminescence (OSL) dating, and the other for the core scanner (DeLong et al., 2020). Cores collected for OSL dating were wrapped in black plastic bags to limit sunlight penetration which could affect sediments (DeLong et al., 2020).



*Figure 4.1 (A) map of the study with all cores taken from 2015 and 2016 shown. (B) the vibracoring system used for sample collection in 2015 and 2016 (DeLong et al., 2020).*



## 4.2 Laboratory Methods

### 4.2.1 Pollen Processing

Samples recovered from two cores at LSU, 15DF1 and 15DF3B, were analyzed and compared for pollen percentage similarities. Previously, Reese et al. (2018) sampled the lower section of core 15DF1 (4.05-4.75 m) at LSU. Samples were collected every 5 cm with one sample taken from a small disjunct layer of peat at 3.23 m (Reese et al., 2018). At each level, 0.6 cm<sup>3</sup> of material was extracted for pollen analysis. In October of 2020, core 15DF3B was sampled from 2.90 m to 4.20 m with samples collected every 5 cm except for samples at 4.0-4.20 m which were collected every 10 cm due to a loss of sediment. Each core sample, 15DF1 and 15DF3B, underwent the same processing technique (Faegri and Iversen, 1989).

Before processing began, a single lycopodium tablet (batch no. 483216, count 18583) was added to the sample to calculate pollen concentration. Standard pollen processing procedures as set forth by Faegri and Iversen (1989) were followed. Samples were subjected to chemical processing to aid in removal and breakdown of organic material. Samples were first exposed to 10% hydrochloric acid (HCL) to remove carbonates. 10% potassium hydroxide (KOH) was added to deflocculate the sample and break down organics. Hydrofluoric acid (HF) was used to dissolve any clay minerals and diatoms that may have been present followed by acetolysis solution for removal of cellulose. The remaining residue was then stained with safranin, suspended in silicone oil, mounted on slides, and counted under a light microscope at 400x. Pollen grains were counted until a minimum of 300 grains had been identified as per standard practice, including grains that were indeterminable. *Key to the Quaternary Pollen and Spores of*

*the Great Lakes Region* (McAndrews et al., 1973) was used to identify pollen grains.

Tilia software was used for pollen percentage calculations and concentrations as well as to present pollen assemblage results graphically (Grimm, 1991; Reese et al., 2018).

Radiocarbon dating was performed on sediment from core 15DF1 (Table 4.1). A sub-sample of sediment located within the peat section was extracted from the 4.14 m depth along with seven additional samples taken at depths: 3.22 m, 4.05 m, 4.19 m, 4.56 m, 4.07 m, and a duplicate sample of 4.14 m (Gonzalez et al., 2017; Reese et al., 2018). Samples were sent to Beta Analytic, Inc. for dating (Gonzalez et al., 2017; Reese et al., 2018). Dates from the sub-sample taken at 4.14 m revealed a  $^{14}\text{C}$  age of  $37.35 \pm 0.33$  ka (41.83 cal ka with a range of 42.235 to 41.350 cal ka) (Gonzalez et al., 2017). The radiocarbon date for the sample taken at 4.05 m, which is located between the interbedded mud and peat and overlain by interbedded mud and sand, had an age of  $41.83 \pm 0.88$  ka (with a median calibration age of 45.210 cal ka and range of 46.690 to 43.625 cal ka) making this sample older than peat from the 4.14 m sample (Gonzalez et al., 2017; Reese et al., 2018). The six other samples came back radiocarbon ‘dead’ (Gonzalez et al., 2017; Reese et al., 2018). These dates have been interpreted with caution as they are near the radiocarbon reliable detection limit (Gonzalez et al., 2017; DeLong et al., 2020).

Sample name	Depth in core (cm)	Material dated	Conventional radiocarbon age ( <sup>14</sup> C a BP)	Calibrated age range (cal a BP) (95% prob.)	Intercept of conventional radiocarbon age with calibration curve (cal a BP)
DF1-322	322	Plant remains	>43 500	—	—
DF1-405	405	Plant remains	41 830 ± 880	46 690–43 625	45 210
DF1-414-1	414	Plant remains	37 350 ± 330	42 235–41 350	41 830
DF1-414-2	414	Plant remains	>43 500	—	—
DF1-419	419	Plant remains	>43 500	—	—
DF1-424	424	Plant remains	>43 500	—	—
DF1-456	456	Plant remains	>43 500	—	—
DF1-466	466	Plant remains	>43 500	—	—

*Table 4.1 Radiocarbon dating results from core DF1 (Reese et al., 2018).*

Only one sample from core 15DF3B, taken from the interbedded mud and peat section, at 3.1 m was sent for radiocarbon dating, and came back radiocarbon ‘dead’ (DeLong et al., 2020). A date from a sister core, 16DF3A, located less than half a meter from 15DF3B was extrapolated and used as a dating control for 15DF3B (Fig. 4.1A). Core 16DF3A was taken at 15.8 m below sea level measuring at 2.32 m in length (DeLong et al., 2020). A sample from 16DF3A was taken at 2.12 m from the interbedded mud and peat section and subjected to optically stimulated luminescence (OSL) dating (Table 4.2) (DeLong et al., 2020). An OSL date for 16DF3A was returned revealing an age of  $72 \pm 8$  ka (DeLong et al., 2020).

Core	Water/sample depth (m)	Facies	<sup>238</sup> U±1σ (μg g <sup>-1</sup> )	<sup>232</sup> Th±1σ (μg g <sup>-1</sup> )	K <sub>2</sub> O±1σ (μg g <sup>-1</sup> )	Water content (%)	d <sub>cosmic</sub> (Gy ka <sup>-1</sup> ) <sup>1</sup>	Size fraction (μm)	d <sub>natural</sub> ±1σ (Gy ka <sup>-1</sup> )	De ±1σ (Gy)	OSL age ±1σ (ka)
16DF3A	15.8/2.12	LPIMP	2.96±0.09	11.61±0.34	1.37±0.04	0.57±0.10	0.15	4–15	1.48±0.17	106±3	72±8

*Table 4.2 Optically Stimulated Luminescence Date (OSL) of 16DF3A (DeLong et al., 2021).*

## CHAPTER V – RESULTS

### 5.1 Core 15DF1

Figure 5.1 represents pollen analysis of core DF1 published by Reese and others (2018). *Quercus* (oak), *Carpinus* (hornbeam), *Carya* (hickory), *Ulmus* (elm), *Liquidambar* (sweetgum), *Betula* (birch), and *Fraxinus* (ash) were found in the lowermost regions of the core as minor components (Reese et al., 2018). *Pinus* (pine) was also found throughout the core but never exceeded >20%. DF1 is found to have high percentages of *Taxodium*, *Nyssa* (tupelo), and Cyperaceae (sedges) in the lower zones of the core between 4.75-4.55 m (Reese et al., 2018). Cypress and tupelo decrease dramatically at 4.5 m and Poaceae (grass) becomes dominant appearing in all samples minus a few near the top mud and peat section at 4.05 m (Reese et al., 2018). Grass declines for a brief period at 4.3-4.2 m and *Typha* (cattail) and *Alnus* (alder) begin to appear at 4.05 m (Reese et al., 2018). Also, within this same range, cypress experiences another spike minus the presence of tupelo (Reese et al., 2018). Grass shows dominance once again at the top mud/peat section while cypress, alder, and birch decline at 4.2 m (Reese et al., 2018). The presence of pollen was found within a disjunct peat layer at 3.23 m separated by interbedded sand and mud (Reese et al., 2018). Pollen grains were poorly preserved with nearly 20% of the grains indeterminable while grain concentrations were highest in the lower regions and decreased ascending the core (Reese et al., 2018).

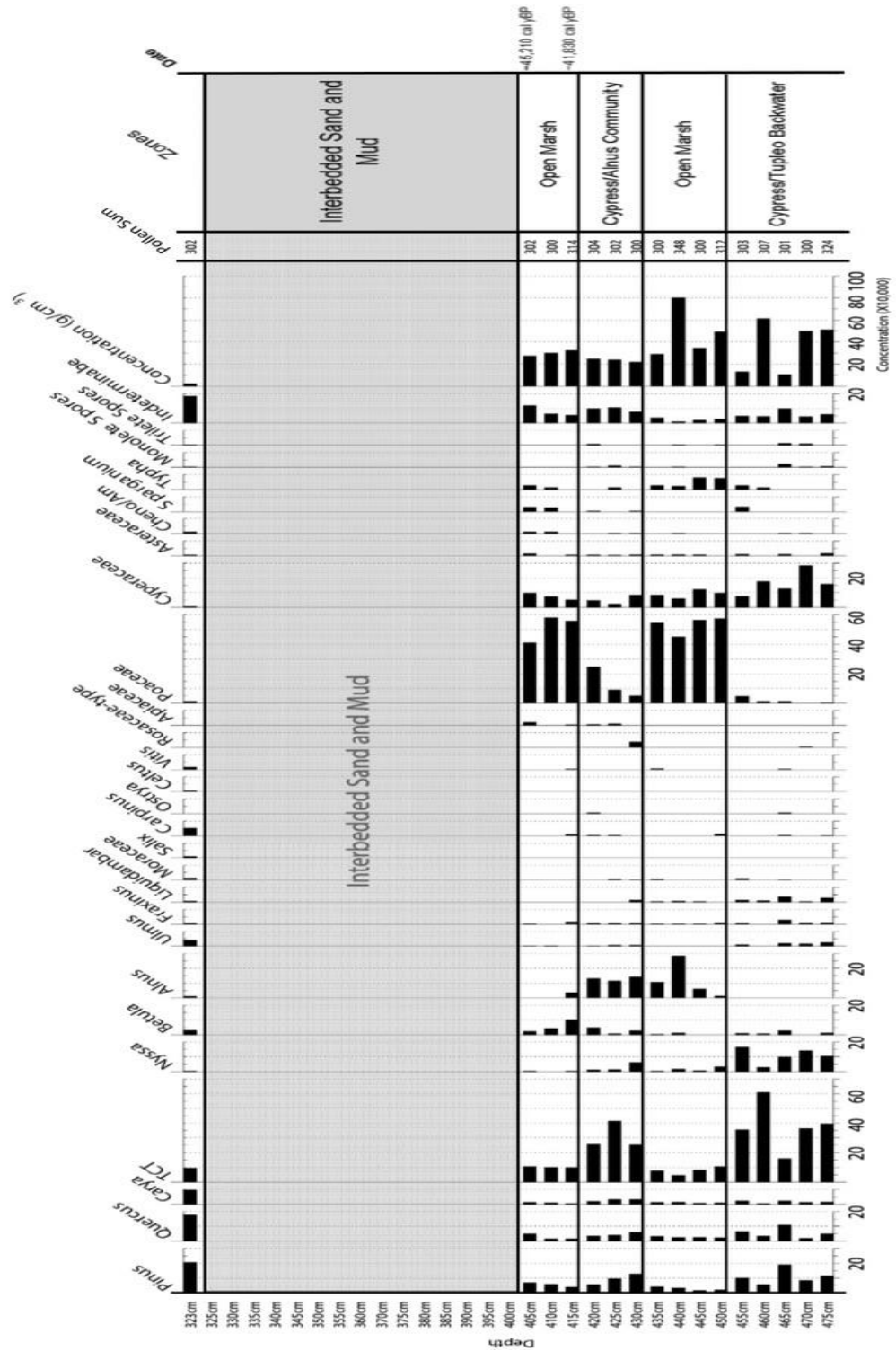


Figure 5.1 Pollen analysis of core 15DF1 (Reese et al., 2018).

## 5.2 Core 15DF3B

High percentage of *Taxodium*, *Nyssa*, and *Quercus* are found in the lowermost zones of the core (Fig. 5.2). *Taxodium* is prevalent throughout the core at percentages >60% in the lowermost zones of the core, but a decrease is shown at 3.35 m with *Taxodium* holding steady before rapidly decreasing at 3.20 m at percentages <20%. *Quercus* is seen throughout the lower zones of the core but rapidly decreases at 3.25 m at percentages <10%. Poaceae is also found in the lower zones of the core and increases moving up the core with the highest percentages beginning at 3.25 m. *Carya*, *Fraxinus*, and *Cyperaceae* are seen as minor components in the lower zones of the core, but *Cyperaceae* extends into the uppermost levels.

At the 3.25 m level is a transition from a swamp type community to more open marsh dominated community. Poaceae is found at consistently higher percentages, which occurs with a drop in *Taxodium*. In this upper section, *Alnus* is also found in higher percentages, spiking to >20% at 3.10 m. *Pinus* is prevalent in all zones of the core but never exceeds >20%. *Betula*, *Ulmus*, *Liquidambar*, *Salix*, *Carpinus*, *Ostrya*, and *Apiaceae* vary throughout the core with no species exceeding >10%. Preservation of this sample was relatively good with <10% of pollen grains indeterminable.

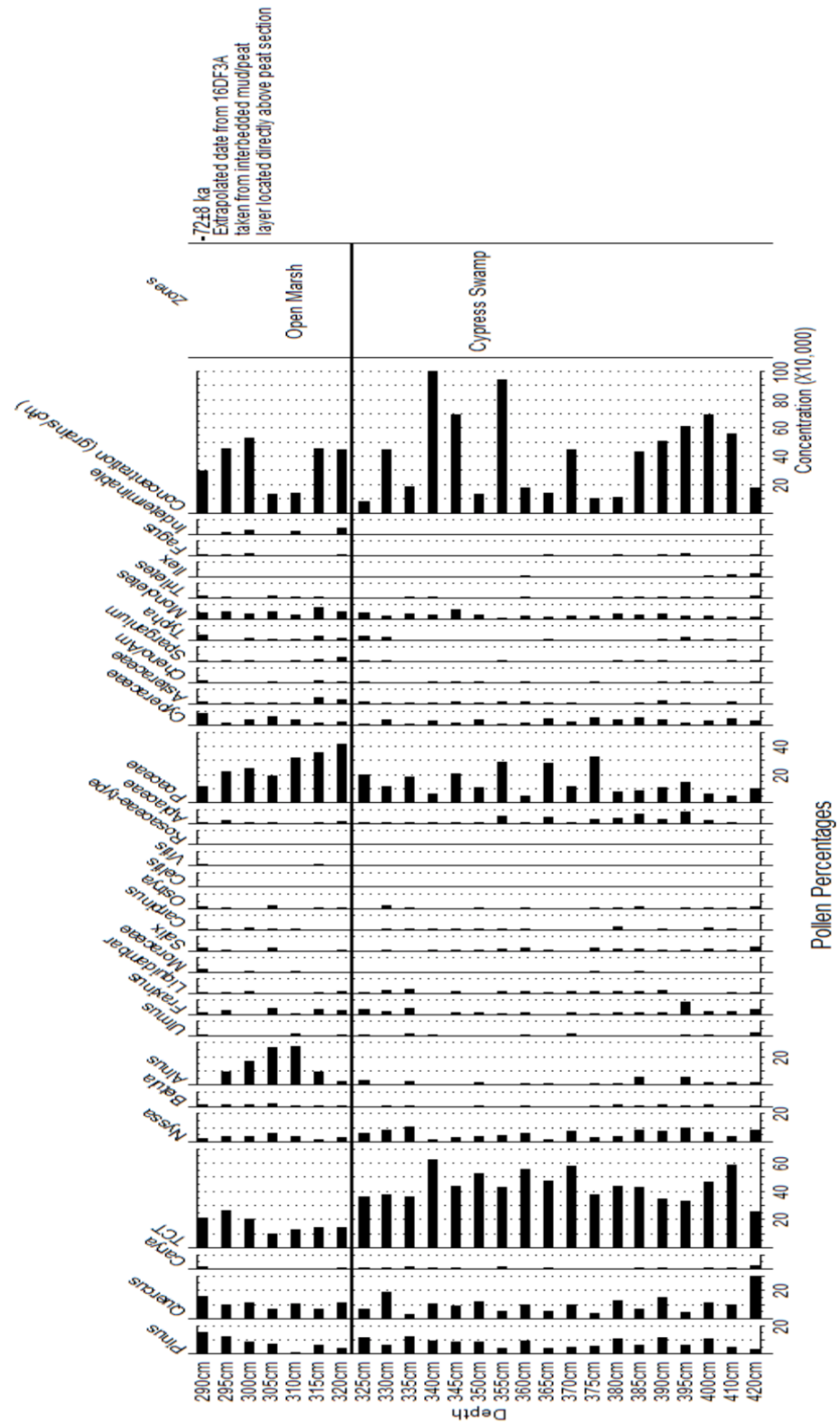


Figure 5.2 Pollen analysis of core 15DF3B.

### 5.3 Comparison of Core 15DF1 and 15DF3B

Core DF1 and DF3B show similarities in pollen assemblages as the forest experiences transitions. Both cores show high percentages of *Taxodium* in the lowermost zones and share pollen assemblages typically found within a cypress backwater community (Schafale, 2012). The rise in Poaceae, and *Typha* at 3.20 m in core DF3B indicate marsh type conditions. Core DF1 transitions from swamp to open marsh, to cypress/alnus community and back to open marsh. High percentages of *Nyssa* and Poaceae are found in lowermost zones of DF1 whereas DF3B shows high percentages of *Nyssa* throughout the core, and Poaceae in the upper zones of the core.

*Pinus* fluctuates throughout both cores reaching percentages just greater than 20% at 3.23 m in core DF1, but never exceeds >20% throughout all layers of DF3B. *Quercus* spikes in the lowest layer of DF3B at 4.20 m >30% whereas DF1 shows a spike in *Quercus* in the top layer at 3.23 m. *Cyperaceae* is found throughout the lower zones of DF1 at 4.75-4.05 m while DF3B shows *Cyperaceae* throughout the core. Both cores show minor components of *Fraxinus*, *Betula*, *Ulmus*, *Liquidambar*, *Carpinus*, *Carya*, and *Ostrya*. Core DF1 contained a zone of interbedded sand and mud, found above the peat section from 4.0-3.25 m, that was found to be absent of pollen. Layers of DF3B that were not sampled for pollen analysis were found to have similar interbedded sand and mud below a surficial sandy unit at 0.60-2.96 m (DeLong et al., 2021).



## CHAPTER VI – DISCUSSION

The analysis of fossil pollen embedded in terrestrial sediments has aided in establishing vegetation dynamics by adding data points, on a continental shelf glacial refuge, in a region that experienced fluctuating sea levels during a glacial period. The results of pollen analysis from core 15DF3B show a similar transition from an older cypress marsh to a more open-water community as previously seen in core 15DF1. Core 15DF3B experiences a spike in alder pollen from 3.15-2.95 m, similar to the spike in alder pollen as seen in core 15DF1 from 4.3-4.2 m. This section of both cores may represent a no-modern analog community dominated by *Alnus*. Though the pollen signatures in this section from each core are not identical, these inconsistencies may be due to the slight elevation difference between the two cores. Other minor differences seen in pollen signatures between the cores may likely be due to micro topographic features of the site, core compaction during collection, length of cores, and the physical location of the cores within the study site. The extrapolated date from sister core, 16DF3A, suggests that the age of the peat in core 15DF3B is older than the peat in core 15DF1. Due to the lack of available dates for each core this date should be inferred with extreme caution. However, the similarities in pollen assemblages between 15DF3B and 15DF1 suggest that these sediments were deposited at the same time, and during the same event.

## 6.1 Justification of Classification of Transitional Communities in Cores

While the similarities in pollen signatures of cores 15DF1 and 15DF3B have already been mentioned, a more in-depth discussion is needed to fully understand the significance of these similarities, and what these results, overall, mean. Previous studies of baldcypress swamps have shown that *Taxodium* (cypress) percentages can range from 20-70% (Frey, 1951; Reese and Liu, 2001; Brugam et al., 2007; Ryu et al., 2018).

Greater than 60% *Taxodium* is seen in the first zone (cypress swamp) of core 15DF1 and 15DF3B. Core 15DF1 also has >15% *Nyssa* (tupelo), which typically stays a minor component in baldcypress swamps between 5-20%, in the first zone (cypress/tupelo backwater) (Frey, 1951; Reese and Liu, 2001; Brugam et al., 2007; Ryu et al., 2018). *Nyssa* is also present in the first zone of core 15DF3B, but percentages do not exceed >15.5%. The minor components of the assemblage, *Pinus*, *Carya*, *Betula*, *Ulmus*, *Fraxinus*, *Liquidambar*, and *Ostrya* are also common components of the bottomland hardwoods that often surround that surround baldcypress swamps, but percentages never exceed 20% (Frey, 1951; Reese and Liu, 2001; Brugam et al., 2007; Ryu et al., 2018). These species are all present in the first zone of 15DF1 and 15DF3B at percentages <20%. Species of *Quercus* found near baldcypress swamps have been found at fluctuating percentages as seen in core 15DF1 at <15%, and >20% in core 15DF3B (Reese and Liu, 2001; Brugam et al., 2007; Willard et al., 2010; Ryu et al., 2018).

Both cores transition from a cypress swamp dominated community to more open marsh. Cypress decreases to <30% followed by tupelo at <10% in both cores. Commonly found marsh-type plants such as Poaceae and Cyperaceae, (Clark and Patterson III, 1985; Byrne et al., 1998; Finklestein and Davis, 2005; Ward, et al., 2008;

Clark, 1986), begin to increase with Poaceae exceeding >40%, and Cyperaceae fluctuating between 10-20% (Figure 18). *Pinus*, *Quercus*, *Carya*, *Fraxinus*, *Liquidambar* and other species are still seen as minor components though percentages do fluctuate throughout the levels of each core. During this marsh period *Alnus* increases exceeding >20% in both cores, but cypress, again, decreases to <20% in 15DF1, and greater than 20% but still below 30% in 15DF3B.

Core 15DF1 again transitions from open marsh to a cypress/alders community. There are several possible explanations for this transition and the significance it holds. Alder pollen is typically found alongside *Betula*, *Fraxinus*, *Celtis*, *Ulmus*, *Carpinus*, *Liquidambar*, *Quercus*, *Taxodium*, Poaceae, and others, in wet habitats such as floodplain forests, bogs, swamps, and along banks and bars of the Atlantic Coastal Plain region (Furlow, 1979; Schafale, 2012; Willard et al., 2015; Gagnon et al., 2021; Hupp, 2000). This same vegetation assemblage is found in the floodplain environment of the Underwater Forest. Furthermore, floodplain environments have little topographic relief and even the slightest difference in elevation can alter the vegetation composition. A small difference in elevation is seen between cores 15DF1 (15.3 mbsl) and 15DF3B (15.8 mbsl), and likely explains the contrast between pollen assemblages. In addition to the difference in elevation, the physical location of the cores within the site also explains the appearance of a cypress/alders community in core 15DF1.

Reese and others (2018) hypothesized that the spike in cypress and alder in core 15DF1 was representative of a no-modern analog cypress/*Alnus* community that shares similarities with the modern day Atlantic Coastal Plain Blackwater Levee/Bar forest assemblage. Previous studies have shown that alder and cypress occur along levees in

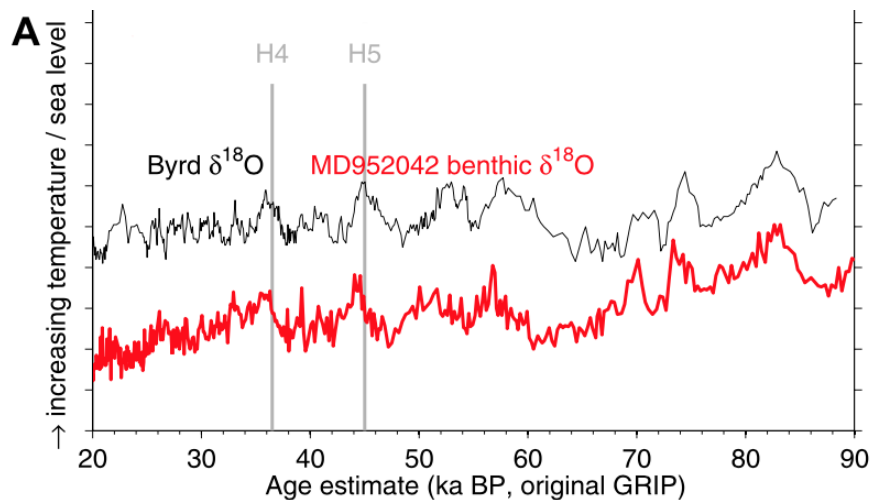
the Atlantic Coastal Plain, usually accompanied by very small amounts of *Betula* and *Fraxinus* (Schafale, 2012). These levees are ridges that are formed when coarse substrate is deposited along a bank during periods of high, or rising sea levels, and experience frequent flooding (Willard et al., 2015; Hupp, 2000; Furlow, 1979; Gagnon et al., 2021; Schafale, 2012). They typically consist of sandy, well drained sediments, and can be bordered by a cypress swamp (Schafale, 2012). These distinguishing features are all seen in the physical location, and pollen assemblage of core 15DF1. Geophysical data results of the Underwater Forest site show core 15DF1 is located along a ridge consisting of sandy substrate, surrounded by a series of troughs, that were likely flooded due to rising sea levels (DeLong et al., 2020; DeLong et al., 2021). Pollen analysis results show less than 10% *Betula* and less than 5% *Fraxinus* in the cypress/*Alnus* community transitional zone (Reese et al., 2018). Also seen in the pollen assemblage of core 15DF1 is a slight spike in Poaceae. Other studies that have recorded increased percentages of Poaceae suggest the spike in grass is due to the environmental transition into a marsh type community when sea levels have risen, and salinity has increased (Willard et al., 2015; Gagnon et al., 2021; Hupp, 2000). All this information further supports the hypothesis of the presence of a no-modern analog cypress/*Alnus* community in core 15DF1 (Reese et al., 2018).

Core 15DF3B is located within the trough in the floodplain. Usually, floodplain environments contain very fine sediments, such as clay and peat, but coarser sediments are often found within a floodplain when overbank flooding occurs (Willard et al., 2015; Hupp, 2000; Schafale, 2012; Gagnon et al., 2021). Core 15DF3B was found to contain these same fine sediments in addition to the longest recorded peat section of all cores

(DeLong et al., 2020; DeLong et al., 2021). Taking all this information regarding floodplain environments into consideration, it is likely that as sea levels were rising during a period of marine transgression, sediment containing alder and cypress pollen from the ridge, where core 15DF1 is located, was washed down the bank, and deposited into the trough where core 15DF3B is now located. However, due to the geomorphological differences between the cores, a cypress/*Alnus* community is not seen in core 15DF3B.

### 6.1.1 Uncertainty of Radiocarbon Dates

The radiocarbon dating results of core 15DF1, compared to the lack of dating results of core 15DF3B, and the result of the extrapolated date from the sister core presents a conundrum. The peat collected from core 15DF1 revealed two conventional, inverted dates of ~45-41 ka. The inversion of the dates may suggest bioturbation or other factors that call the reliability of these dates into question. If these dates are correct, it would place the deposition of this sediment during MIS 3, a period where global ice volume was beginning to decrease slightly resulting in somewhat higher sea levels (Figure 6.1) (Reese et al., 2018; DeLong et al., 2020; DeLong et al. 2021; Gonzalez et al., 2017; Siddall et al., 2008; Simms et al., 2009). Previous studies have documented the deposition of sediments, with similar facies and in a setting similar to the Underwater Forest, occurring during MIS 3 in the northwestern Gulf of Mexico area (Anderson et al., 2016; Simms et al., 2009; Siddall et al., 2008). This information further supports that the radiocarbon dates returned for core 15DF1 might be correct, and that the period in which sediments were deposited was indeed MIS 3.



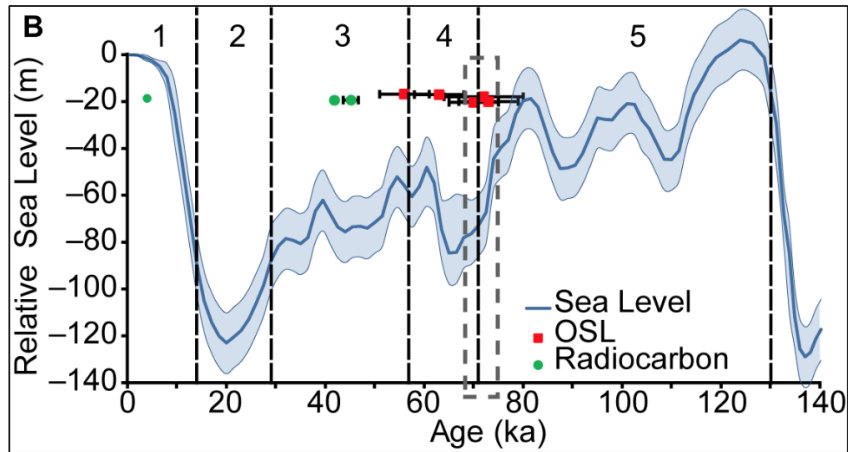


Figure 6.1 Sea level estimates for the last 140 ka. A. Marine oxygen isotope records from core MD952042 with MIS 3 occurring between 60 and 25 ka BP (Siddall et al., 2008). B. Sea level estimates with radiocarbon and OSL (green dots and red squares) dating results.

The gray dashed box outlines the OSL date of core 16DF3A at ~72 ka. Interval 3 represents MIS 3 and the green dots represent the two radiocarbon dates returned from core 15DF1 (Waelbroeck et al., 2002; DeLong et al., 2020).

Samples collected from core 15DF3B for radiocarbon dating were returned radiocarbon ‘dead’. OSL dating was used as an alternate absolute method of dating to extend the age range of sediments from the radiocarbon results (Gonzalez et al., 2017). Sister core, 16DF3A, was collected at 15.8 mbsl, and sampled at 2.12 m revealing an OSL date of  $72 \pm 8$  ka. If this date is correct, this would place sediment from core 15DF3B, at a much earlier time than 15DF1, and 16DF3A being deposited during MIS 5a-4, a period of rapid cooling where global ice volume was increased, and sea levels were decreased (Shackleton et al., 2021; Simms et al., 2009; Potter et al., 2004). However, the global sea level estimates suggest that sea levels were much higher during

MIS 3 when 15DF1 occurred, and not lower as seen during MIS 5a-4 when 16DF3A occurred.



## CHAPTER VII – CONCLUSION

The research summarized in this thesis aimed to provide additional information concerning the vegetation composition and dynamics of a preserved Pleistocene cypress forest using fossil pollen analysis from core 15DF3B. We hypothesized that this forest was buried due to rapid floodplain aggradation caused by increasing sea levels, or overbank flooding, during glacial age climate fluctuations. With additional pollen analysis from previously published results by Reese and others (2018) of core 15DF1, we have provided supplementary information that establish vegetation dynamics on a continental shelf glacial refuge, and the likely cause of burial.

Pollen analysis from both cores revealed the occurrence of similar transitional communities, and similarities in overall pollen signatures. In these transitional communities was the appearance of a possible no-modern analog cypress/alder community in core 15DF1. The same appearance of cypress and alder was seen in core 15DF3B but at lower percentages. This was likely due to the physical location of the cores and the geomorphology within the site. Core 15DF1's location along the ridge likely experienced overbank flooding, which resulted in the deposition of coarser sediment containing cypress and alder fossil pollen into the trough where 15DF3B is located.

Peat sampled from core 15DF1 revealed a radiocarbon date of ~45,210 cal y BP, and ~41,830 cal y BP, placing it during MIS 3 when sea levels were regularly fluctuating, and global ice volume was decreased. All samples collected from 15DF3B for radiocarbon dating were returned 'dead'. The extrapolated date from sister core 16DF3A revealed an OSL date of  $72 \pm 8$  ka, placing it during MIS 5a-4 when sea levels were

decreased, and global ice volume was increased due to a period of cooling. Despite the two different dates, the pollen results lead us to believe that these sediments were deposited at the same time. It would be unlikely to find such similar pollen assemblages, as well as similar transitional communities within the pollen assemblages at two different time periods. Therefore, we believe that it is more likely that the radiocarbon and OSL dates are erroneous due to the date and range limits for radiocarbon, and the large error bars associated with OSL dating.

Though this study has aided in establishing additional data points regarding vegetation dynamics of a continental shelf glacial refuge using fossil pollen, the full composition of this Underwater Forest is still unknown. In order to exactly understand how this forest came to be additional work is needed across a large scale. More cores need to be recovered and analyzed for fossil pollen, and compared to previously published findings to help reconstruct the vegetation assemblage before it was overtaken by marine conditions.

Future studies would benefit most from a more reliable chronology. The lack of radiocarbon and OSL dates in this study leaves unanswered questions that cause us to rely more heavily on what little evidence has already been proposed. This forest contains a wealth of information that is crucial to our understanding of past vegetation dynamics, and with additional pollen analysis, and a consistent method of dating, a more comprehensive explanation of this site is possible.

## REFERENCES

- Aharon, P. 2003. Meltwater flooding events in the Gulf of Mexico revisited: Implications for rapid climate changes during the last deglaciation. *Paleoceanography* 18(4): 1-15.
- Anderson, J. T. 2016. Plant fitness in a rapidly changing world. *New Phytologist* 210: 81-87.
- Auer, V. 1927. Stratigraphical and morphological investigations of peat bogs of southeastern Canada. *Communicationes ex Instituto Quaestionum Forestalium Finlandiae Editae* 12: 1-62.
- Baker, R. G. 1989. Vegetational Changes in Western Illinois During Onset of Late Wisconsinan Glaciation. *Ecology* 70(5): 1363-1376.
- Becker, B. and Kromer, B. 1986. Extension of the Holocene Dendrochronology by the Preboreal Pine Series, 8800 to 10,100 BP. *Radiocarbon* 28(2B): 961-967.
- Berglund, B. E. et al. 2008. Late Quaternary landscape and vegetation diversity in a North European perspective. *Quaternary International* 184: 187-194.
- Bhattacharya, R. et al. 2016. Ecological response to hydrological variability and catchment development: Insights from a shallow oxbow lake in Lower Mississippi Valley, Arkansas. *Science of the Total Environment* 569-570: 1087-1097.
- Birks, H. J. B. and Berglund, B. E. 2018. One hundred years of Quaternary pollen analysis 1916-2016. *Vegetation History Archaeobotany* 27: 271-309.

- Brandon, S. 2013. Discovery of baldcypress fossil leaves at the Gray Fossil Site, Tennessee and their ecological significance. Undergraduate honors thesis, East Tennessee State University.
- Breen, A. L. et al. 2012. Genetic consequences of glacial survival: the late Quaternary history of balsam poplar (*Populus balsamifera* L.) in North America. *Journal of Biogeography* 39: 918-928.
- Broström, A. et al. 2008. Pollen productivity estimates of key European plant taxa for quantitative reconstruction of past vegetation: a review. *Vegetation History Archaeobotany* 17: 461-478.
- Brown, K. J. and Pasternack, G. B. 2005. A palaeoenvironmental reconstruction to aid in the restoration of floodplain and wetland habitat on an upper deltaic plain, California, USA. *Environmental Conservation* 32(2): 103-116.
- Brown, P. et al. 2014. Identification and dendrochronology of wood found at the Ziegler Reservoir fossil site, Colorado, USA. *Quaternary Research* 82: 575-579.
- Brugam, R. B. 1978. Pollen Indicators of Land-Use Change in Southern Connecticut. *Quaternary Research* 9: 349-362.
- Brugam, R. B. et al. 2007. Historical Development of the Cypress/Tupelo Swamp at Horseshoe Lake, Alexander County, Illinois, USA. *Wetlands* 27(2): 305-318.
- Bryant Jr, V. M. and Holloway, R. G. 1985. A Late-Quaternary Paleoenvironmental Records of Texas: An Overview of the Pollen Evidence. *Pollen Records of Late-Quaternary North American Sediments*, p. 39-70.
- Brush, G. S. 1989. Rates and patterns of estuarine sediment accumulation. *Limnology and Oceanography* 34(7): 1235-1246.

- Byrne, R. et al. 2001. Carbon-Isotope, Diatom, and Pollen Evidence for Late Holocene Salinity Change in a Brackish Marsh in the San Francisco Estuary. *Quaternary Research* 55: 66-76.
- Caetano-Andrade, V. et al. 2020. Tropical Trees as Time Capsules of Anthropogenic Activity. *Trends in Plant Science* 25(4): 369-380.
- Cheddadi, R. and Bar-hen, A. 2009. Spatial gradient of temperature and potential vegetation feedback across Europe during the late Quaternary. *Climate Dynamics* 32: 371-379.
- Clark, T. S. 1986. Late-Holocene Vegetation and Coastal Processes at a Long Island Tidal Marsh. *Journal of Ecology* 74(2): 561-578.
- Clark, P. U. and Mix, A. C. 2002. Ice Sheets and sea level of the Last Glacial Maximum. *Quaternary Science Reviews* 21: 1-7.
- Clark, J. S. and Patterson III, W. A. 1985. The Development of a Tidal Marsh: Upland and Oceanic Influences. *Ecological Monographs* 55(2): 189-217.
- Collinvaux, P. A. 1996. A Long Pollen Record from Lowland Amazonia: Forest and Cooling in Glacial Times. *Science* 274 (5284): 85-88.
- Conner, S. E. and Kvavadze. 2008. Modeling late Quaternary changes in plant distribution, vegetation and climate using pollen data from Georgia, Caucasus. *Journal of Biogeography* 36: 529-545.
- Curry, B. B. and Follmer, L. R. 1992. The last interglacial-glacial transition in Illinois: 123-25 ka. Special paper 270, *Geological Society of America*.

- Dalton, A. S. et al. 2017. Pollen and macrofossil-inferred palaeoclimate at the Ridge Site, Hudson Bay Lowlands, Canada: evidence for a dry climate and significant recession of the Laurentide Ice Sheet during Marine Isotope Stage 3. *Boreas* 46(3): 388-401.
- Davis, M. B. 1983. Quaternary History of Deciduous Forests of Eastern North America and Europe. *Annals of the Missouri Botanical Garden* 70(3): 550-563.
- Davis, B. A. S. et al. 2003. The temperature of Europe during the Holocene reconstructed from pollen data. *Quaternary Science Reviews* 22: 1701-1716.
- Delcourt, P. A. and Delcourt, H. R. 1980. Pollen Preservation and Quaternary Environmental History in the Southeastern United States. *Palynology* 4: 215-231.
- Delcourt, P. A. and Delcourt, H. R. 1987. Late-Quaternary dynamics of temperate forests: Applications of paleoecology to issues of global environmental change. *Quaternary Science Reviews* 6(2): 129-146.
- DeLong, K et al. 2020. Investigation of an ancient bald cypress forest in the Northern Gulf of Mexico. New Orleans (LA): US Department of the Interior, Bureau of Ocean Energy Management. 108 p. Agreement No.: M15AC00016. Report No.: 2020-034.
- Delcourt and Delcourt. 1987. Late-Quaternary dynamics of temperate forests: Applications of paleoecology to issues of global environmental change. *Quaternary Science Reviews* 6(2): 129-146.
- DeLong, K et al. 2021. Late Pleistocene baldcypress (*Taxodium distichum*) forest deposit on the continental shelf of the northern Gulf of Mexico. *Boreas*.

- Denk, T. and Tekleva, M. V. 2006. Comparative pollen morphology and ultrastructure of *Plantanus*: Implications for phylogeny and evaluation of the fossil record. *Grana* 45: 195-221.
- Dimichele, W. A. and Flacon-Lang, H. J. 2011. Pennsylvanian 'fossil forests' in growth position (T<sup>0</sup> assemblages): origin, taphonomic basis and palaeoecological insights. *Journal of the Geological Society, London* 168: 585-605.
- Doody, P. 2004. 'Coastal-squeeze' - a historical perspective. *Journal of Coastal Conservation* 10: 129-138.
- Dupont, L. M. and Wyputta, U. 2003. Reconstructing pathways of aeolian pollen transport to the marine sediments along the coastline of SW Africa. *Quaternary Science Reviews* 22: 157-174.
- Dupont, L. M. et al. 2007. Variability in glacial and Holocene marine pollen records offshore from west southern Africa. *Vegetation History and Archaeobotany* 16: 87-100.
- Edwards, K. J. 2018. Pollen, women, war and other things: reflections on the history of palynology. *Vegetation History and Archaeobotany* 27: 319-335.
- Faegri, K and Iversen, J. 1964. *Textbook of Pollen Analysis*. John Wiley & Sons: New York.
- Finkelstein, S. A. and Davis, A. M. 2005. Modern Pollen Rain and Diatom Assemblages In A Lake Erie Coastal Marsh. *Wetlands* 25(3): 551-563.
- Finkelstein, S. A. et al. 2006. Improved resolution of pollen taxonomy allows better biogeographical interpretation of post-glacial forest development: analyses from the North American Pollen Database. *Journal of Ecology* 94: 415-430.

- Frey, D. G. 1951. Pollen Succession in the Sediments of Singletary Lake, North Carolina. *Ecology* 32(3): 518-533.
- Friedrich, M. et al. 2004. The 12,460-Year Hohenheim Oak and Pine Tree-Ring Chronology from Central Europe-A Unique Annual Record For Radiocarbon Calibration and Paleoenvironment Reconstructions. *Radiocarbon* 46(3): 1111-1122.
- Flower, B. P. et al. 2004. Phasing of deglacial warming and Laurentide Ice Sheet meltwater in the Gulf of Mexico. *Geology* 32(7): 597-600.
- Fowler, A. C. 1997. Glaciers and Ice Sheets. Conference paper for *The Mathematics of Models for Climatology and Environment*, p. 301-336.
- Furlow, J. T. 1979. The Systematics of the American Species of *Alnus* (Betulaceae). *Rhodora* 81(825): 1-121.
- Gagnon, P. R. et al. 2021. Fire in Floodplain Forests of the Southeastern USA. *Fire Ecology and Management: Past, Present, and Future of US Forested Ecosystems*, Managing Forest Ecosystems 39: 201-242.
- Gaillard, M. et al. 2018. “Think horizontally, act vertically”: the centenary (1916-2016) of pollen analysis and the legacy of Lennart von Post. *Vegetation History and Archaeobotany* 27: 267-269.
- Garibotti, I and Villalba, R. 2017. Colonization of mid and late Holocene moraines by lichens and trees in the Magellanic sub-Antarctic province. *Polar Biology* 40: 1739-1753.
- Gavin, D. G. et al. 2001. Postglacial history of subalpine forests, Olympic Peninsula, Washington, USA. *The Holocene* 11(2): 177-188.



- Giraldo, J. A. 2020. Dendrochronological Potential of Trees from America's Rainiest Region. Chapter, *Latin American Dendrochronology*, p. 91-131.
- Gonzalez, S. 2018. Stratigraphic Reconstruction of a Late Pleistocene Bald Cypress Forest Discovered on the Northern Gulf of Mexico Continental Shelf. Master's Thesis, Louisiana State University.
- Granlund, E. 1932. De svenska högmossarnas geologi. Deras bildningsbetingelser, utvecklingshistoria och utbredning jämte sambandet mellan högmossebildning och försumpning. Sveriges Geologiska Undersökning Series C 373: 1-193.
- Griggs, C. et al. 2017. A tree-ring chronology and paleoclimate record for the Younger Dryas-Early Holocene transition from northeastern North America. *Journal of Quaternary Science* p. 1-6.
- Grimm, E.C. 1991. TILIA and TILIA GRAPH. Illinois State Museum, Springfield, IL.
- Grimm, E. C. and Jacobson Jr., G. L. 1992. Fossil-pollen evidence for abrupt climate changes during the past 18000 years in eastern North America. *Climate Dynamics* 6: 179-184.
- Gugger, P. F. and Sugita, S. 2010. Glacial populations and postglacial migration of Douglas-fir based on fossil pollen and macrofossil evidence. *Quaternary Science Reviews* 29: 2052-2070.
- Haberle, S. G. and Maslin, M. A. 1999. Late Quaternary Vegetation and Climate Change in the Amazon Basin Based on a 50,000 Year Pollen Records from the Amazon Fan, ODP Site 932. *Quaternary Research* 51: 27-38.
- Hantemirov, R. and Shiyatov, S. 2002. A continuous multimillennial ring-width chronology in Yamal, northwestern Siberia. *The Holocene* 12(6): 717-726.

- Harbert, R. S. and Nixon, K. C. 2018. Quantitative Late Quaternary Climate Reconstruction from Plant Macrofossil Communities in Western North America. *Open Quaternary* 4 (8): 1-13.
- Hupp, C. R. 2000. Hydrology, geomorphology, and vegetation of Coastal Plain rivers in the southeastern United States. *Hydrological Processes*.
- Jackson, S. T. et al. 2000. Vegetation and environment in Eastern North America during the Last Glacial Maximum. *Quaternary Science Reviews* 19: 489-508.
- Jacobson Jr., G. L. et al. 1987. Patterns and rates of vegetation change during the deglaciation of eastern North America. *The Geological Society of America* K-3: 277-288.
- Lawson, D. E. Mobilization, Movement and Deposition of Active Subaerial Sediment Flows, Matanuska Glacier, Alaska. *The Journal of Geology* 90(3): 279-300.
- Li, H. et al. 2019. Modelling the vegetation response to the 8.2 ka BP cooling event in Europe and Northern Africa. *Journal of Quaternary Science* 34(8): 650-661.
- Little, E. 1980. Baldcypress (*Taxodium distichum*) in Oklahoma. Proceedings of the Oklahoma Academy of Sciences 60:105-107.
- Liu, K. and Fearn, M. L. 2000. Holocene History of Catastrophic Hurricane Landfalls along the Gulf of Mexico Coast Reconstructed from the Coastal Lake and Marsh Sediments. *Current Stresses and Potential Vulnerabilities: Implications of Global Change for the Gulf Coast Region of the United States*, p. 38-47.
- Mackay, A. et al. 2003. *Global Change in the Holocene*. Routledge: New York.
- Magri, D. et al. 2017. Quaternary disappearance of tree taxa from Southern Europe: Timing and trends. *Quaternary Science Reviews* 163: 23-55.

- Maladonado, A. and Villagrán. 2006. Climate variability over the last 9900 cal yr BP from a swamp forest pollen record along the semiarid coast of Chile. *Quaternary Research* 66: 246-258.
- Mamet, S. 2012. Dendrochronology and treeline dynamics within arctic and alpine localities in western and central Canada. Doctorate Thesis, University of Alberta.
- Mancini, M. 2002. Vegetation and Climate during the Holocene in Southwest Patagonia, Argentina. *Review of Palaeobotany and Palynology* 122: 101-115.
- Martinelli, N. 2004. Climate from dendrochronology: latest developments and results. *Global and Planetary Change* 40: 129-139.
- Mauri, A. et al. 2015. The climate of Europe during the Holocene: a gridded pollen-based reconstruction and its multi-proxy evaluation. *Quaternary Science Reviews* 112: 109-127.
- May, L. and Lacourse, T. 2012. Morphological differentiation of *Alnus* (alder) pollen from western North America. *Review of Palaeobotany and Palynology* 180: 15-24.
- McAndrews, J. et al. 1973. *Key to the quaternary pollen and spores of the Great Lakes region*. Royal Ontario Museum: Canada.
- McGraw, D.. 2003. Andrew Ellicott Douglass and the Giant Sequoias in the Founding of Dendrochronology. *Tree-Ring Research* 59(1): 21-27.
- Muhs, D. R. 2001. Vegetation and paleoclimate of the last interglacial period, central Alaska. *Quaternary Science Reviews* 20: 41-61.

- Nascimento, L. 2015. Modern pollen rain in Canary Island ecosystems and its implications for the interpretation of fossil records. *Review of Palaeobotany and Palynology* 214: 27-39.
- Ogbahon, O. 2019. Palynological Study of OSE 1 well in Offshore Niger Delta Basin: Implications for Age, Paleoclimate and Depositional Paleoenvironment. *International Journal of Geosciences* 10: 860-883.
- Parducci, L. et al. Ancient plant DNA in lake sediments. *New Phytologist* 214: 924-942.
- Scott, L. et al. 2012. Terrestrial fossil-pollen evidence of climate change during the last 26 thousand years in Southern Africa. *Quaternary Science Reviews* 32: 100-118.
- Schmidtling, R. C. and Hipkins, V. 1998. Genetic diversity in longleaf pine (*Pinus palustris*): influence of historical and prehistorical events. *Canadian Journal of Forest Research* 28: 1135-1145.
- Shen, Z., Aeschliman, M., and Conway, N. 2021. Paleodischarge reconstruction using oxbow lake sediments complicated by shifting hydrological connectivity. *Quaternary International* 10: 75-81.
- Panyushkina, I and Leavitt, S. 2007. Insights into Late Pleistocene-Early Holocene Paleoecology from fossil wood around the Great Lakes Region. Chapter, Late-Glacial History of East-central Wisconsin, p. 47-57.
- Payette, S. et al. 2002. The Circumboreal Tundra-Taiga Interface: Late Pleistocene and Holocene Changes. *AMBIO A Journal of the Human Environment* 12: 15-22.
- Penland, S. et al. 1990. Coastal Land Loss In Louisiana. *Gulf Coast Association of Geological Societies Transactions* 40: 685-699.

- Peyron, O. et al. 1998. Climatic Reconstruction in Europe for 18,000 yr B.P. from Pollen Data. *Quaternary Research* 49: 183-196.
- Potter, E. et al. 2004. Suborbital-period sea-level oscillations during marine isotope substages 5a and 5c. *Earth and Planetary Science Letter* 225: 191-204.
- Prentice, I. C. et al. 1991. Vegetation and Climate Change in Eastern North America Since the Last Glacial Maximum. *Ecology* 72(6): 2038-2056.
- Reese, C. A. et al. 2018. Stratigraphic pollen analysis performed on a late Pleistocene cypress forest preserved on the northern Gulf of Mexico continental shelf. *Journal of Quaternary Science* 33(8): 865-870.
- Reese, C. A. and Liu, K. 2001. Late-Holocene Vegetation Changes at Bluff Swamp, Louisiana. *Southeastern Geographer* 41(1): 20-35.
- Ryu, J. 2018. Palynological and Geochemical Records of Environmental Changes in a *Taxodium* swamp near Lake Pontchartrain in Southern Louisiana (USA) during the last 150 years. *Journal of Coastal Research* 85: 381-385.
- Schafale, M.P. 2012. Atlantic Coastal Plain Blackwater Levee/Bar Forest. United States National Vegetation Classification. Federal Geographic Data Committee: Washington, DC.
- Selwood, K. E. and Zimmer, H. C. 2020. Refuges for biodiversity conservation: A review of the evidence. *Biological Conservation* 245.
- Serrano, E. et al. 2012. Mountain glaciation and paleoclimate reconstruction in the Picos de Europa (Iberian Peninsula, SW Europe). *Quaternary Research* 78: 303-314.
- Shackleton, S. et al. 2021. Evolution of mean ocean temperature in Marine Isotope Stage 4. *Climate of the Past* 17: 2273-2289.

- Shafer, A. B. A. et al. 2010. Of Glaciers and refugia: a decade of study sheds new light on the phylogeography of northwestern North America. *Molecular Ecology* 19: 4589-4621.
- Sheldon, N. D. and Tabor, N. J. 2009. Quantitative paleoenvironmental and paleoclimatic reconstruction using paleosols. *Earth-Science Reviews* 95: 1-52.
- Shen, Z. et al. 2021. Paleodischarge reconstruction using oxbow lake sediments complicated by shifting hydrological connectivity. *Quaternary International* 604: 75-81.
- Shu, J. and Wang, W. 2013. A Miocene pollen flora from the petroliferous deposits in the Bohai Bay Basin, North China, and its palaeoclimatic and stratigraphic significance. *Paleoworld* 22: 109-118.
- Shuman, B. et al. 2002. Parallel climate and vegetation responses to the early Holocene collapse of the Laurentide Ice Sheet. *Quaternary Science Reviews* 21: 1793-1805.
- Siddall, M. et al. 2008. Marine Isotope Stage 3 Sea Level Fluctuations: Data Synthesis and New Outlook. *Reviews of Geophysics* 46: 1-29.
- Simms, A. R. et al. 2009. Revisiting marine isotope stage 3 and 5a (MIS3-5a) sea levels within the northwestern Gulf of Mexico. *Global and Planetary Change* 66: 100-111.
- Stahle, D. W. and Cleaveland, M. K. 1992. Reconstruction and Analysis of Spring Rainfall over the Southeastern U.S. for the Past 1000 Years. *Bulletin American Meteorological Society*.
- Stahle, D.W., et al. 2011b. Visiting the ancient baldcypress trees on the Black River. *Afield*, the North Carolina Chapter of the *Nature Conservancy*, p 1-6.

- Stahle, D. et al. 2012. Tree-ring analysis of ancient baldcypress trees and subfossil wood. *Quaternary Science Reviews* 34: 1-15.
- Sugden, D. E. 1977. Reconstruction of the morphology, dynamics, and thermal characteristics of the Laurentide Ice Sheet at its maximum. *Arctic and Alpine Research* 9(1): 21-47.
- Tarasov, P. et al. 2005. Quantitative reconstruction of the last interglacial vegetation and climate based on the pollen record from Lake Baikal, Russia. *Climate Dynamics* 25: 625-637.
- Therrell, M. et al. 2020. Streamflow Variability Indicated by False Rings in Bald Cypress (*Taxodium distichum* (L.) Rich.). *Forests* 11: 1-18.
- Tucker, C and Pearl, J. 2021. Coastal tree-ring records for paleoclimate and paleoenvironmental applications in North America. *Quaternary Science Reviews*. 265: 1-14.
- Ülker, E. D. et al. 2018. Ecological niche modelling of pedunculate oak (*Quercus robur*) supports the ‘expansion-contraction’ model of Pleistocene biogeography. *Biological Journal of the Linnean Society* 123: 338-347.
- Valiela, I. 2009. *Global Coastal Change*. Blackwell Publishing: Malden, MA.
- Von Post, L. 1910. Das Skagershultmoor. In: Post L von, Sernander R (eds) *Pflanzenphysiognomische Studien auf Torfmooren in Närke*. Intern. Geol. Congr., 11th, Stockholm, Congr. Guide 14 (Excursion A7), pp 1–24
- Von Post, L. and Granlund, E. 1926. Södra Sveriges torvtillgångar 1. *Swedish Geological Survey*, Stockholm, Sweden.

- Waelbroeck, C. et al. 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. *Quat Sci Rev.* 21(1– 3):295–305.
- Wang, Y. et al. 2019. Bayesian ages for pollen records since the last glaciation in North America. *Scientific Data* 6(176): 1-8.
- Ward, G. M. 2008. Gulf Coast Rivers of the Southeastern United States. Chapter, *Rivers of North America*. Elsevier Academic Press.
- Webb III, T. et al. 1987. Climatic change in eastern North America during the past 18,000 years; Comparisons of pollen data with model results. Chapter, *North America and Adjacent Oceans During the Last Deglaciation*.
- Whitehead, D. R. 1964. Fossil Pine Pollen and Full-Glacial Vegetation in Southeastern North Carolina. *Ecology* 45(4): 767-777.
- Whitehead, D. R. 1972. Developmental and Environmental History of the Dismal Swamp. *Ecological Monographs*, 42 (3): 301-315.
- Wiles, G. et al. 1999. Dendrochronology and Late Holocene History of Bering Piedmont Glacier, Alaska. *Quaternary Research* 52: 185-195.
- Willard, D. et al. 2010. Development and application of a pollen-based paleohydrologic reconstruction from the Lower Roanoke River Basin, North Carolina, USA. *The Holocene* 21(2): 305-317.
- Willard, D. A. et al. 2015. Coastal and wetland ecosystems of the Chesapeake Bay watershed: Applying palynology to understand impacts of changing climate, sea level, and land use. Conference paper, The Geological Society of America.



- Yansa, C. H. 2006. The timing and nature of Late Quaternary vegetation changes in the northern Great Plains, USA and Canada: a re-assessment of the spruce phase. *Quaternary Science Reviews* 25: 263-281.
- Yi, S. et al. 2012. Pliocene-Pleistocene boundary determination in hemipelagic sediment from the Ulleung Basin (East Sea, offshore Korea) inferred from terrigenous and marine palynofloras. *Review of Palaeobotany and Palynology* 181: 54-63.
- Yu, S. et al. 2017. A last glacial and deglacial pollen record from the northern South China Sea: New insight into coastal-shelf paleoenvironment. *Quaternary Science Reviews* 157: 114-128.