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SHORT COMMUNICATION

LAKE OR ESTUARY? – SEDIMENTARY AND BENTHIC FORAMINIFERAL CHARACTERIZATION OF A GULF OF MEXICO COASTAL DUNE LAKE

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INTRODUCTION

Coastal dune lakes are shallow, fresh to saline lakes located in dune environments that share a closed or occasionally intermittent connection with the sea (Jennings 1957, FNAI 2010, VanTassel and Janosik 2018, Hyman and Stephens 2020). Within the context of other estuaries, coastal dune lakes can be broadly described as immature, wave-dominated barrier estuaries (Roy 1984, Roy et al. 2001) and more precisely described as intermittently closed and open lakes and lagoons (ICOLLs; Haines et al. 2006) or intermittently open/closed estuaries (IOCE; McSweeney et al. 2017). However, a key distinguishing feature of coastal dune lakes from other intermittent estuaries is their confinement within a coastal dune environment and occasional closure by a sandy berm.

During lake closure, longshore drift and other marine littoral processes promote dune and berm accretion at the terminal seaward extent of coastal dune lakes. However, elevated lake levels following hydrologic or oceanographic loading can lead to berm failure during episodic events known as blow-outs (Elwaney et al. 2003, Haines and Thom 2007, Sadat-Noori et al. 2016). Blow-outs establish a temporary connection with the sea, known colloquially in the northern Gulf of Mexico (GOM) as an outfall (Bhadha and Jawitz 2008, VanTassel and Janosik 2018). While the outfall is open, coastal dune lakes exchange saline water with the sea under tidal flow regimes. When the outfall is closed, surface seawater exchange is effectively terminated and landward hydrologic processes dictate water chemistry and flow. This cyclical, sometimes dramatic dynamic in water chemistry and flow leads to a unique estuarine ecosystem that supports a diverse assemblage of organisms (Gamito et al. 2005, Vadineanu 2005). Because coastal dune lakes act as infrequently flushed accumulation basins for nutrients and other land-derived solutes, they are particularly vulnerable to anthropogenic activities and considered to be one of the most sensitive types of estuaries (Boyd et al. 1992, Shallenberg et al. 2010, Sadat-Noori et al. 2016, Hyman and Stephens 2020).

While examples of coastal dune lakes can be found in locations throughout the world including the United States, Australia, Madagascar, Tasmania, and New Zealand, there is a lack of literature comparing these rare and sensitive lakes to other coastal estuaries. Furthermore, conflicting terminology

and definitions related to coastal dune lakes and other similar lacustrine and estuarine systems provide challenges for environmental managers, stakeholders, and governmental agencies to develop science-based management policies. There is also a deficit of scientific attention devoted to coastal dune lakes in the northern hemisphere. In the panhandle region of Florida, local coastal dune lakes are acknowledged as both rare and imperiled ecosystems that host endangered species and provide critical breeding habitat for migrating birds (FNAI 2010). However, extensive residential and commercial development of the Florida panhandle area as a center for tourism has become a persistent and growing threat to the resilience of these unique systems (Bhadha and Jawitz 2008, VanTassel and Janosik 2018, Hyman and Stephens 2020). Furthermore, coastal dune lakes are commonly grouped with freshwater lakes for management with generic water quality criteria and lack estuary-specific numeric water quality criteria for dissolved nutrient concentrations and chlorophyll *a* like the rest of Florida's coastline (VanTassel and Janosik 2018).

If GOM coastal dune lakes are functionally similar to other estuaries despite their smaller size and intermittent connection to the sea, there should be similar depositional environments, or facies, with distinct sedimentary and biogeological characteristics. These facies are well-described in the literature for many of the larger GOM estuaries (Poag 2015); however, such facies have not been identified in coastal dune lakes. Here, we conduct a sedimentary and benthic foraminiferal analysis of a representative coastal dune lake in order to identify and delineate modern sedimentary and biogeological facies. The results of this study demonstrate key similarities between coastal dune lakes and other well-described estuaries, and therefore, could place coastal dune lakes within the proper management context.

MATERIALS AND METHODS

Site Description

Eastern Lake of Walton County FL, USA (N 30.30907° W 86.0935°; Figure 1), was selected for investigation because of its intermittent connection with the sea (VanTassel and Janosik 2018) and roughly linear geometry. Eastern Lake is one of 15 named coastal dune lakes in Walton County and has a surface

FIGURE 1. Maps of Eastern Lake. A. Lake location in Walton County, FL. B. Ekman sampling stations. C. Interpolated plot of percentage of agglutinated foraminifera. D. Interpolated plot of percentage sand. E. Interpolated plot of percentage of organic carbon (loss on ignition). F. Interpolated plot of mean grain size in microns.

area of 0.254 km², an average depth of 2.1 m, and watershed area of 1.536 km² (VanTassel and Janosik 2018). Land use surrounding the lake consists of heavy residential and commercial

development near the southern coastline and undeveloped woodlands of the Point Washington State Forest in the remainder of the northern upland watershed.

A partial causeway extends across the northern portion of Eastern Lake (i.e., Highway 30A), and north of this causeway are a pair of headwater wetlands with anastomosing, deltaic confluences with the main lake. The presence of these channels suggests limited surface water contributions to Eastern Lake; however, no tributaries are noted in the United States Geological Survey National Hydrographic Dataset (U.S. Geological Survey 2020). Coastal dune lake hydrology in Walton County is thought to be controlled by groundwater exchange, precipitation, evaporation, and oceanographic processes (Bhadha and Jawitz 2008, VanTassel and Janosik 2018). Elsewhere, ICOLLS including coastal dune lakes are considered groundwater dominated coastal systems (Sadat-Noori et al. 2016).

Average salinity of Eastern Lake surface waters between 2003 and 2019 was 10.8 and bottom water salinity averaged 15.3, indicating potential stratification (Hyman and Stephens 2020). Hyman and Stephens (2020) report an average pH of 7.4, average total dissolved phosphorous concentration of 14.2 µg/L, average total dissolved nitrogen concentration of 337.7 µg/L, and average chlorophyll *a* concentration of 4.8 µg/L. VanTassel and Janosik (2018) note a significant increase in nutrient concentrations and a decrease in transparency in Eastern Lake between 1997 and 2016 while Hyman and Stephens (2020) indicate no significant change in these parameters between 2003 and 2019.

The sediments surrounding Eastern Lake and other nearby coastal dune lakes consists of recent coarse beach and dune sand in addition to interbedded silt and clay of the estuarine Biloxi formation (Otvos 1985). A continuous dune ridge of about 6 m elevation, with individual dunes rising to 9.3 m, shapes the region (Liu and Fearn 2000). The mean tidal range in nearby Panama City FL is about 0.4 m; thus, Eastern Lake and the surrounding coastal dune lakes are classified as wave-dominated estuaries.

Tropical cyclones impact the region and can lead to acute changes in sediment deposition during lagoon overwash (Lambert et al. 2008). These changes in deposition have been noted in sediment cores from coastal dune lakes and have been used to reconstruct hurricane landfall patterns through the last 7,000 years (Liu and Fearn 2000). Overwash deposition from storms has the potential to obscure spatial facies relationships.

To date, the only available ecological data for Eastern Lake consists of plant surveys conducted by the Choctawhatchee Basin Alliance (VanTassel and Janosik 2018). Fish surveys have been conducted in 2 Walton County coastal dune lakes, but none have been completed in Eastern Lake. VanTassel and Janosik (2018) acknowledged the need for species inventories for the Walton County coastal dune lakes to better understand and manage biodiversity.

Sample Collection

A total of 10 surface (i.e., 2–3 cm deep) sediment Ekman grabs were collected from Eastern Lake in May 2017 along a transect with a sampling interval of about 250 m (Figure 1B). Sampling was conducted following a quiescent tropical cyclone period, with the most recent direct impact to the Walton County, FL area occurring 8 years prior during tropical storm

Claudette in 2009. The sediment samples were placed into sealed plastic bags in the field for transport to the laboratory and removed from the bags for air drying. Following drying, samples were homogenized then split into 4 roughly 50 g subsamples for further analysis (i.e., granulometric analysis, loss on ignition, grain morphology, mineralogy inspection, and foraminifera identification). Rose bengal stain was not used for staining live foraminiferal analysis.

Sedimentary Analysis

Subsamples for sedimentary analyses were further heated to 125°C to remove residual moisture. Granulometric analysis was completed using the pipette and sieve method (Coventry and Fett 1979). Statistical analyses of the grain size distributions (e.g., mean grain size, sorting, kurtosis, etc.) were completed using the program GSSTAT (Folk 1974, Poppe et al. 2003). Organic carbon content was determined gravimetrically following loss on ignition at 550°C (Heiri et al. 2001). Grain morphology and mineralogy was completed following microscopic examination (Folk 1954, Deer et al. 2013). Results from the granulometric analysis and loss on ignition were spatially interpolated using the inverse-distance method with Golden Software Surfer and plotted using QGIS 3.6.

Benthic Foraminiferal Analysis

Subsamples for foraminiferal analysis were gently wet sieved at 63 µm to remove silt and clay fractions and then further sieved using a nested stack to preserve the 125 to 250 µm fraction for picking and identification. Sieved fractions from each sample were transferred to gridded picking trays and viewed under a binocular microscope for picking. At least 100 individuals were picked from each subsample, where possible, and transferred to gridded microscope slides for identification. Individuals were identified following Moore (1964) and Poag (2015), and separate counts were recorded from each subsample for biotype determination. Percentages of calcareous foraminifera were spatially interpolated using the inverse-distance method with Surfer and plotted with QGIS 3.6.

Facies Identification

The results were further analyzed statistically using R version 3.4.1 (R Core Team 2020) to elucidate relationships between sediment characteristics and foraminiferal assemblages. Non-redundant grain size distribution characteristics (i.e., mean grain size, standard deviation, kurtosis, skewness, and percent mud), percentage of organic carbon, and percentage of calcareous foraminifera from each sample were compiled and then log-transformed. A principle component analysis (PCA) was completed (prcomp) and populations sharing similar environmental characteristics (i.e. facies) were identified through k-means clustering (kmeans).

RESULTS

Lake Sedimentology

The sedimentology of Eastern Lake exhibits several gradations from the outfall to the northern reaches (e.g., grain size, sorting, and organic carbon; Figure 1D–F). Sediment near the outfall (samples 1 and 2) was classified as moderately well sorted to moderately sorted, fine skewed, mesokurtic to leptokur-

tic sand with less than 0.5 % organic carbon. Sediment in the wider basin of the lake (samples 3 through 6) was classified as very poorly sorted, near symmetric to strongly fine skewed, very platykurtic to mesokurtic sand, silt, and clay with between 8.4 and 14.5% organic carbon. Sediment north of Highway 30A in the meandering headwater portion of Eastern Lake (samples 7 through 10) was classified as very poorly to poorly sorted, strongly fine skewed, very leptokurtic to platykurtic silty sand to sand with between 0.3 and 5.7% organic carbon. Sand sized grains were nearly exclusively well rounded and composed of quartz with trace amounts of opaque lithic minerals (e.g., staurolite, ilmenite, zircon, etc.).

Lake Benthic Foraminifera

Thirteen benthic species and one planktonic group of foraminifera were identified in the Eastern Lake samples (Table 1). The planktonic group was not speciated but consisted of juveniles (i.e., enlarged proloculus) with 9 calcareous of 14 total specimens. The benthic foraminiferal distribution in Eastern Lake was predominantly calcareous species from the outfall up to Highway 30A (> 88 % calcareous in samples 1 and 3 through 6) and predominantly agglutinated north of Highway 30A (> 79% agglutinated in samples 7–10; Figure 1C).

Facies Identification

The 2 principle axes of the PCA (i.e., PC1 and PC2) accounted for 90.8% of the variance for sedimentary and foraminiferal parameters (Figure 2). PC1 accounted for 68.1% of the variance and had the highest magnitude of loading from mean grain size (0.455), grain size standard deviation (0.426), and percent mud (−0.416). PC2 accounted for 22.7% of the variance and was loaded most heavily by kurtosis (0.600), percent calcareous foraminifera (0.448), and percent carbon (0.448). Furthermore, PC2 was minimally loaded by grain size (−0.001).

minifera (−0.488), and percent carbon (0.448). Furthermore, PC2 was minimally loaded by grain size (−0.001).

Although the sample to variable ratio for the PCA was only 1.4 and hinders inferences about the contributions of individual variables, 3 distinct populations were resolved by k-means clustering (Figure 2). These groups were labeled as separate facies (i.e. dune, marsh, or mud basin) through consideration of the apparent environmental properties (e.g., water depth, emergent vegetation, proximity to shore, etc.) and foraminiferal assemblages associated with each sample (Figure 1C; Table 1).

DISCUSSION

The surficial sedimentary facies of Eastern Lake were not dissimilar to the coastal dune lakes of Australia described by Roy et al. (2001). Roy et al. (2001) suggests that coastal lagoon and dune lake facies include a sandy barrier consisting of coarse sand near the outfall, a central mud basin dominated by organic-rich silt and clay, and a fluvial delta comprised of poorly sorted sands. This distribution of sedimentary facies is also present in other, larger estuaries in the northern GOM including Choctawhatchee Bay and Mobile Bay (Poag 2015), suggesting that depositional processes in Eastern Lake are similar to other estuaries despite its small size and intermittent connection to the GOM.

The similarity of the beach sand and central mud basin facies in Eastern Lake to facies described in other coastal dune lakes by Roy et al. (2001) and elsewhere in the northern GOM (Poag 2015) is expected due to analogous depositional processes (e.g., tidal exchange, organic matter production, etc.) and geomorphic features (e.g., tidal inlets, central basins, etc.). How-

FIGURE 2. Principle component analysis for percentage calcareous foraminifera, percentage mud, percentage of organic carbon, mean grain size, grain size skewness, grain size standard deviation (i.e. sorting), and grain size kurtosis. Blue, green, and red circles indicate the 3 k-means clusters (i.e. sedimentary and biogeological facies). Numbers indicate samples within Eastern Lake as indicated on Figure 1.

TABLE 1. Percent abundance of foraminifera identified in each of 10 samples from Eastern Lake, FL following descriptions from Moore (1964) and Poag (2015).

Foraminifera	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10
Total individuals (N)	4	172	103	318	65	34	95	103	122	226
Agglutinated (% abundance)										
¹ <i>Jadammina macrescens</i> /										
<i>Haplophragmoides</i> sp.	-	14.5	8.7	11.3	-	-	53.7	8.7	23	16.4
<i>Triphotrocha comprimata</i>	-	-	-	-	-	-	-	-	-	3.5
<i>Miliammina fusca</i>	-	-	-	-	-	-	-	-	-	9.3
<i>Ammobaculites</i> sp. A	-	64	-	-	-	-	-	-	-	-
<i>Ammobaculites dilatata</i>	-	-	-	-	-	-	-	-	-	0.9
<i>Ammobaculites exiguus</i>	-	-	-	-	-	-	2.1	1	3.3	8.4
<i>Ammotium crassus</i>	-	-	-	-	-	-	-	-	2.5	-
<i>Ammotium fragile</i>	-	-	-	-	-	-	30.5	42.7	53.3	38.5
<i>Ammotium salsum</i>	-	-	-	-	-	-	-	27.2	6.6	21.7
Calcareous (% abundance)										
<i>Ammonia parkinsoniana typica</i>	-	20.3	48.5	33.3	75.4	5.9	9.5	14.6	9.8	0.4
<i>Ammonia parkinsoniana tepida</i>	-	-	6.8	11.6	10.8	11.8	3.2	-	-	-
<i>Elphidium guntari salsum</i>	-	-	1.9	8.2	-	2.9	-	-	0.8	-
<i>Haynesina germanica</i>	100	1.2	32	35.5	7.7	67.6	1.1	-	-	0.4
Planktonic (% abundance)	-	-	1.9	-	6.2	11.8	-	4.9	0.8	0.4

ever, the presence of poorly sorted, muddy sand in the northern portion of Eastern Lake (i.e., marsh facies – Figure 2) is not as easily explained due to the lack of a prominent fluvial delta or other fluvial analogue as described in the Roy et al. (2001) model that could contribute sand to the area. There are a few possible explanations for the muddy sand. First, fluvial deposition from the 2 headwater wetlands north of Highway 30A during low water conditions. Second, aeolian deposition from the surrounding undeveloped dune forest. Third, restricted connectivity between the northern and central reaches of Eastern Lake produced by Highway 30A's partial causeway that precludes sand transport southward. Fourth, decreased sand erosion and subsequent nearshore deposition from land surrounding the shoreline in the central and southern reaches of Eastern Lake brought about by extensive residential development and changes in land use (e.g., land clearing, landscaping, shoreline armament and stabilization, etc.). Fifth, decreased proximity to the shoreline and increased influence of overland runoff and sediment transport north of Highway 30A. Additional sampling in other undeveloped coastal dune lakes in the region may help resolve the uncertainty surrounding the source of sand in the marsh facies.

The foraminiferal assemblages and distributions in Eastern Lake were also similar to nearby northern GOM estuaries (Table 1; Poag 2015). In particular, calcareous species found near the outfall (samples 1 and 2) and within the central mud basin (samples 3 through 6) were nearly identical to those found in the more saline reaches of Choctawhatchee Bay, FL (Goldsmith

1966, Pastula 1967), although *Milliolid* was notably absent from Eastern Lake. Salt marsh assemblages including *Ammobaculites dilatata*, *Ammotium* spp., and *Miliammina fusca* (Goldstein et al. 1995) were found in the upper reaches north of Highway 30A (samples 7 through 10). The general gradation from calcareous to agglutinated foraminifera in the landward direction is common in estuaries of the GOM and is attributed to decreasing salinity gradients from sea to land due to dilution from rivers and streams (Poag 2015).

CONCLUSION

Results from both sedimentary and foraminiferal analyses reveal at least 3 unique depositional environments in Eastern Lake. These include (1) a coarse grained, moderately well sorted, organic poor, sandy beach facies with a mixture of agglutinated and calcareous estuarine foraminifera located near the outfall and shoreline, (2) a fine grained, very poorly sorted, organic rich central mud basin facies with an abundance of calcareous foraminifera, and (3) a coarse grained, poorly sorted silty sand marsh delta facies dominated by agglutinated foraminifera. The 3 identified environments are further elucidated by a k-means cluster analysis of the sedimentary and foraminiferal data. It is worth noting that these 3 environments are found in much larger nearby estuaries including Choctawhatchee Bay, FL Pensacola Bay, FL and Mobile Bay, AL. These results therefore suggest that geologically, coastal dune lakes may serve as down-scaled micro-estuaries and may be functionally related to other nearby estuaries of the Gulf Coast despite their small sizes, intermittent connections to the sea, and unique hydrology.

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