THE CONTROL OF BOTH CLIMATE AND HOLOCENE SEA-LEVEL RISE ON AQUATIC ENVIRONMENTAL CONDITIONS IN A COASTAL SINKHOLE ON ANDROS ISLAND, THE BAHAMAS

A Thesis

by

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ABSTRACT

Andros Island is one of the largest island areas in the Bahamas, yet its paleoclimate and paleocological history remains poorly understood and largely based on inference from research on other Bahamian Islands. Understanding the Holocene history of Andros may provide insight into broader paleoenvironemental history of the region. Kemps Bay Bluehole is located on the eastern shore of South Andros Island. It is a terrestrial bluehole that is currently 4 m deep, 35 m in diameter, and located 51.3 m inland from the shoreline. Prior to 6500 Cal yr BP, microfossils (foraminifera; ostracodes) indicate that the basin transitioned from a polyhaline to oligohaline aquatic environment into an ephemeral pond, likely promoted by a regional trend toward drier conditions during the middle Holocene. Thereafter until 1000 Cal yrs BP, the site was dominated by lacustrine-like conditions, as indicated by the appearance of fresh to mesohaline microfossils (ostracodes: *Cyprideis vidua; Perissocytheridea cribrosa*; gyrogonites from charophytes), no foraminifera and deposition of carbonate marl. This environmental change was perhaps caused by concomitant groundwater table and Holocene sea-level rise that eventually inundated the floor of the sinkhole. In the last 1000 years, sedimentation shifted from carbonate marl to algal sapropel, and salinity in the basin increased based on the appearance of both foraminifera and ostracodes. During this time, it is also likely that Kemps Bay Blue Hole experienced intermittent oxygenation of bottom water based on abrupt oscillations in microfossil abundance versus absence. It is likely that regional precipitation changes combined with relative sea-level rise over the middle to late Holocene both contributed to environmental change in Kemps Bay Blue Hole.

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1. INTRODUCTION

Sinkholes and blueholes are abundant on Caribbean carbonate landscapes and their sedimentary successions can document long-term regional environmental change. Dissolution of antecedent carbonates over Quaternary timescales has produced mature karst landscapes with abundant dissolution features, including caves, sinkholes and blueholes (Carew and Mylroie, 1997; Mylroie and Carew, 1995; Mylroie et al., 1995). Terrestrial sinkholes and blueholes develop as subsurface voids in the antecedent carbonate that subsequently experience ceiling collapse and become subaerially exposed, while offshore blueholes are formed when pre-existing sinkholes or blueholes on a terrestrial surface are inundated by sea-level rise (Collins et al., 2015; Mylroie et al., 1995). Colloquially, the terms bluehole and sinkhole are used interchangeably, but for the purpose of this paper, "Kemps Bay Bluehole" is a subaerial sinkhole. Many coastal sinkholes are currently flooded by tidally-influenced groundwater that is stratified: an upper meteoric lens is separated from a lower saline groundwater mass by an intervening halocline or mixing zone (Beddows et al., 2007; van Hengstum and Scott, 2012). Sea level exerts a significance influence on karst processes as it controls the elevation of the freshwater lens and groundwater conditions which influence the location of the mixing zone and ultimately dissolution processes (Carew and Mylroie, 1997; Collins et al., 2015; van Hengstum and Scott, 2012).

Sediment records provide important environmental information regarding changes in sea level (Collins et al., 2015; Dix et al., 1999; Khan et al., 2017), groundwater (van Hengstum and Scott, 2012), large storm events (Donnelly et al., 2015; van Hengstum et al., 2014), and regional precipitation (Haug et al., 2001). On carbonate landscapes, paleoenvironmental information is typically derived from tree ring records, changes in speleothem geochemistry, and sedimentary records of inland lakes. In addition, the sediment records in sinkholes, blueholes and underwater caves can also provide valuable information regarding changes in karst processes, paleoclimate and sea level (Gischler et al., 2008; Kjellmark, 1996; van Hengstum et al., 2016; van Hengstum et al., 2014; van Hengstum et al., 2011).

Bahamian blueholes and sinkholes can also provide habitat for microorganisms that can preserve long-term records of hydrographic change in the stratigraphy (Donnelly et al., 2015; Gischler et al., 2008; van Hengstum et al., 2016). Foraminifera are protozoans with reticulating pseudopods found mostly in marine environments, with a few species living in brackish or fresh water (Murray, 2014). Ostracodes are meiofaunal crustaceans that live in almost all aquatic environments including hydrated soils with little to no standing water (Thorp and Covich, 2009). Benthic microfaunal communities are valuable stratigraphic and paleoecological tools based on their small size, large abundance, and great preservation potential of their tests or carapaces in the sediment record (Alvarez-Zarikian et al., 2001; Cushman, 1948). For example, different species of ostracodes are extremely sensitive to salinity changes, so changes in ostracode assemblages through time can indicate long-term salinity changes in the bluehole (Alvarez-Zarikian et al., 2001; Erez, 2003; Jorissen et al., 2007; Teeter, 1995). These salinity changes may be related to concurrent groundwater-level or sea-level change, or possibly changes in groundwater salinity from changes in regional precipitation patterns.

The Bahamian archipelago is comprised of carbonate islands and banks along the Northwestern margin of the tropical North Atlantic Ocean. Andros Island is one of the largest islands in the Caribbean Sea, encompassing about 6,000 km^2 if both North and South Andros are considered collectively (Kjellmark, 1996). Although there are no rivers on the island, an intricate network of tidal creeks and mangrove swamps are present (Black, 1932; Kjellmark, 1996; Shinn et al., 1969). The regional antecedent geology is Pleistocene limestones that extend less than 6 meters above sea-level. (Black, 1932; Kjellmark, 1996; Shinn et al., 1969).

Although Andros Island is the largest of the Bahamian Islands, there remains much to learn regarding its Holocene history. Kjellmark (1996) provided the first paleoecological record from Andros Island in a sediment core from Church's Blue Hole. Pollen analyses indicates that around 1500 Cal yr BP, the vegetation surrounding the bluehole consisted of shrub species that typically grow in dry open areas followed by a mesic hardwood thicket until about 740 Cal yr BP before it was displaced by pinewoods.

A peak in charcoal concentration during the transition to pinewoods and the coincidence of these vegetation changes with the known events in human colonization, depopulation and recolonization of the Bahamian Island suggest humans played a major role in altering the vegetation of Andros Island.

1.1 Research Objective and Questions

The central research objective for this project is to reconstruct millennial-scale environmental change in a bluehole on Andros Island, Bahamas, and evaluate its potential response to changes in regional sea level or rainfall. This will be accomplished by completing a detailed microfossil and sedimentary analysis on a sediment core collected from Kemp's Bay Bluehole (KBBH). The following questions motivate this research:

1. How have environmental conditions in Kemps Bay Bluehole changed over the Holocene?
2. Do microfossils assemblages and occurrence (e.g., benthic foraminifera, ostracodes) document salinity variations through time?
3. If so, what environmental factors are controlling salinity change in the bluehole through time?

2. STUDY SITE

In general, Caribbean climate is driven by the location of the Intertropical Convergence Zone (ITCZ) combined with numerous other oceanic and atmospheric forces formed by the coupling of the northern and southern hemispheres (Schneider et al., 2014; Waliser and Gautier, 1993). Paleohydroclimate records in the tropics indicate that precipitation has varied on Holocene timescales in response to a southern shift in the ITCZ (Haug et al., 2001; McGee et al., 2014). The ITCZ is a zonal band of high precipitation thus the position, structure and migration of the ITCZ are important in driving regional precipitation patterns on longer timescales (Fensterer et al., 2013; Schneider et al., 2014; Waliser and Gautier, 1993). In addition, the absolute position of sea level, and ultimately coastal groundwater, determines whether aquatic environments in coastal blueholes or sinkholes are perennial from permanent groundwater flooding, ephemeral in response to seasonal rainfall, or neither (van Hengstum et al., 2011).

The Bahamian archipelago encompasses a total of 300,000 km^2, with shallow banks making up 136,000 km^2, and 11,400 km^2 existing as subaerial land (Carew and Mylroie, 1997; Meyerhoff and Hatten, 1974). These islands were formed by the accumulation of carbonate and bioclastic turbidite sediments since the late Jurassic (Mullins and Lynts, 1977). Kemps Bay Blue Hole is located ~2.5 km south of Kemps Bay Settlement and is 51.3 meters inland from the eastern shore of South Andros Island (Figure 1). It is currently 35 meters in diameter with a total depth of 4.4 meters. The hydrographic conditions at the time of core collection was a salinity and temperature range of 7.4 to 8.1 psu and 24.3°C to 25.0°C, respectively, from surface to the sediment-water interface (Figure 2). Mangrove trees currently surround the periphery of the bluehole.

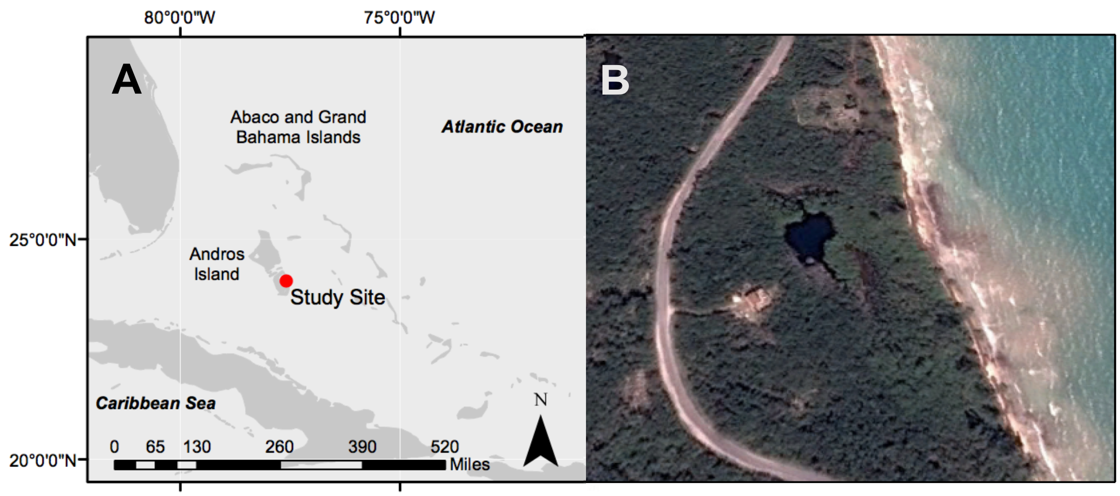

Figure 1. (**A**) Caribbean region with location of study site on Andros Island; (**B**) satellite image of Kemps Bay Bluehole.

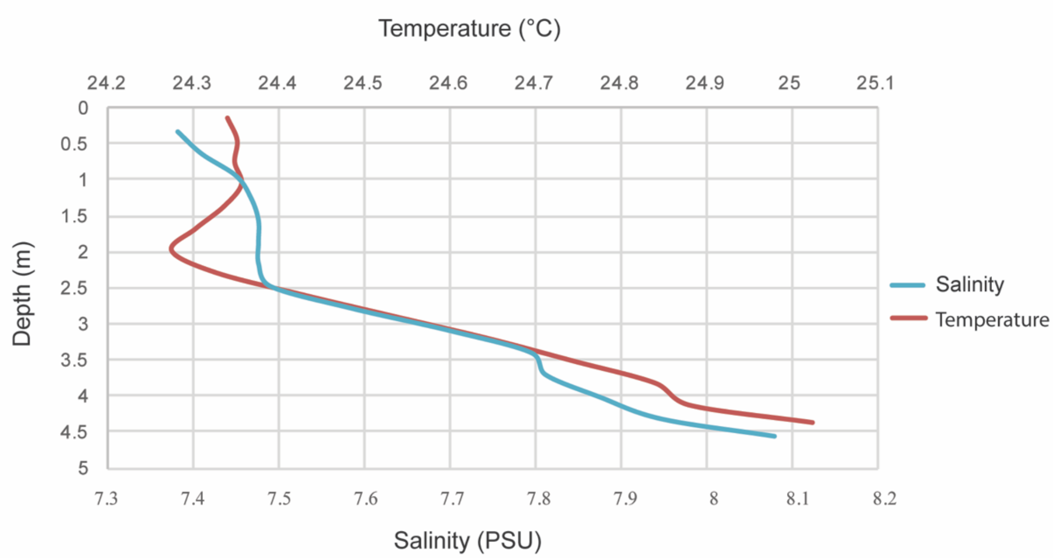

Figure 2. Vertical profile of temperature and salinity of KBBH in November of 2014 from the water surface to the sediment-water interface (4.36 m) at time of core collection.

3. METHODS

In November of 2014, two incremental piston cores were retrieved from the middle of the basin (24° 4'25.83"N, 77°32'44.34"W) that sampled the uppermost 188 cm of the sub-bottom stratigraphy. A Castaway™ CTD multiparameter sonde was used to measure salinity with ±0.1 PSU accuracy, temperature with ±0.05°C accuracy, and depth with ±0.25% accuracy at the location of the coring site (as described above in Section 2.0). Two incremental drives collected the upper 188 cm of the sediment record in the bluehole. The first drive (135 cm) collected the sediment water interface, while the second drive (130 cm) was pushed deeper into the sediment at the same location before tying-off the piston to collect a sample from deeper in the stratigraphic record. In the field, each core was cut into sections for transport back to the laboratory. The first section of the second drive (KBBH-D2_1:2) was broken in the field, but was replicated in the bottom-half of the first drive (KBBH-D1_2:2). When overlapping sections of the stratigraphy are accounted for, these two drives are collectively known as KBBH1, which reliably sampled the upper 188 cm of stratigraphy in the basin. Individual drives were shipped back to Texas A&M University at Galveston and stored at 4°C until further examination.

In the laboratory, all cores were first split lengthwise, photographed, x-radiographed, examined visually and lithologically described based on an established classification scheme of lacustrine sediments (Schnurrenberger et al., 2003). The relative quantity of bulk organic matter in the core was estimated with a standard Loss-On-Ignition (LOI) procedure (Dean Jr, 1974; Heiri et al., 2001) at 1 cm increments throughout all core sections for a total of 188 samples. Original weight of the samples was documented prior to drying overnight at 60°C. The dried weight was recorded before igniting the samples in a muffle furnace at 550°C for 4.5 hours. After the organic matter was removed during the ignition process, the mass remaining was recorded and percent organic matter of the original sample was calculated. The variability in coarse, inorganic sediment was determined using the Sieve-First LOI procedure (van Hengstum et al., 2016) in contiguous 1 cm sub-samples downcore. An initial volume of 2.5 cm^3 were rinsed over a 63 μm sieve to isolate sand sized sediment fractions and dried overnight at a 60°C. The original weight of the sample was recorded before and after drying overnight. Samples were then ignited at 550°C in a muffle furnace to burn off organic matter and concentrate the remaining coarse sediment residue. The final measurement is expressed as mass (mg) of coarse particles ($D_{>63\ um}$) per cm^3 of sediment.

A chronologic timeline for KBBH1 was established by radiocarbon dating terrestrial plant macrofossils (e.g., wood or leaves). The samples were sent to the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at Woods Hole Oceanographic Institute for standard AMS analysis. Using IntCal13 (Reimer et al., 2013) in Calib 7.1, the radiocarbon ages were converted into calibrated years before present (Cal yrs BP). Four samples were targeted at significant stratigraphic or microfossil occurrences to interpret broad environmental changes in the blue hole through time, however, two of these samples were at the same salient stratigraphic horizon (contact between the carbonate marl and algal sapropel horizon: 67 cm).

Detailed microfossil analysis was conducted using optimal stereomicroscopy on 69 samples downcore. No testate amoeba or agglutinated foraminifera were observed on wet sediment sieved over 45 μm mesh throughout the core, only calcareous microfossils were observed. Thereafter, benthic foraminifera, ostracodes, and charophytes were concentrated by wet sieving separate samples over a 63 μm sieve, with fine particulate organic matter decanted as necessary to rid the sample of loose organic flocs. The remaining sediment was washed into a small beaker and placed in a drying oven overnight at 60°C. The dried sediment residue was then examined under a microscope and microfossils were picked onto a 60-box paleontological slide for subsequent taxonomic identification and census counts. A total of 17,672 individual microfossils were counted. Taxonomic identification of the microfossils was verified using existing literature (Bermúdez, 1949; Bock and Jones, 1971; Cushman, 1918; Cushman, 1948; Furtos, 1936; Keyser, 1977; Krutak, 1971; Loeblich and Tappan, 1964; Loeblich and

Tappan, 1988; Michelson, 2012; Pérez et al., 2010; Teeter, 1980) with dominant and environmentally significant species imaged with Hitachi TM3000 scanning electron microscope (SEM). For each sample, the species richness (S) of ostracodes and benthic foraminifera were calculated separately, however, the total microfossils (ostracodes + foraminifera) was considered in the calculations of relative abundance because not all core depths had one type of microfossil. The relative abundance of all microfossils (ostracodes; foraminifera) was calculated by

$$Fi = \left(\frac{x_i}{n}\right) \times 100$$

where n is the total number of microfossils (ostracodes + foraminifera) in a sample, and x_i is the total number of individuals of a specific taxonomic unit in that sample. The downcore relative abundance of dominant taxa were plotted in C2 software program, with final graphics designed in Adobe Illustrator CC.

4. RESULTS

Five different lithofacies are present in the uppermost 188 cm of stratigraphic layers in Kemps Bay Blue Hole, so named as (1) *Neritina* carbonate sand, (2) detrital peat, (3) carbonate sand, (4) carbonate marl, and (5) algal sapropel. The downcore changes in ostracodes and foraminifera can be grouped into five separate biofacies that generally accord with the primary lithologic units. The oldest radiocarbon date indicates that the recovered stratigraphy captures the last 7200 Cal yrs BP (Table 1) of time. However, sedimentation rates in the bluehole were not consistent through time. The base of the sedimentary sequence was a *Neritina* carbonate sand unit that was succeeded by a detrital peat deposit before reverting back to carbonate sand deposition. Following this, a carbonate marl accumulated before abruptly transitioning into the uppermost algal sapropel unit at ~1000 Cal yrs BP. The lithofacies and microfossil biofacies are summarized in Figure Three and described in detail below. Microfossil analysis throughout the recovered sedimentary sequence does not indicate any wash-over events, despite the close proximity to the shoreline.

Table 1. Radiocarbon ages obtained from organic debris in the sediment cores.

Index No.	Lab number	Core	Core depth (cm)	Material dated	Conventional ^{14}C age	$\delta^{13}C$ (‰)	Fraction Modern (F14C)	1σ Calibrated years BP_{1950} (probability)	2σ Calibrated years BP_{1950} (probability)
1	OS-124640	KBBH-C1	67 (a)	twig	1210 ± 20	–27.2	0.8602 ± 0.0023	1083-1113 (0.380)	1065-1182(0.962)
								1120-1161 (0.523)	1213-1224(0.038)
								1171-1178 (0.098)	
2	OS-124663	KBBH-C1	67 (b)	twig	1230 ± 20	–28.73	0.8585 ± 0.0020	1088-1110 (0.196)	1072-1163(0.490)
								1124-1138 (0.108)	1169-1187(0.157)
								1145-1159 (0.140)	1203-1257(0.353)
								1172-1184 (0.187)	
								1207-1234 (0.369)	
3	OS-124664	KBBH-C1	118	twig	6020 ± 30	–26.4	0.4729 ± 0.0015	6798-6818 (0.235)	6792-6937(1)
								6832-6838 (0.53)	
								6841-6896 (0.712)	
4	OS-122730	KBBH-C1	155	twig	6290 ± 30	–25.26	0.4573 ± 0.0016	717-7220 (0.645)	7166-7267 (1.0)
								7235-7256 (0.355)	

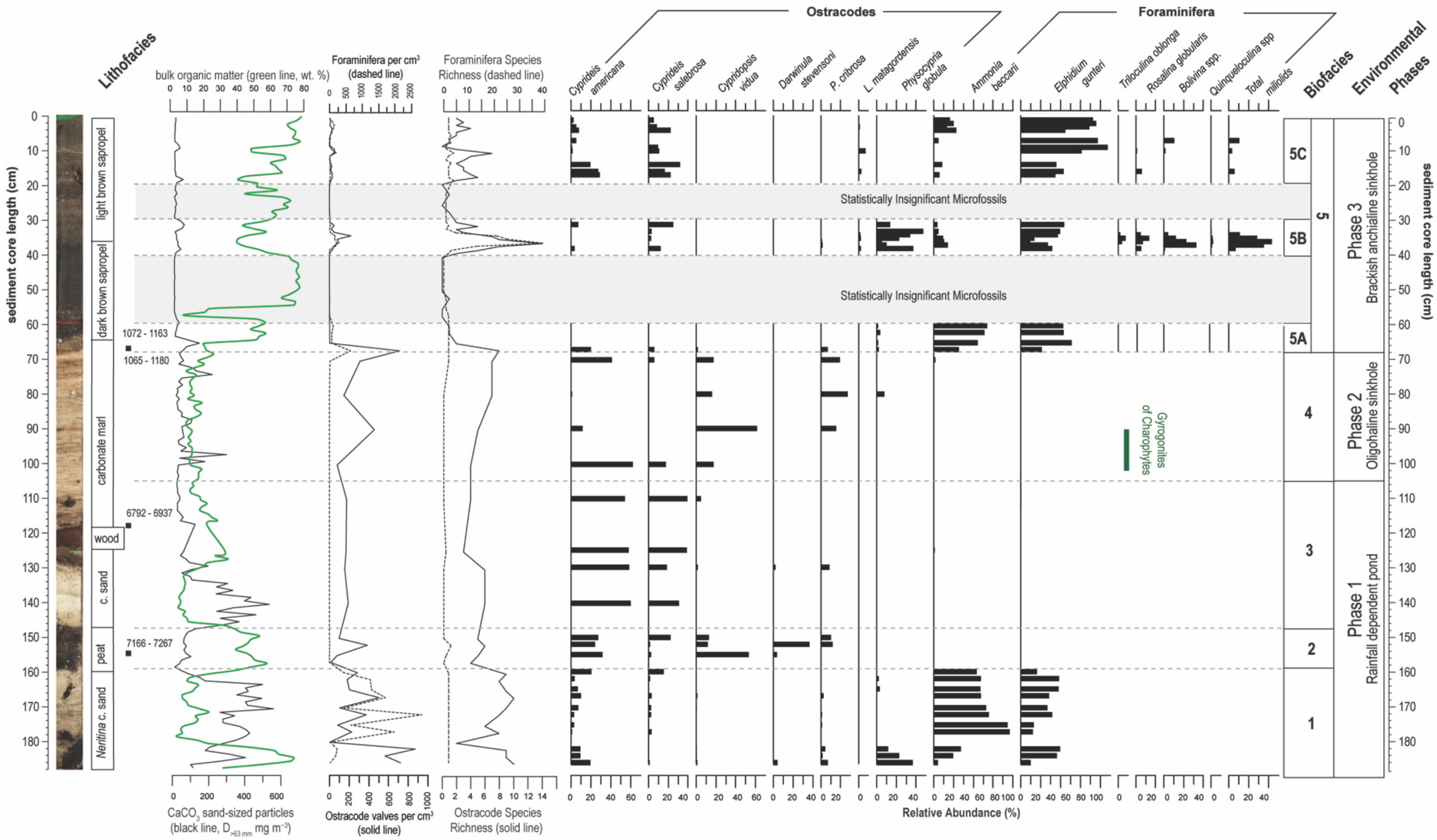

Figure 3. Described from left to right: Sediment core photograph with location of lithofacies (red line at ~60 cm in sediment core is a core cap and the green line at ~125 cm is floral foam, which indicates where the core was sectioned in the field); fraction of $CaCO_3$ coarse sediment ($D_{>63\ um}$) and bulk organic matter content; absolute abundance of dominant microfossils (ostracodes and foraminifera); species richness; relative abundance of dominant microfossils; location of Biofacies 1-5; and interpreted environmental phases on the far right.

4.1 Neritina Carbonate Sand Facies

The *Neritina* carbonate sand facies is located from the base of the core (188 cm) up to 160 cm and is light brown to tan in color, medium bedded sand with carbonaceous debris and shell fragments. The carbonate sand facies had a mean fraction of ~300.7 mg cm^3 of coarse sediment ($D_{>63\ um}$), which is the coarsest of all facies. Three separate clasts of organic matter, that are likely erosional in origin, occur in this lithofacies with the largest taking up about half of the last 8 cm of the sedimentary sequence. Radiocarbon results indicates this facies was deposited prior to ~7300 Cal yrs BP. There is a sharp transition from the *Neritina* carbonate sand facies into the detrital peat facies above.

The Neritina carbonate sand facies corresponds to Biofacies 1, which contains abundant microfossils (ostracodes, foraminifera) and macrofossils (gastropods) throughout. This unit also contains a common intertidal gastropod that is intact and not fragmented (little evidence of transport from elsewhere), which is tentatively identified as *Neritina virginea* (Figure 4)(Abbott and Morris, 2001; Sweat, 2017). *Neritina virginea* is not present in large abundances anywhere else in the recovered succession. This biofacies had the highest absolute abundance of foraminifera throughout the core but only two species were present: *Ammonia beccarii* (48.4%) and *Elphidium gunteri* (30.8%)(Figure 5). Ostracodes represented 20.9% of the assemblages, represented by 8 different taxa, with dominant taxa including *Cyprideis americana (9.6%)*, *Physocypria globula (4.2%)*, *Cyprideis salebrosa (3.4%)*, *Perissocytheridea cribrosa* (1.6%)(Figure 6).

4.2 Detrital Peat Facies

The detrital peat facies occurs between 146-160 cm of the sequence and can be described as a dark brown, fragmental woody peat based on Schnurrenberger's classification of lacustrine sediments (Schnurrenberger et al., 2003). This layer consists of a mean bulk organic matter of 74.8% with seeds and small wood fragments, and a mean sedimentary coarse fraction of 45.8 mg cm^3 ($D_{>63\ um}$). The lithofacies accords with Biofacies 2, consisting mostly of the ostracodes *Cyprideis americana* (26.1%), *Darwinula stevensoni* (25.6%), *Cypridopsis vidua* (19.1%), *Perissocytheridea cribrosa* (11.6%) and *Cyprideis salebrosa* (6.1%). Gastropods are present throughout the peat layer, but foraminifera are not statistically significant. Based on the radiocarbon date in this layer, the detrital peat accumulated ~7200 Cal yrs BP.

Figure 4. Gastropods present in core from 188-160 cm, tentatively identified as *Neritina virgenea* (~1 cm in length).

Figure 5. Scanning electron micrographs of selected foraminifera and gyrogonite. **A:** *Ammonia beccarii* (ventral)**; B:** *Ammonia beccarii* (dorsal); **C**: *Bolivina variabilis*; **D:** *Abditodentrix rhomboidalis*; **E:** *Bolivina sp.*; **F:** *Trifarina occidentalis*; **G:** *Bolivina striatula*; **H:** *Bolivina paula*; **I:** *Fischerina* sp.*;* **J:** *Atriculina pacifica*; ***K:*** *Quinqueloculina subrotunda*; **L:** *Elphidium gunteri*; **M:** *Trilouculina oblonga***; N:** *Rosalina globularis***; O:** *Triloculina* sp.; **P:** Gyrogonite of charophyte; **Q:** *Cibicides lobatulus*; **R:** *Conicospirillina exleyi* (dorsal); **S:** *Conicospirillina exleyi* (ventral)

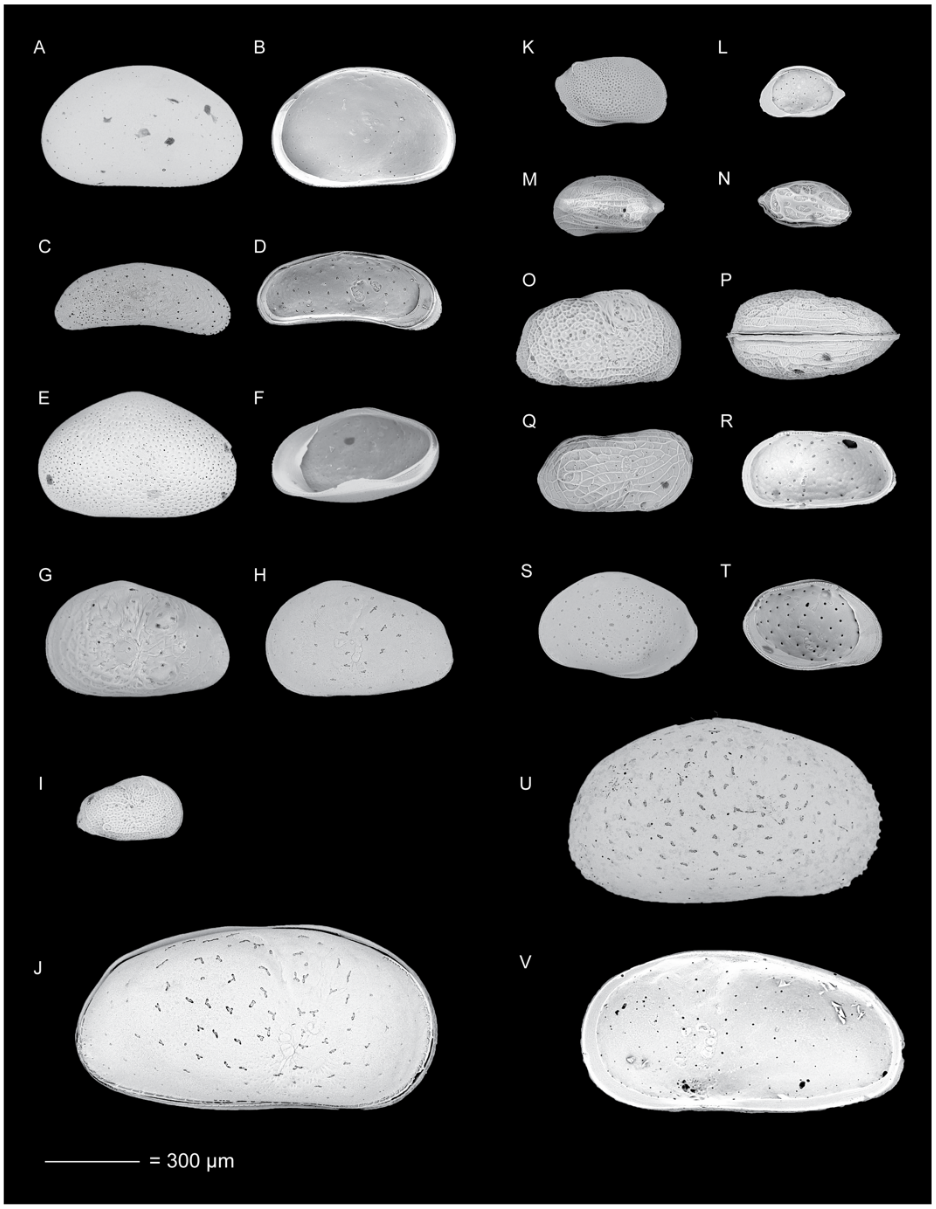

Figure 6. Scanning electron micrographs of selected ostracodes. **A:** *Physocypria globula* (exterior); **B:** *Physocypria globula* (interior); **C:** Unknown species 1 (exterior); **D:** Unknown specie 1 (interior); **E:** *Cypridopsis vidua* (exterior); **F:** *Cypridopsis vidua* (interior); **G:** *Cyprideis americana* with nodes (exterior) **H:** *Cyprideis americana* (exterior); **I:** juvenile *Cyprideis americana* (exterior); **J:** *Cyprideis salebrosa* (exterior); **K:** *Loxocorniculum tricornata* (exterior); **L:** *Loxoconcha matagordensis* (interior); **M:** Unknown species 2 (exterior) **N:** Unknown specie 2 (interior); **O:** *Perissocytheridea cribrosa* (exterior) **P:** *Perissocytheridea cribrosa* (fully intact, sideview); **Q:** *Perissocytheridea cribrosa* (exterior); **R:** *Perissocytheridea cribrosa* (interior); **S:** *Loxoconcha matagordensis* (exterior); **T:** *Loxoconcha matagordensis* (interior); **U:** *Haplocytheridea setipunctata* (exterior) **V:** *Cyprideis salebrosa* (interior).

4.3 Carbonate Sand Facies

According to radiocarbon results, the carbonate sand facies likely accumulated between ~7000 to 7200 Cal yrs BP and extends from 130-146 cm. A light brown carbonate sand layer indistinctly transitions into a light grey carbonate sand that has a thin green algal sand layer at 136-137 cm. Overall, this facies had the lowest bulk organic matter content of 10.8% with a high mean coarse sediment fraction content ($D_{>63\ um}$) of 247.9 mg cm^3. Gastropods were present in the carbonate sand layer in very small numbers. Biofacies 3 (146-105 cm) extends from the beginning of the carbonate sand lithofacies up into the bedded carbonate mud. Dominant benthic fauna in this biofacies include *Cyprideis americana* (55.2%) and *Cyprideis salebrosa* (30.4%) although, *Perissocytheridea cribrosa* (8.6%), *Darwinula stevensoni* (1.0%), *Cypridopsis vidua* (4.6%), *Elphidium gunteri* (0.3%) are also observed.

4.4 Carbonate Marl Facies

The carbonate marl facies occurs from a depth of 130 cm to 65 cm. This layer consists of a variably colored (i.e., brown, tan, green, and hints of purple laminations) unit with small clasts of organic matter. The core sampled a large piece of wood between 118-124 cm (Figure 7). The bulk organic matter content was found to be 48.8% with coarse sediment fractions of 16.0 mg cm^3 ($D_{>63\ um}$). Radiocarbon results suggests that this facies accumulated between about ~7000 to ~ 1000 Cal yrs BP, indicating slow sedimentation rates in Kemps Bay Bluehole during this time. Gastropods, ostracodes, and bivalves were present throughout this layer, and foraminifera were absent. Biofacies 3 (130-106 cm) and Biofacies 4 (106-68 cm) occur in the carbonate marl lithofacies. Biofacies 3 is consistent with what is described previously in the carbonate sand layer with the exception of the reoccurrence of abundant gastropods. Macrofossils (bivalves, gastropods) and microfossils (gyrogonites, ostracodes, foraminifera) are present in Biofacies 4. Ostracodes are observed with high abundances of *Cyprideis americana* (28.6%), *Cypridopsis vidua* (32.9%), *Perissocytheridea cribrosa* (26.7%) and *Cyprideis salebrosa* (9.1%) while foraminifera (*Ammonia beccarii*: 0.6%), *Elphidium gunteri*:

0.3%) are nearly nonexistent. Gyrogonites of charophytes were present in this layer between 90-100 cm, corresponding with a peak in abundance of the limnic to slightly oligohaline ostracode, *Cypridopsis vidua* to ~60% at 90 cm core depth.

4.5 Algal Sapropel Facies

The sapropel facies is divided into two sub-units that are termed the light brown sapropel (0-36 cm) and the dark brown sapropel (37-65) based on sedimentary features. Overall, the algal sapropel facies corresponds with Biofacies 5, which is further subdivided as 5A, 5B and 5C. This is the only place in the sequence where miliolid foraminifera (e.g., *Quincueloculina* spp.) and *Loxoconcha matagordensis* was observed. According to radiocarbon results, the current sedimentary environment began around 1070 Cal yrs BP and was observed from 65-0 cm, indicating the highest sedimentation rates since the middle Holocene. Small wood fragments and the occasional leaf are found throughout the sapropel facies.

The Dark Brown Sapropel (65-40 cm) has an abundance of gastropods at the beginning of the lithofacies and transitions into a black brown sedimentary layer with little to no gastropods present. It has a mean coarse sediment of 12.5 mg cm^3 ($D_{>63\ um}$) and a bulk organic content of 61.7%. The Dark Brown Sapropel includes Biofacies 5A (68-60 cm) as the carbonate marl progresses into the algal sapropel. It contains both macrofossils (bivalves, gastropods) and microfossils (ostracodes, foraminfera). Foraminifera sp. *Ammonia beccarii* (30.4%) and *Elphidium gunteri* (25.4%) are found throughout 5A while ostracodes *Cyprideis americana* (17.4%) *Perissocytheridea cribrosa* (16.6%), *Cyprideis salebrosa* (5.5%) are primarily present at the transition of Biofacies 4 into Biofacies 5. From 60-40 cm, there are statistically insignificant microfossils, although *Cyprideis salebrosa*, *Ammonia beccarii* and *Elphidium gunteri* are observed in rare occurrences.

The Light Brown Sapropel (40-0 cm) is medium brown in color with green and white laminations between 11-12 cm. Clear layers where gastropods occur in high

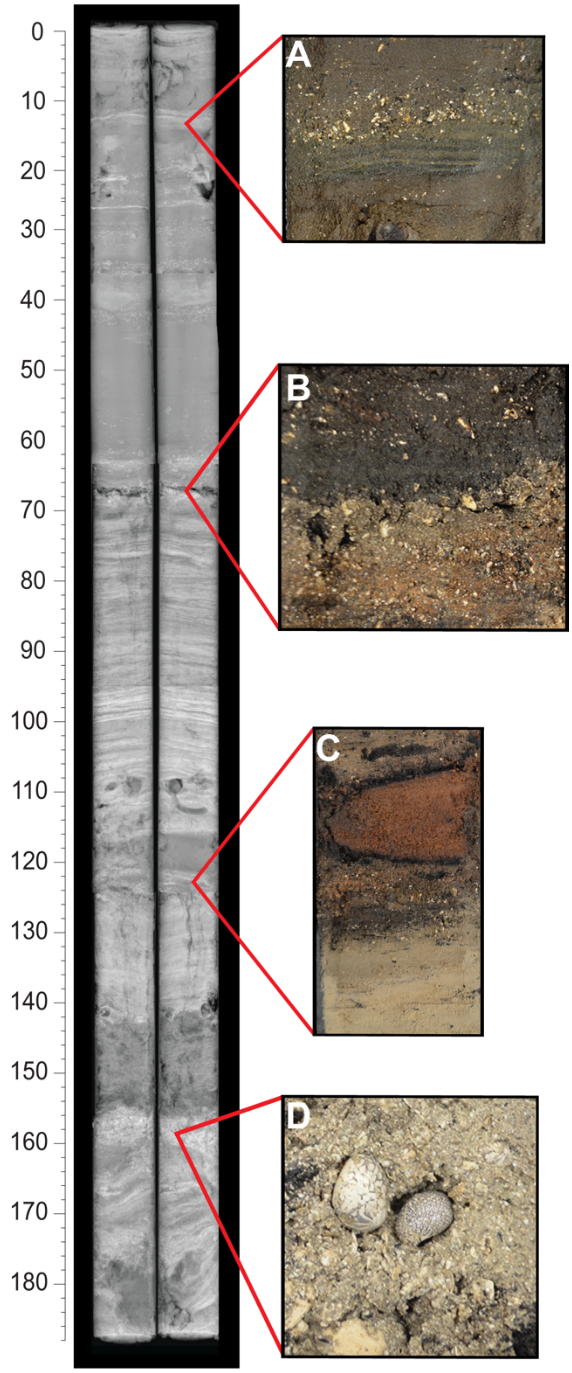

Figure 7. X-radiograph of the uppermost 188 cm of stratigraphy in Kemps Bay Blue Hole with insets of important sedimentary features. **A**: laminations in sapropel lithofacies; **B**: lithologic horizon between carbonate marl and algal sapropel lithofacies; **C**: wood fragment and transition from carbonate sand to carbonate marl lithofacies; **D**: *Neritina virginea* as found in split core.

abundances are present throughout this lithofacies (e.g., 10-11 cm)(Figure 7A). Crushed shell fragments of *Neritina virgenea* were observed in small abundances. It has a mean coarse sediment of 13.2 mg cm^3 and a bulk organic content of 60.2%. The Light Brown Sapropel includes Biofacies 5B and 5C. Biofacies 5B extends from 30-42 cm and displays the highest diversity of both ostracode and foraminifera throughout the 188 cm sequence retrieved. Between 36-37 cm, overall species richness reaches a peak of 52 species. Miliolids collectively make up 24.5% of the microfossils present in 5B. Dominant species in this biofacies include *Elphidium gunteri* (26.2%), *Physocypria globula* (21.0%), *Ammonium beccarii* (8.0%), *Quinequeloculina seminulum* (9.0%), and *Triloculina oblonga* (6.0%). From 30-20 cm, there are statistically insignificant microfossils (*Elphidium gunteri; Cyprideis americana*). Biofacies 5C is the most current sedimentary deposit and extends to a depth of 22 cm. The present-day environment is dominated by *Elphidium gunteri* with 62.9% of all microfossils present. *Cyprideis salebrosa* (13.0%), *Ammonium beccarii* (10.3%), and *Cyprideis americana* (7.2%) are also present in noteworthy abundances. Miliolids make up 1.5% of the microfossils in 5C. Each sedimentary environment is summarized below in Table 2.

Table 2. The average bulk organic matter (OM), coarse sediment fraction (CS), associated biofacies, and dominant fauna in each lithofacies.

Lithofacies	Texture	Biofacies	Dominant Fauna
Light Brown Sapropel	OM: 60.24%	5C (0-20 cm)	*E. gunteri* (40.86%); *P. globula* (12.69%);
	CS: 13.22 mg cm^3	5B (30-40 cm)	*A. beccarii* (8.87%); *C. salebrosa* (7.11%)
Dark Brown Sapropel	OM: 61.72%	5A (60-68 cm)	*A. beccarii* (53.83%); *E. Gunteri* (42.75%)
	CS: 12.50 mg cm^3		
Carbonate Marl	OM: 48.83%	4 (66-127 cm)	*C. americana* (25.86%); *C. vidua* (15.00%);
	CS: 15.99 mg cm3	3 (106-128 cm)	*A. beccarii* (14.34%); *E. gunteri* (11.95%);
			P. cribrosa (11.06%)
Carbonate sand	OM: 10.81%	3 (128-146)	*C. americana* (59.72%); *C. salebrosa* (25.93%);
	CS: 247.87 mg cm3		
Detrital peat	OM: 45.79%	2 (146-160 cm)	*C. americana* (26.10%); *D. stevensoni* (25.55%);
	CS: 74.57 mg cm^3		*C. vidua* (19.06%)
Neritina Carbonate Sand	OM: 24.7%	1 (160-188 cm)	*A. beccarii* (48.35%); *E. gunteri* (30.75%);
	CS: 300.7 mg cm^3		*C. americana* (8.03%)

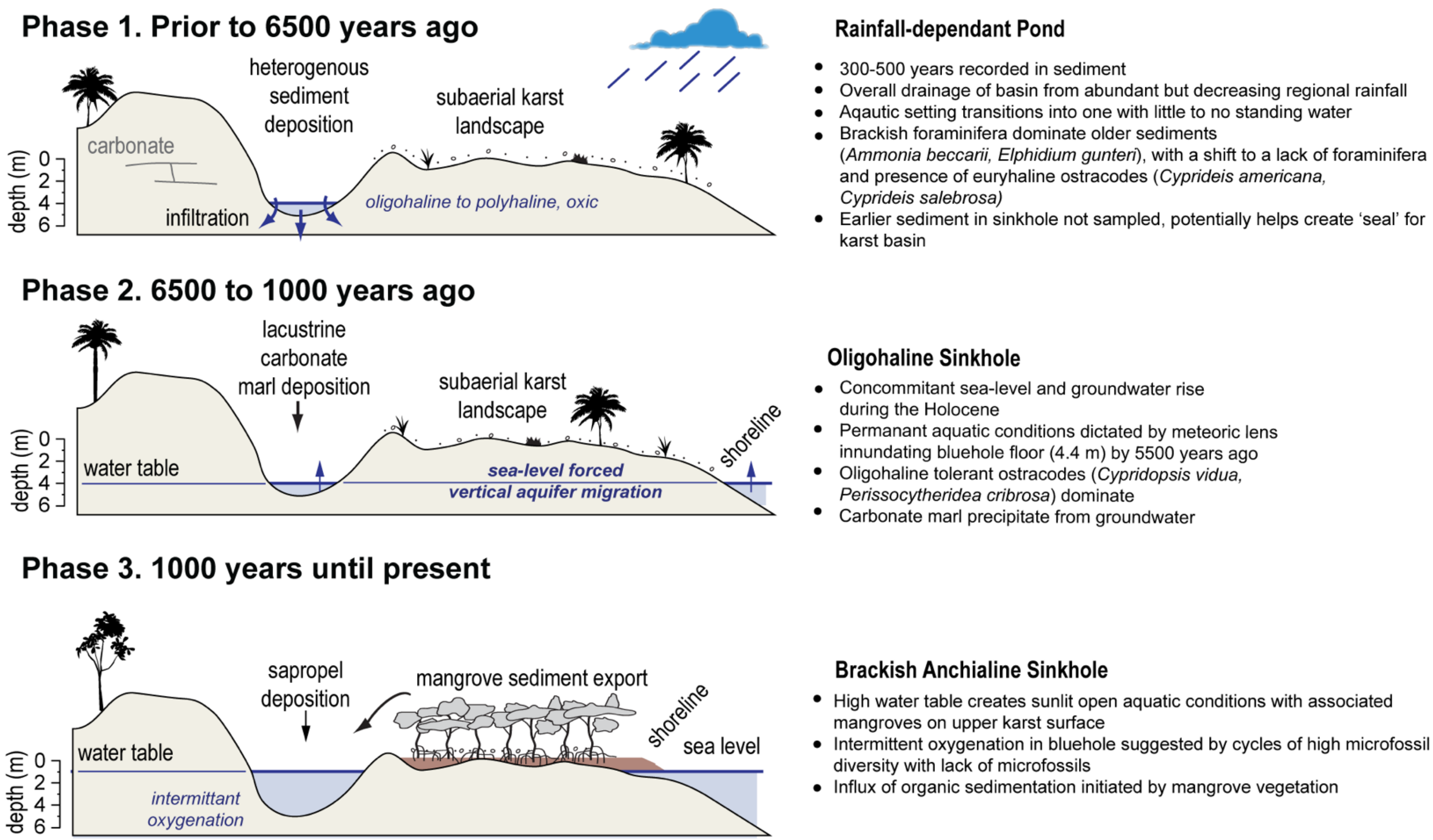

Figure 8. A conceptual model depicting interpreted environmental changes in Kemps Bay Blue Hole.

5. DISCUSSION

Based on microfossil and sedimentary analysis, Kemps Bay Bluehole experienced three main environmental phases (Figure 8). A polyhaline environment transitioned into an environment with little to no standing water prior to 6500 years ago due to overall abundant but decreasing regional precipitation. Mid to late Holocene sea level rise then forms a fresh aquatic environment in the bluehole from ~6500-1000 years ago before the basin experiences intermittent oxygenation cycles that correlate with periods of high microfossil diversities and the absence of microfossils over the last millenium (Figure 3).

5.1 Phase 1: Rainfall dominated environment prior to ~6500 Cal yrs BP

Microfossil analysis suggests a polyhaline aquatic environment transitioned into one with little to no standing water in a span of about 500 years around 6500 Cal yrs BP (Fig. 5, Phase 1). The dominance of *Ammonia beccarii* and *Elphidium gunteri* at the base of the collected sequence (Biofacies 1) suggests brackish conditions. For example, in Galveston Bay, these species are present in polyhaline conditions near the Trinity River bayhead delta (Phleger, 1965). The presence of *Neritina virginea* in the carbonate sand layer further supports this argument as they are known to inhabit intertidal brackish waters with sandy bottoms (Sweat, 2017). With the accumulation of the peat layer, evidence for increased freshwater input is suggested by the presence of the limnic ostracodes *Cyprideis* v*idua* and *Darwinula stevonsoni* (Alvarez-Zarikian et al., 2001; Pérez et al., 2010) and the lack of foraminifera. *Cyprideis americana* and *Cyprideis salebrosa*, known as euryhaline species, (Meyer et al., 2016) are also present within this environment. The peat layer contained fragments of wood but lacked the lower portions of the plants, suggesting they were transferred into this environment and did not form in-situ in a terrestrial environment. The disappearance of almost all microfossils, with the exception of *Cyprideis americana* and *Cyprideis salebrosa,* indicates a continued change into an environment with little to no standing water.

Based on evidence from Khan et al. (2017) at 7 ka, Holocene sea level in the Bahamas was ~5.6 meters below the present level, so concomitant Holocene groundwater and sea-level rise had not yet inundated the bluehole floor at a depth of ~4.4 meters (Figure 9). During this time, it is likely that regional precipitation and evaporation would have exerted a primary influence on environmental conditions of Kemps Bay Blue Hole. Since the peak of the Holocene Thermal Maximum, regional precipitation has experienced a long-term decreasing trend (Haug et al., 2001), perhaps allowing the basin to eventually dry out.

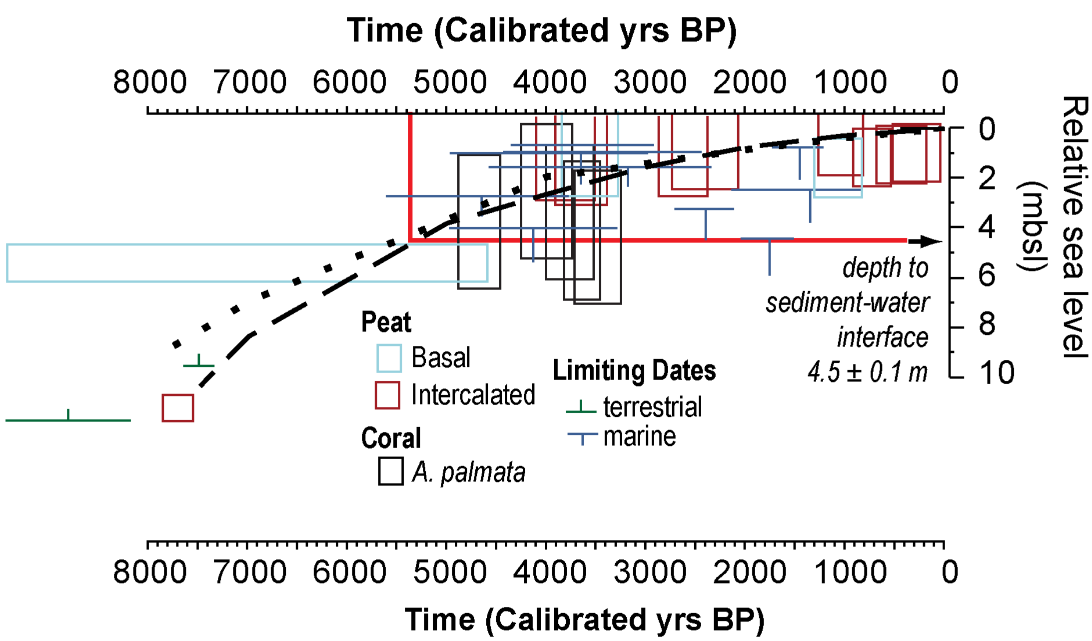

Figure 9. Regional sea-level framework after Khan et al. (2017), with additional older sea-level indicators from Abaco Island (Neumann and Land, 1975; Rasmussen et al., 1990), and ICE-5G model results with an upper mantle viscosity (UMV) = 5 x 1021 Pas and lower mantle viscosity (LMV) of 5 x 1022 Pas (dotted line) and EUST3 with an UMV = 2 x 1021 Pas and LMV = 5 x 1022 Pas (dashed line) (after Milne and Person, 2013). The red line highlights the likely onset of aquatic conditions forced by regional groundwater conditions, as caused by Holocene relative sea-level rise.

5.2 Phase 2: Environmental change and Sea level inundation at ~6500-1000 Cal yrs BP

The carbonate marl and microfossil assemblages from ~6500 to 1000 Cal yrs BP indicate a fresh to slightly brackish palustrine to lacustrine environment. Laminations are generally formed by a variety of mechanisms that produce variable sedimentary input into a basin (Schnurrenberger et al., 2003), and in Kemps Bay Bluehole are likely formed from variations in regional precipitation and evaporation. The environment is dominated by euryhaline and freshwater ostracodes including, *Cyprideis americana*, *Cyprideis salebrosa*, *Perissocytheridea cribrosa* and *Cypridopsis vidua*. *Cypridopsis vidua* prefers oligohaline environments while *Perissocytheridea cribrosa* can tolerate a broad range of salinity from 5-48 ppt (Engel et al., 2013), similar to *Cyprideis americana* and *Cyprideis salebrosa*. Gyrogonites from charophytes were also present in this layer, further indicating fresh to slightly brackish aquatic conditions (Soulié-Märsche, 2008).

Middle to late Holocene sea-level rise is most likely the driving force of the freshwater environment in Kemps Bay Blue Hole during this time. Inundation of the karst basin likely occurred around 5500 years ago as Holocene sea-level rise forced the bluehole to begin inundation by the meteoric lens of the local coastal aquifer (Figure 9)(Khan et al., 2017). This would initiate the transition to when aquatic conditions would start to become dependent on groundwater as the sinkhole become part of the phreatic zone, and not solely dependent upon water delivery through rainfall. The flooding by groundwater would also promote carbonate deposition in the sinkhole, and groundwater is typically saturated with respect to carbonate. However, the middle to late Holocene is a period known for decreasing regional precipitation, thought to be related to a long-term southern migration of the mean latitude of the ITCZ (Fensterer et al., 2013; Haug et al., 2001; Hodell and Curtis, 1991). These long-term precipitation changes, combined with ongoing seasonal variability likely contributed to intervals of increased aridity during this 5000-year period, precluded the site from becoming a completely limnic habitat and promoted the formation of carbonate particles from the evaporation of groundwater.

5.3 Phase 3: Anoxic and high diversity cycles from 1000 years ago to present

The transition from carbonate marl into an algal sapropel indicates a change to high primary productivity and changing sediment supply at Kemps Bay Bluehole. In the Yax Chen Cave in Quintana Roo on the Yucatan Peninsula, colonization of mangroves on the adjacent epikarst surface provided a sediment source for the adjacent underwater cave system basin (Collins et al., 2015). Similarly, it is likely that colonization of mangroves on the epikarst surface adjacent to Kemp's Bay Bluehole provided a sediment source and nutrients to increase primary productivity and promote accumulation of a sapropel deposit. In general, the onset of mangroves suggest moister environmental conditions during the last 1000 years, however, Kjellmark (1996) found drier conditions with a transition from mesic hardwood thickets to pines around 740 Cal yr BP on North Andros. Additional work is required to understand this apparent discrepancy.

The reoccurrence of *Elphidium gunteri* and *Ammonia beccarii* as dominant taxa suggests at least brackish water conditions persisted in Kemps Bay Bluehole after ~1000 Cal yrs BP. The transition from freshwater to brackish aquatic conditions during this time is likely caused by varying precipitation patterns that have the potential to cause abrupt hydrological changes to the meteoric lens (van Hengstum et al., 2010). In addition, the benthic environment then experiences cycling intervals where microfossil diversity is the highest of the entire record, versus intervals complete devoid of microfossils. Indeed, the presence of diverse microfossils indicates at least marine conditions in the bluehole during some times. The absence of microfossils in two separate intervals in the third phase of the environmental reconstruction suggests anoxic bottom water conditions (Figure 6). Previous research has found that foraminifera assemblages are largely controlled by oxygen and food as demonstrated in terms of the TROX (Trophic Oxygen) model, in which infaunal taxa dominate the assemblages in eutrophic environments where food is plentiful, but oxygen content is reduced (Jorissen et al., 2007). These anoxic conditions are likely promoted by increased flooding of the benthos by saline groundwater from the local coastal aquifer, while the reoccurrence of diverse microfossils suggests an overall mixing of the water column, perhaps by hurricanes or storms (van Hengstum and Scott, 2012). The lack of lagoonal foraminifera throughout the recovered stratigraphy suggests there was no in-wash of sediments from the adjacent lagoon.

6. CONCLUSION

A detailed paleoenvironmental reconstruction of Kemps Bay Bluehole in the Bahamans indicates that regional precipitation and sea-level rise were drivers of environmental change in Kemps Bay Bluehole over the last ~7,000 years. Prior to 6500 Cal yr BP, approximately 500 years of sedimentation indicate that Kemps Bay Bluehole transitioned from a polyhaline to oligohaline aquatic environment before an overall decrease in regional precipitation caused the basin to reach little to no standing water. Thereafter, sedimentation rates decreased for the next 5000 years, and a fresh water ecosystem containing *Cyprideis vidua* and *Darwinula stevensoni* as well as gyrogonites from charophytes was maintained until ~1000 Cal yr BP. This transition to an environment with limnic and euryhaline microfossils indicate likely flooding of the sinkhole benthos by the meteoric lens of the upper coastal aquifer in response to sea-level rise ~5500 years ago. Further radiocarbon dating would help resolve outstanding temporal uncertainties on the timing of this event. Eventually, hydrologic conditions caused an initial mixing of the meteoric lens with the saline groundwater, forming a brackish environment dominated by *Ammonia beccarii* and *Elphidium gunteri*. Recently, Kemps Bay Bluehole has experienced intermittent cycles of anoxic bottom water conditions with no microfossils present with highly diverse microfossil assemblages from ~1000 Cal yr BP to present, perhaps related to water column mixing from storm activity. This reconstruction further contributes to our understanding of how environments in sinkholes and blueholes change over millennial timescales in response to broader ocean and atmospheric forcing.

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