Sea-level rise and coastal circulation controlled Holocene groundwater development in Bermuda and caused a meteoric lens to collapse 1600 years ago

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A B S T R A C T

The recent report from Working Group II of the Intergovernmental Panel on Climate Change (IPCC) called for an increased understanding of how groundwater interacts with the ocean-atmospheric system. This remains a prerequisite to better understand how groundwater will respond to climate change. However, achieving this goal is hampered by several problems, including: (1) our minimal understanding of how current groundwater conditions evolved and responded to previous climatic perturbations, and (2) the scarcity of techniques available for evaluating prehistoric groundwater. Subfossil benthic foraminifera in underwater caves are an overlooked method of evaluating prehistoric groundwater on coastal carbonate terrain because they provide a proxy for groundwater salinity and circulation. Twelve radiocarbon dates and foraminiferal paleoecology from two sediment cores obtained from Green Bay Cave (GBC), Bermuda, provide the first Holocene-scale groundwater reconstruction. First, the cave floor (−20.7 mbsl) was flooded at 7.7 ka as North Atlantic sea level and groundwater rose in near synchrony. Over the Holocene, groundwater conditions (salinity, circulation and degree of oxygenation) shifted a minimum of five times, primarily in response to sea-level rise. Most importantly, we provide evidence that a prehistoric meteoric lens collapsed at 1.6 ka as sea-level rise breached a local sill and completely altered Bermudian coastal circulation. The complete loss, or retreat, of a groundwater mass associated with a minor sea-level change validates some numerical predictions that small changes in sea level can destabilize coastal groundwater resources, when coastal geometry and circulation are considered.

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1. Introduction

How will global groundwater resources respond to climate change? This is one of the most neglected issues in climate change impact assessments, so understanding the feedbacks between the ocean–atmospheric system and coastal groundwater remains an IPCC research priority (Kundzewicz et al., 2007). There are few instrumental records of long-term groundwater variability (Alley, 2001), and even fewer methods to study prehistoric groundwater–ocean–climate dynamics. As such, numerical modeling is heavily relied upon to forecast climate, sea level and anthropogenic impacts on groundwater on both global and regional scales (Budd and Vacher, 1991; Bobba et al., 2000; Alcamo et al., 2003; Wada et al., 2010), but there exists little capability to ground-truth these estimates over millennial timescales.

Coastal groundwater is of particular concern because it is threatened by: salinization from over abstraction, climate-forced changes to aquifer recharge, and saltwater intrusion from projected sea-level rise over the next century. The effect of sea-level rise on coastal groundwater is particularly challenging to predict along side the myriad of other variables that control local hydrogeology, such as precipitation changes. Some authors have argued that sea-level rise will only gradually affect coastal groundwater (Oude Essink, 2001), whereas others present evidence that only minor sea-level shifts can cause immediate negative impacts to coastal groundwater resources, especially on small islands (Bobba et al., 2000). This is troubling because coastal groundwater is the main source of drinking water on many carbonate platforms and islands. Perhaps understanding how groundwater responded to prehistoric climate and sea-level forcing will help contextualize current groundwater forecasts. However, achieving this goal is hampered by the lack of techniques available for studying prehistoric groundwater.

The sedimentary records in coastal karst basins (e.g., underwater caves, sinkholes, and blueholes) provide an innovative solution on karst landscapes (Fig. 1). Coastal karst basins (CKBs) are open systems because the high porosity of carbonate allows for the constant circulation of groundwater through the basin (Whitaker and Smart, 1990; Moore et al., 1992; Beddows et al., 2007). CKBs also provide sea-level independent accommodation space for sediments and habitat for microorganisms (van Hengstum et al., 2008; 2009; van...
Hengstum and Scott, 2011), which can be used to study prehistoric groundwater (van Hengstum et al., 2010). Here we use benthic foraminiferal paleoecology and organic matter geochemistry (δ¹³Corg: C:N) to reconstruct the prehistoric groundwater flooding Green Bay Cave, Bermuda, and question how it responded to previous climate and sea-level changes in the sub-tropical North Atlantic Ocean.

2. Coastal karst basins (CKBs) and their environments

Coastal karst basins (CKBs) include a variety of geomorphologic features that develop on limestone terrain from the long-term dissolution and karstification of limestone (speleogenesis), such as underground caves, sinkholes, and blueholes (Fig. 1). Over geologic time, CKBs have been repeatedly flooded and drained by groundwater because Quaternary sea-level oscillations force a concomitant vertical shift in the groundwater (Shinn et al., 1996; Surič et al., 2005). Four discrete environments can develop in CKBs from the combined effects of sea level, the groundwater mass or hydrozones (meteoric lens, saline groundwater, and mixing zone), and the influence of terrestrial versus marine processes on the system (van Hengstum et al., 2011). Vadose environments develop above the water table in the unsaturated ( vadose) zone (Fig. 1), whereas, the three other environments develop in the saturated ( phreatic) zone. Littoral environments have the groundwater table or sea level positioned predominantly within the CKB. This characteristic can promote specific environmental or sedimentary processes, such as the development of mangrove swamps in subaerial sinkholes with intertidal conditions (Gabriel et al., 2009), or calcite raft precipitation in littoral caves (Fornós et al., 2009). Anchialine environments are more complex: they have restricted atmospheric access, they can be flooded by meteoric lenses (brackish to fresh water) or saline groundwater (marine water), have subaerial access through sinkholes, and most conceptually important, they are dominated by terrestrial processes (e.g., hydrogeological, sedimentological). Finally, submarine environments are completely flooded by sea level and saline groundwater, they usually have entrances opening below sea level into the ocean, and they are dominated by marine processes (e.g., blueholes and caves).

3. Regional setting

The island of Bermuda is a basalt core overlain by alternating eolianites and paleosols that developed during Quaternary sea-level highstands and lowstands, respectively (Bretz, 1960; Land et al., 1967; Vacher and Rowe, 1997). Caves are ubiquitous in Bermuda (Mylroie et al., 1995), especially between Castle Harbour and Harrington Sound, and between North Shore Lagoon and Harrington Sound (Fig. 2). There are five major freshwater lenses in Bermuda: Somerset (117 ha), Southampton (110 ha), Warwick (53 ha), Devonshire (672 ha), and St. Georges (40 ha; Vacher, 1978) that are buoyed on saline groundwater intruding from the Sargasso Sea (Fig. 2A). Average annual precipitation in Bermuda is 1.5 m yr⁻¹ and average aquifer recharge is ~1 mm d⁻¹.

Two processes characterize coastal circulation in Bermuda: seasonal density gradients between water on the shallow platform and the Sargasso Sea, and tidal currents transporting seawater from the ocean into coastal basins. Coastal water experiences greater thermal seasonality than surface water in the Sargasso Sea, which is most pronounced in the winter. Sea surface temperature (SST) in the upper 16 m of the Sargasso Sea at Hydrostation “S” has ranged from 18.0 °C to 28.9 °C from 1954 until now, whereas, inshore SST has varied from 15.9 °C to 29.8 °C from 2000 to 2010 (www.weather.bm; Goodkin et al., 2008). As a result, seawater in the Great Sound is less dense than the Sargasso Sea during the summer, which acts to retain seawater in Bermuda’s coastal habitats (Boden and Kampa, 1953; Morris et al., 1977). In contrast, coastal seawater actively circulates off the platform in the winter as it becomes denser than the Sargasso Sea.

Tidal exchange of seawater into the inland water bodies (e.g., North Lagoon, Harrington Sound, and Castle Harbour) is also critical to Bermudian coastal circulation. The strongest tidal current flows through the narrow Flatts Inlet as it re-circulates seawater into Harrington Sound (Fig. 2A). Flatts Inlet has a sill at ~2.25 m below sea level, but this may have been shallower before colonial sediment dredging or tidal erosion. The velocity of Flatts Inlet current is 120 cm s⁻¹ during the flooding tidal cycle, but it only has a return velocity of 60 cm s⁻¹ during the ebb tidal cycle (see Table 6.7 in Morris et al., 1977). This provides evidence, along with additional numerical estimates (Morris et al., 1977), that almost 50% of the water flooding Harrington Sound during high tide is draining back to the ocean through the subterranean karst network. The modern distributions of benthic foraminifera in Green Bay Cave also indicate that seawater is actively discharging from Harrington Sound through the subterranean karst and into the ocean, but not traveling in the reverse direction (van Hengstum and Scott, 2011).

Green Bay Cave (GBC) is located in the phreatic zone on the northeastern shore of Harrington Sound (Fig. 2). The cave can be accessed...
through either the anchialine cave entrance at the base of Cliff Pool Sinkhole, or the submarine cave entrance opening into Harrington Sound (Fig. 3). The groundwater flooding GBC is typical of most Bermudian caves where a thin brackish meteoric lens (≤0.6 m, salinity > 20) is buoyed on saline groundwater (Maddocks and Iliffe, 1986; van Hengstum and Scott, 2011). Tidal pumping of seawater into GBC through the submarine cave entrance allows for seawater from the saline groundwater to regularly mix with Harrington Sound (van Hengstum and Scott, 2011). Current velocity through the submarine cave entrance can reach 150 cm s$^{-1}$ during peak tidal flow (Cate, 2009), but currents are minimal throughout the rest of the cave (Fig. 3C).

Modern benthic foraminifera in GBC define the cave passages that are anchialine versus submarine environments (van Hengstum and Scott, 2011), and they further subdivide these cave environments into specific habitats with unique sedimentological and hydrogeological characteristics (Fig. 4). The modern anchialine environment consists of two assemblages in different habitats: a group of brackish foraminifera in the brackish meteoric lens habitat (e.g., Helenina anderseni), and the anchialine cave assemblage that is located below the halocline in cave passages proximal to Cliff Pool Sinkhole (e.g., Bolivina striatula and Rosalina globularis). In contrast, the submarine cave environment consists of three separate habitats colonized by different assemblages of foraminifera. The circulated submarine cave assemblage is the most diverse (Fisher alpha of 16.8) and dominated by Triloculina oblonga and Spirillina vivipara. The isolated submarine cave assemblage is dominated by S. vivipara and Spiroplectidium emaciatum and located in passages most distal to cave entrances. The final submarine cave assemblage is common lagoonal miliolids living in the light-limited cavern zone (e.g., Quinqueloculina spp.). Overall, the ecology of modern

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**Fig. 2.** A: The location of Green Bay Cave (GBC) in Bermuda with inset positioning Bermuda in the North Atlantic. The five major freshwater lenses on Bermuda (after Vacher, 1978) are positioned relative to the evidence presented here for a prehistoric lens on the land between Harrington Sound and North Lagoon. B: The primary underground passages that comprise GBC. The cave system has two access points, one through the anchialine cave entrance at Cliff Pool Sinkhole (X) and another through the submarine cave entrance opening into Harrington Sound (Y). This map was adapted after original cave survey completed by Robert Powers in 1986. C: Twelve sediment cores were collected along the transect from X to Y in 2008 and 2009 (van Hengstum et al., 2011).

**Fig. 3.** Photomosaics of the anchialine cave entrance in Cliff Pool Sinkhole (A) and the submarine cave entrance at Harrington Sound (B). The minimal currents present inside the subterranean cave passages is illustrated by a undisturbed skeleton resting on fine carbonate mud that even retains some articulation (C). Photography credits: Tamara Thomsen and Bruce Williams.
foraminifera in GBC is governed by groundwater salinity, and the delivery of nutrients (sedimentary or dissolved) by groundwater circulation or sedimentation, which is similar to other coastal environments.

4. Methods

Twelve sediment cores were previously collected using advanced cave SCUBA diving techniques to understand Holocene-scale sedimentary processes in GBC (van Hengstum et al., 2011). Nineteen radiocarbon dates provide a chronology for the stratigraphy (Table 1), which were calibrated with IntCal09 and Marine09 (Reimer et al., 2009). A reservoir correction with local offsets from the global mean (ΔR value of −48 ± 40) was used when calibrating biogenic carbonates (Druffel, 1997). The two most expanded cores (5 and 9) were selected for the present analysis because they are centrally located in the cave away from lagoonal wave action and strong tidal currents (Figs. 2 and 3). Core 5 is from −19.5 mbsl and 68 cm long, whereas core 9 is from −19.8 mbsl and 65 cm.

Foraminifera were first concentrated by wet sieving −1.25 cm³ sediment samples, from a 0.5 to 1 cm interval, over a 45-μm mesh, every 0.5 to 2 cm downcore. Samples were then wet-counted in Petri dishes and taxonomy followed van Hengstum and Scott (2011). A census of greater than 300 individuals per sample was sought to achieve reasonable standard error estimates on dominant taxa (Patterson and Fishein, 1989; Fatela and Taborda, 2002). Five microfossil indices or techniques were used to interpret paleohydrogeology in GBC:

i. stratigraphically-constrained cluster analysis (Legrande and Legandre, 1998) to isolate primary groups, or biofacies, of foraminifera reflecting long-term groundwater conditions;
ii. comparative analysis of dominant subfossil foraminifera in the biofacies to their ecology in other modern environments;
iii. groundwater salinity changes were examined by the relative abundance of brackish foraminifera, especially Physalidia simplex and Conicospirillina exleyi n. sp.;

Foraminiferal assemblages & cave habitats

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**Table 1** Radiocarbon dates from all cores in GBC.

<table>
<thead>
<tr>
<th>Index no.</th>
<th>Lab number</th>
<th>Core</th>
<th>Core interval (cm)</th>
<th>Material</th>
<th>Conventional ¹⁴C age (yrs BP)</th>
<th>δ¹³C (%)</th>
<th>Calibrated age (yrs BP ± 2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>05-74175</td>
<td>GBC1</td>
<td>10 ± 0.5</td>
<td>Woody debris</td>
<td>2910 ± 35</td>
<td>−27.27</td>
<td>3080 ± 130</td>
</tr>
<tr>
<td>2</td>
<td>05-74176</td>
<td>GBC1</td>
<td>21.5 ± 0.5</td>
<td>Woody debris</td>
<td>4190 ± 45</td>
<td>−24.91</td>
<td>4710 ± 130</td>
</tr>
<tr>
<td>3</td>
<td>05-74177</td>
<td>GBC1</td>
<td>71.5 ± 0.5</td>
<td>Woody debris</td>
<td>5070 ± 70</td>
<td>−25.89</td>
<td>5820 ± 165</td>
</tr>
<tr>
<td>4</td>
<td>05-79473</td>
<td>GBC5</td>
<td>14.5 ± 0.5</td>
<td>Bivalve − Barbatia domingensis</td>
<td>645 ± 25</td>
<td>2.79</td>
<td>350 ± 95</td>
</tr>
<tr>
<td>5</td>
<td>05-78020</td>
<td>GBC5</td>
<td>27.5 ± 0.5</td>
<td>Bivalve − Barbatia domingensis</td>
<td>1610 ± 25</td>
<td>0.39</td>
<td>1200 ± 100</td>
</tr>
<tr>
<td>6</td>
<td>05-78019</td>
<td>GBC5</td>
<td>31.25 ± 0.25</td>
<td>Bivalve − Barbatia domingensis</td>
<td>2040 ± 25</td>
<td>−0.57</td>
<td>1670 ± 130</td>
</tr>
<tr>
<td>7</td>
<td>05-78451</td>
<td>GBC5</td>
<td>38.25 ± 0.25</td>
<td>Bulk organics</td>
<td>3590 ± 30</td>
<td>−27.12</td>
<td>3900 ± 70</td>
</tr>
<tr>
<td>8</td>
<td>05-74180</td>
<td>GBC5</td>
<td>46.25 ± 0.25</td>
<td>Bulk organics</td>
<td>3800 ± 40</td>
<td>−27.48</td>
<td>4200 ± 190</td>
</tr>
<tr>
<td>9</td>
<td>05-74179</td>
<td>GBC5</td>
<td>49.75 ± 0.25</td>
<td>Bulk organics</td>
<td>4930 ± 45</td>
<td>−25.23</td>
<td>5670 ± 80</td>
</tr>
<tr>
<td>10</td>
<td>05-80321</td>
<td>GBC5</td>
<td>51.5 ± 1</td>
<td>Foraminifera and ostracods</td>
<td>6800 ± 50</td>
<td>−0.14</td>
<td>7360 ± 120</td>
</tr>
<tr>
<td>11</td>
<td>05-79218</td>
<td>GBC5</td>
<td>61.25 ± 0.75</td>
<td>Foraminifera and ostracods</td>
<td>7160 ± 65</td>
<td>−1.59</td>
<td>7690 ± 150</td>
</tr>
<tr>
<td>12</td>
<td>05-79474</td>
<td>GBC5</td>
<td>65.25 ± 0.25</td>
<td>Terrestrial gastropod − Poecilozonites</td>
<td>11,100 ± 65</td>
<td>−8.02</td>
<td>12,940 ± 200</td>
</tr>
<tr>
<td>13</td>
<td>05-74186</td>
<td>GBC5</td>
<td>27.5 ± 0.5</td>
<td>Bivalve</td>
<td>1140 ± 40</td>
<td>−0.18</td>
<td>760 ± 110</td>
</tr>
<tr>
<td>14</td>
<td>05-81363</td>
<td>GBC9</td>
<td>11.5 ± 0.5</td>
<td>Bivalve − Barbatia domingensis</td>
<td>595 ± 25</td>
<td>2.9</td>
<td>280 ± 140</td>
</tr>
<tr>
<td>15</td>
<td>05-81364</td>
<td>GBC9</td>
<td>37.5 ± 0.5</td>
<td>Bivalve − Barbatia domingensis</td>
<td>2000 ± 25</td>
<td>0.29</td>
<td>1630 ± 130</td>
</tr>
<tr>
<td>16</td>
<td>05-81373</td>
<td>GBC9</td>
<td>59.5 ± 0.5</td>
<td>Foraminifera and ostracods</td>
<td>6700 ± 35</td>
<td>−0.72</td>
<td>7280 ± 110</td>
</tr>
<tr>
<td>17</td>
<td>05-81365</td>
<td>GBC11</td>
<td>37.25 ± 0.25</td>
<td>Bivalve − Barbatia domingensis</td>
<td>2020 ± 25</td>
<td>0.88</td>
<td>1650 ± 130</td>
</tr>
<tr>
<td>18</td>
<td>05-81366</td>
<td>GBC11</td>
<td>41 ± 0.75</td>
<td>Foraminifera and ostracods</td>
<td>7030 ± 30</td>
<td>0.42</td>
<td>7560 ± 100</td>
</tr>
<tr>
<td>19</td>
<td>05-81369</td>
<td>GBC11</td>
<td>46.75 ± 0.75</td>
<td>Foraminifera and ostracods</td>
<td>7210 ± 40</td>
<td>−0.93</td>
<td>7720 ± 120</td>
</tr>
<tr>
<td>20</td>
<td>05-81367</td>
<td>GBC12</td>
<td>29.5 ± 0.5</td>
<td>Bivalve − Barbatia domingensis</td>
<td>1630 ± 25</td>
<td>−0.1</td>
<td>1230 ± 100</td>
</tr>
</tbody>
</table>
iv. groundwater dissolved oxygen levels were estimated with the benthic foraminiferal oxygen index (BFOI; Kaiho, 1994), which were then used to understand groundwater circulation; and
v. foraminiferal diversity changes, representing favorable versus stressed conditions, were estimated with Fisher’s alpha:

$$S = F_n \times \ln(1 + N/F_n),$$

where $S$ is the number of taxa (species richness), $N$ is the number of individuals, and $F_n$ is the Fisher alpha index (Fisher et al., 1943).

Two original data matrices of foraminiferal counts were produced for cluster analysis from each core, totaling 95 samples and 96 different taxonomic units (species). However, 31 species were deemed statistically insignificant because they were present in only one sample, or the estimated standard error for the observation was greater than the relative abundance in all samples (Patterson and Fishbein, 1989). The final data matrix for core 5 was 52 samples × 65 observations, and 43 samples × 64 observations for core 9 (Appendix A). Raw abundance data was first square-root transformed to emphasize broader community patterns (Legrande and Legrande, 1998), and then subjected to stratigraphically-constrained Paired Group Q-mode cluster analysis using a Euclidean Distance co-efficient to identify biofacies. As a simple test of consistency, other distance coefficients produced similar dendrograms (e.g., Bray–Curtis).

The benthic foraminiferal oxygen index (BFOI) of Kaiho (1994) was calculated to estimate groundwater oxygenation and provide a first-order estimate of groundwater circulation. Although originally developed for the open ocean, modern taxa in GBC are responding to similar hydrographic variables as the open ocean, suggesting that the BFOI can also be used in underwater caves (van Hengstum and Scott, 2011). In general, the test morphology of foraminifera has been correlated to their life mode and tolerance to oxygenation (Corliss, 1991; Jorissen, 1999). Biserial to triserial taxa (e.g., Bolivina and Hopkinsina) are relatively more adapted to living within the sediments with lower dissolved oxygen concentrations as compared to biconvex-shaped taxa (Corliss, 1991; Jorissen et al., 1995). Even though the interplay between dissolved oxygen versus organic matter may confound the interpretation of foraminiferal shell characteristics (Jorissen et al., 1995; Thomas and Gooday, 1996; Bernhard and Sen Gupta, 1997), the BFOI has proven useful for reconstructing dissolved oxygen levels in the stratigraphic record (Kaiho and Hasegawa, 1994; Beniamovski et al., 2003). Therefore, we calculated the oxygen index to provide a prehistoric proxy of groundwater oxygenation. The benthic foraminiferal oxygen index (BFOI) is calculated by: if $D > 0$, then BFOI = $[O/(O+D)] \times 100$; but if $O \leq 0$, then BFOI = $[I/(I+D)] \times 1$; where, $O$ is the number of oxic foraminifera, $D$ is the number of dysoxic foraminifera, and $I$ is the combined total number of suboxic $A$ and suboxic $B$ foraminifera (Kaiho, 1994).

Sedimentary organic matter was characterized by total organic matter (the quantity), C:N ratio (the quality), and $\delta^{13}C_{org}$ (the source). Basin-wide measurements of these parameters were discussed in van Hengstum et al. (2011), but the results from cores 5 and 9 are reproduced here for comparison to the foraminifera. As such, the calculated geochemical averages for the biofacies are slightly different than the basin-wide averages for the lithofacies presented in van Hengstum et al. (2011), but the interpretations remain identical. Total organic matter was estimated by loss on ignition at 550 °C for 4.5 h, with reproducibility on replicates less than ±2% (Ball, 1964; Heiri et al., 2001). For $\delta^{13}C_{org}$ and C:N measurements, bulk sediment was first digested with 10% HCl, rinsed to neutrality, then dried. Dried residues were powdered using a mortar and pestle. Subsamples were then subjected to isotope ratio mass spectrometry, and $\delta^{13}C_{org}$ measurements are compared against international standards and expressed in the standard delta ($\delta$) notation in per mil (%). Lastly, the relative abundance of terrestrial versus marine organic matter in the cores was estimated by isotopic mass balance: $\delta X = F_{m} \times \delta X_{m} + F_{t} \times \delta X_{t}$; where $1 = F_{m} + F_{t}$; the terrestrial endmember (\$\delta X_{t}$ was $-26.7\%$; and the marine endmember (\$\delta X_{m}$ was $-16.8\%$ (van Hengstum and Scott, 2011).

### 5. Foraminiferal results

van Hengstum et al. (2011) proposed a facies model for environmental evolution in coastal karst basins (CKBs) after a detailed analysis of the stratigraphy in GBC. They proposed that CKBs systematically evolve from a vadose environment, to a littoral environment, then an anchialine environment, and finally into a submarine environment in response to sea-level rise, thus providing a broader principle to unify research in CKBs (Figs. 1 and 5). GBC provides the first complete stratigraphic sequence spanning the Holocene from a CKB and provides the archetype for this facies model. The sedimentary units throughout GBC can be organized into four facies that represent the Holocene depositional environments in GBC: (i) the vadose facies (prior to 7.7 ka), (ii) the littoral facies (7.7 to 7.3 ka), (iii) the anchialine facies (7.3 to 1.6 ka), and (iv) the submarine facies (<1.6 ka, Fig. 6).

The foraminiferal biofacies complement these stratigraphic results by providing a detailed perspective of the groundwater conditions during these four depositional environments. Cluster analysis identified five biofacies that are so-named to reflect their interpreted hydrogeological conditions (Fig. 7). In stratigraphic order, from oldest to youngest, the biofacies are: (i) oligotrophic littoral, (ii) marine anchialine, (iii) brackish anchialine, (iv) low-oxic submarine, and (v) circulated submarine. It is assumed that bioturbated and transported individuals have caused minimal taphonomic bias on the final assemblages because the core sites are located distal to cave entrances, subjected to low groundwater current velocities (Fig. 3C), and cave foraminifera are distinct from other assemblages of coastal foraminifera (van Hengstum et al., 2010; van Hengstum and Scott, 2011).

The oldest radiocarbon age of 12.9 ka was from the basal vadose facies in core 5 on a terrestrial gastropod (Table 1), and no foraminifera were recovered from within the vadose facies. This is expected considering sea level at Bermuda and far-field localities was greater than 60 m below present at this time, and since groundwater oscillates in near synchrony with sea level on carbonate platforms, groundwater was not flooding GBC at this time (Fig. 6). Detailed differences between the recovered biofacies are described below.

#### 5.1. Oligotrophic littoral (OL) biofacies from 7.7 to 7.3 ka

The OL biofacies is at the base of cores 9 and 5, from 59 to 62.5 cm and 50.5 to 62 cm, respectively. The vadose facies passes up into the littoral facies at 7.7 ka, and is characterized by calcite rafts, endemic aquatic cave microfossils, and fine carbonate mud (Fig. 5). Based on the radiocarbon ages, it existed from 7.7 ka to 7.3 ka, or a period of ~400 years. The sediment matrix is a fine carbonate mud matrix (micrite) that contains ~5% organic matter derived from both terrestrial and marine sources (Table 2), along with calcite rafts. Calcite rafts are a speleothem that precipitate at air–water interfaces in caves (Jones, 1989; Taylor and Chafetz, 2004; Fornós et al., 2009). Calcite rafts coeval with aquatic marine microfossils provide unambiguous evidence that a marine environment formed in GBC at 7.7 ka as local groundwater and sea level rose in synchrony (Fig. 6). Calcite rafts were present in the sedimentary matrix throughout the OL biofacies, which indicates that a water table (air–water interface) persisted in GBC throughout deposition of the OL biofacies.

The OL biofacies is dominated by a moderately diverse group of marine foraminifera based on a comparison of the Fisher alpha index between the different biofacies (Table 2). _Spirophthalmidium emaciatum_ is the most common taxon in both cores (mean 22%), with a high relative abundance of _Sigmoilina tenuis_ in both cores (Table 2, Fig. 7). _Spirillina vivipara_ is dominant in core 5 (mean 12.5%), but is less abundant in core 9 (mean 6.1%). _Rotulairel lartia_ is also more dominant in core 5 (mean 11.3%) than core 9 (6.3%). In contrast, _Mesorotula simplex_ is more common in core 9 (mean 7.6%), but
not prevalent in core 5. Other associated taxa in the biofacies include Trilocula oblonga (mean 6%), Tubinella funalis, bolivinids, and Patellina corrugata. Taxa comprising less than 1% of the total assemblage include: Fissurina spp., Rosalina williamsoni, Quinqueloculina spp., Melonis barleeanum, Heronallenita craigi, and Globocassidulina subglobosa. Negligible Trochammina and Reophax occur in the OL biofacies, and a BFOI of 50–100 throughout OL biofacies indicates that dissolved oxygen in the groundwater was >3 ml/l (Kaiho, 1994).

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**Fig. 5.** Stratigraphic correlation and facies analysis for all sediment cores collected from Green Bay Cave.

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**Fig. 6.** Comprehensive analysis of relative sea-level rise in Bermuda (Ellison, 1993; Vollbrecht, 1996; Javaux, 1999; van Hengstum et al., 2011) compared to sea level observations at far-field sites (Bard et al., 1996; Peltier and Fairbanks, 2006; Bard et al., 2010). Local freshwater peat data (green points) are often interpreted as the local sea-level curve, but these provide a sea-level maximum only (Redfield, 1967; Neumann, 1971; Ashmore and Leatherman, 1984; Kuhn, 1984; Vollbrecht, 1996). The flooding history of GBC, depicted by blue squares, closely follows the Holocene sea-level trends observed by Tahiti and Barbados corals. Foraminiferal biofacies: oligotrophic littoral (OL), marine anchialine (MA), brackish anchialine (BA), low oxic submarine (LS), circulated submarine (CS).
Fig. 7. Detailed results from cores 5 and 9, illustrating: lithology, radiocarbon dates, diversity and relative abundance of dominant foraminifera, dendrograms from cluster analysis and their resultant biofacies, and organic geochemical data. The BFOI from the brackish anchialine facies must be approached cautiously because the BFOI has yet not been calibrated in brackish settings. Foraminiferal biofacies: oligotrophic littoral (OL), marine anchialine (MA), brackish anchialine (BA), low oxic submarine (LS), circulated submarine (CS). Symbols are equivalent to Fig. 5.
Table 2
Arithmetic mean of the relative abundance of dominant taxa and organic matter characteristics in each biofacies. MA is not present in core 9 due to an interval of low sedimentation, and the BFOI for the BA biofacies is likely suspect (see text). Species with a mean of <1% relative abundance in the biofacies were marked with a dash so dominant species could be emphasized. See Appendix A for full micropaleontological dataset.

<table>
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5.2. Marine anchialine (MA) biofacies from 7.3 to 4.2 ka

The littoral facies passes up into the anchialine facies at 7.3 ka (Fig. 5). The MA biofacies is only represented in core 5, from 46 to 50.5 cm, indicating a period of slow- or non-deposition at the site of core 9. However, it is possible that the single sample from core 9 with the bloom of Metarotaliella simplex represents this condensed interval (59 to 59.5 cm, Fig. 7). The sediment of the MA biofacies is fine-grained, laminated, and organic rich (17% organic matter). The organic matter is predominantly derived from terrestrial sources (62.9%) based on the δ13Corg mass balance, and the C:N ratio indicates that mostly relictory (nitrogen-poor) organic matter was available to the foraminifera (Table 2). No calcite rafts were present in the stratigraphy after 7.3 ka and indicate that sea- and groundwater-level rise drowned the cave ceiling to create a completely phreatic cave passage (Fig. 6).

Mostly marine foraminifera dominated the MA biofacies, including M. simplex (mean 55%), S. emaciatum (18%), and Bolivina paula (5%). The rare taxa identified provide further evidence that marine conditions were contemporaneous in GBC, including Nonionella iridea and R. williamsoni. A few euryhaline taxa were indeed observed, such as B. variabilis (5%) and Physalidia simplex (3%, Fig. 7). This biofacies is less diverse (F, of 3.9), indicating that a stressed foraminiferal community was living in unfavorable environmental conditions. Importantly, less than 10 individuals of Quinqueloculina or Triloculina were observed in the entire biofacies (Appendix A). The BFOI drops as low as 17, indicating that dissolved oxygen in the groundwater dropped to ~1.7 ml l−1, but gradually increases through the biofacies.

5.3. Brackish anchialine (BA) biofacies from –4.2 to 1.6 ka

The BA biofacies was the thickest sequence in both core 9 (40 to 58.5 cm) and core 5 (33 to 46 cm, Fig. 7). The fine-grained sediment contained 24% total organic matter that is completely derived from terrestrial sources (Table 2). This biofacies has the second lowest diversity (Fisher alpha of −5), and is dominated by both P. simplex (mean 57%) and C. exleyi n. sp. (mean 18 to 20%, Fig. 8). Physalidia simplex is a diagnostic brackish water indicator (discussed below), so we attribute a small value to the BFOI calculated from this biofacies because this index has not yet been calibrated in brackish environments (Kaiho, 1994). A low abundance of Textularia earlandi occurs throughout the biofacies (mean<2%), and Trochammina charlottensis increases upcore in the biofacies. Bolivinids account for ~5% of the total population, and M. simplex had a mean 3% to 4%. Several other euryhaline species S. vivipara, T. oblonga, R. globularis, and R. williamsoni were also observed (1% or less). Furthermore, although not tabulated and analyzed with the foraminifera, brackish-tolerant thecamoebians (freshwater testate rhizopods) were routinely observed in association with this biofacies (e.g., Centropyxis aculeata and Cyclopyxis eurystoma, see Appendix A). Based on the dominance of brackish water indicators in the BA biofacies, the cave benthos was brackish from −4.2 to 1.6 ka.

Vanhengstum and Scott (2011) summarized the taxonomy of the foraminifera in GBC, but upon further analysis, Conicospirillina exleyi was determined to be a new species that is described here:

order Foraminiferida (von Eichwald, 1830)
suborder Rotalinina (Delage and Héroard, 1896)
superfamily Spirillinae (Reuss, 1862)
subfamily Spirillininae (Reuss, 1862)
genus Conicospirillina (Cushman, 1927)
Conicospirillina exleyi n. sp.

Figs. 8A–C.

Description: Test is quite small, translucent, free, hyaline, consisting of a proloculus followed by an undivided, enrolled, and tubular second chamber. The spiral (dorsal) side is low evolute, subconical to almost rounded in appearance. The umbilical (ventral) side is involute allowing only the final chamber to be visible, with an umbilical opening. Aperture is on the open end of tubular second chamber. Typically large individuals achieve 4–5 whorls maximum, and smaller individuals with 1–3 whorls are confusingly similar to microspheric Spirillina vivipara.

Etymology: After the pioneer of technical cave diving, Sheck Exley (1949–1994).

Haplotype: Fig. 8A, deposited in the Smithsonian Institution (USNM No.: 543042).
Paratypes: Fig. 8B and C, deposited in the Smithsonian Institution (USNM No.: 543043, 543044).

Remarks: The only other species in the genus is C. trochoide (Berthelin, 1879). The authors and Dr. Martin Buzas compared the holotype of C. trochoide to C. exleyi in November 2010 and determined that C. exleyi was a new species. In short, C. trochoide is significantly larger, apical, and keeled; whereas C. exleyi secretes a small, rounded test with a maximum of 4 to 5 whorls. Thousands of C. exleyi have been now observed from Bermuda (examine USNM No.: 543045), and Mexico (Crustacea Cave, examine USNM No.: 543046), and there is evidence that C. exleyi exists in Spanish carbonate environments. Therefore, C. exleyi is globally distributed and exhibits a stabilized morphology.

5.4. Low oxic submarine (LS) biofacies from 1.6 to −0.4 ka

At 1.6 ka, GBC transitioned into the modern submarine cave environment. This is demarcated by fine carbonate mud deposition, a
condensed layer of Barbatia domingensis bivalves (epifaunal, sessile), serpulid worm tubes, cave-adapted corals, and other marine invertebrates. There is also an instantaneous foraminiferal turnover from brackish to marine fauna. However, the groundwater conditions are not constant through time because the submarine facies contains two different foraminiferal biofacies: the low oxic submarine (LS)
biofacies (1.6 to −0.4 ka), and the circulated submarine (CS) biofacies (−0.4 ka to present, see Section 5.5).

The LS biofacies is located in core 9 from 20 to 38.5 cm, and in core 5 from 20 to 32.5 cm. There is a sharp decrease in the quantity of organic matter entering the cave, from 24% in the BA biofacies, to 9.7% in the LS biofacies. There is a mean 55% terrestrial organic matter in the biofacies, however, the organics shift from entirely terrestrial at the base of the LS biofacies to 40% terrestrial at the top. The BFOI starts low, 14 in core 5 and 17 in core 9, but increases to ~50 in both cores by the top of the biofacies. This suggests a gradual trend from low- to high-oxic groundwater conditions in GBC.

The most dominant taxon is *R. arctica* (14.2% in core 5, 16% in core 9), and bolivinids account for 29% of the population (core 5: mean 16.4%, core 9: mean 11.2%, core 10: mean 14%, core 11: mean 8%). Other associated species include *Trocchaolina ochracea* (mean relative abundance >10%), *M. simplex* (mean 3.6%), and *S. emaciatum* (−1.5%). This is the only biofacies where *Reophax nana* (mean 3%) and *R. scottii* (mean 1.5%) are common (Fig. 9). Other associated species include *B. striatula, H. craigi, Rosalina spp.*, *M. barleeanum, Fissurina, and T. charlottensis*. It is noteworthy that miliolids known to be intolerant to dysoxia are rare in this biofacies (e.g., *Triloculina* and *Quinqueloculina*).

### 5.5. Circulated submarine (CS) biofacies from 0.4 ka to present

This biofacies is dominated by marine foraminifera and located at the tops of core 9 (0 to 20 cm) and core 5 (0 to 18 cm). This unit is characterized by fine-grained carbonate mud with ~9.5% total organic matter like the LS biofacies, but is comprised of increased bulk organic matter that is primarily from marine sources. The BFOI exceeds 50 in both cores, indicating that high oxic groundwater (>3.0 ml l⁻¹) was flooding the cave. This biofacies corresponds to the modern Circulated Submarine Cave Assemblage described by van Hengstum and Scott (2011) while studying the modern ecology of foraminifera in GBC, and clearly demarcates the onset of modern cave conditions.

The most important characteristic is that the CS biofacies is the most diverse (Table 2). Both *S. emaciatum* (core 9: mean 11.2%, core 5: mean 16.4%), *T. oblonga* (core 5: mean 14%, core 9: mean 8%) dominate the CS biofacies, and *S. tenuis, P. corrugata,* and *S. vivipara* are common. Bolivinids are less common in the CS biofacies (mean 14%) than in the LS biofacies, and the abundance of *R. arctica* decreased from 15% in the LS biofacies to 5% in the CS. Both rotulid and miliolid groups are significantly diversified, including several additional species of *Miliolinella, Spiroloculina*, *Triloculina*, and *Quinqueloculina*, as well as *Siphonina*, *Svratkina*, and *Loxostomum*. Other notable additions to the population include *Cyclagyriva inovlens* and *Bulimina*. Finally, *Melonis barleeanum* is more abundant in the CS biofacies than in the LS biofacies, a species that favors regular, albeit not necessarily high quality, inputs of organic matter to the benthos (Caralp, 1989a, 1989b).

### 6. Discussion: groundwater implications from foraminifera

The three most significant variables influencing benthic foraminiferal ecology are organic matter availability (food resources), dissolved oxygen, and salinity (Kaiho, 1994; Jorissen et al., 1995; Thomas and Gooday, 1996; Bernhard and Sen Gupta, 1997; Scott et al., 2001; Debenay and Guillou, 2002; Murray, 2006). In deeper oceanic environments, where salinity is considerably more stable relative to coastal settings, foraminifera are generally interpreted in terms of organic matter versus dissolved oxygen. For deep-sea reconstructions, it is generally agreed that epifaunal foraminifera dominate oligotrophic habitats that are organic matter limited (food) and dissolved oxygen rich. In contrast, infrafaunal foraminifera begin to dominate under more mesotrophic to eutrophic settings where organic matter is abundant, which promotes dysoxia (Corliss, 1991; Jorissen et al., 1995; Bernhard and Sen Gupta, 1997; Jorissen, 1999; Abu-Zied et al., 2008). In coastal settings, however, salinity is critical and gives rise to entire foraminiferal assemblages living in coastal habitats with discrete salinity ranges (Debenay and Guillou, 2002).

In sinkholes and underground caves that are flooded by ground-water, it cannot be assumed that either salinity, organic matter, or dissolved oxygen will remain constant through time. This is because these abiotic variables can differ between groundwater masses (hydrozones), which are ultimately under the control of sea-level forcing (Fig. 1). A tempting perspective is to interpret the cave foraminiferal faunas analogously to silled coastal basins, where foraminifera turnover as sills become inundated and basins become connected to the ocean. However, this perspective is wrong because it ignores the fact that the high porosity of karst allows for the unimpeded vertical migration of groundwater under sea-level forcing.

#### 6.1. Initial cave flooding and marine oligotrophy: 7.7 to 7.3 ka

Based on relative sea level in Bermuda and at far-field localities, the floor of GBC became flooded at ~7.7 ka because sea level caused concomitant vertical migration of the local aquifer (Fig. 6). Prior to this point, permanent aquatic habitats did not exist in GBC because the cave was in the vadose (unsaturated) zone. The marine foraminifera recovered in the OL biofacies, along with bryozoans, marine gastropods, and fish bones represent when marine conditions became established in GBC at 7.7 ka. The groundwater was oxic based on the high BFOI (Fig. 7).

*Spirophthalmidium emaciatum* dominates the cave habitat after initial flooding, a species that currently lives in the most isolated areas of GBC that are perhaps the most nutrient-depleted or oligotrophic (Fig. 4). This is also the only biofacies where *Sigmolina* tenuis dominates, a species that is rare in other Bermudian coastal habitats except underwater caves (Javais and Scott, 2003). Both of these taxa are epi-faunal, along with all the other dominant foraminifera in the LO biofacies (e.g., *Patellina, Spirillina,* and *Tubinella*). *Sigmolina* and the taxonomically confusing *Spirophthalmidium−Ophthalmidium* are more typically known from deep-sea mesotrophic to oligotrophic environments. For example, *Spirophthalmidium* and *Sigmolina* are found >2400 mbsl in the central North Atlantic Ocean (Hermelin and Scott, 1985), and *Spirophthalmidium* (categorized as *Ophthalmidium*) occurs >2500 mbsl in the southeast Indian Ocean (Corliss, 1979). *Spirophthalmidium* also bloomed during an oligotrophic trend in the eastern Mediterranean (Levantine Sea) from ~17 to 12.5 ka (Abu-Zied et al., 2008). These results suggest that the saline groundwater that first flooded GBC at 7.7 ka was highly oxic and nutrient-depleted.

#### 6.2. Mid-Holocene marine sub-oxia: 7.3 to 4.2 ka

For a period of ~3.2 ka, the cave was colonized by the MA biofacies, and the low BFOI indicates that the bottom water was sub-oxic. This interval is dominated by the microforaminifer *M. simplex* (>90%). *Metarotaliella* is a coastal genus from both brackish and marine settings (Pawlowski and Lee, 1991; Pawlowski and Zaninetti, 1993; Colleen, 1998), and *M. simplex* occurs in brackish ponds on Spanish carbonate terrain (Usara et al., 2002; Guillem, 2007; Blázquez and Usara, 2010). However, the MA biofacies is not indicative of brackish conditions because other common brackish taxa are infrequent (i.e., *Physalida simplex* and *Marine foraminifera* are common (e.g., *S. emaciatum*). Furthermore, the C:N ratio and δ¹⁵Norg is similar between the LO and MA biofacies, and indicate a primarily marine source for the bulk organic matter that is being produced in, or supplied to, the cave benthos (Table 2).

Based on a comprehensive analysis of the MA biofacies, GBC was most likely flooded by sub-oxic saline groundwater from 7.3 to 4.1 ka. This created an oxygen-stressed marine anoxic environment for the foraminifera. The abundances of *M. simplex* and *B. variabilis* are inversely correlated to *S. tenuis* and *S. emaciatum* in
the MA biofacies (Fig. 7), which indicates intermittent shifts to more oxygenated conditions occurred that are preferred by milio liths. The oscillating BFOI through the MA biofacies reflects these oscillating oxygen levels.

Two possibilities exist for the bottom water in the cave from 7.3 to 1.4 ka: either (a) long-term suboxic saline groundwater flooded the benthos with intermittent fluxes of oxygenated seawater to cause some oxygenation (e.g., storm or hurricane pumping of the aquifer), or (b) long-termoxic saline groundwater flooded the benthos that received intermittent upwelling of anoxic saline groundwater through the carbonate bedrock from below. At this stage it is challenging to isolate the correct hydrogeologic mechanism, but it seems more plausible that GBC was flooded by sub-oxic saline groundwater because milio liths intolerant to dysoxia are absent (Quinqueloculina, Triloculina, and Tubinella). Perhaps Spiotholithoida and Sigmolina are opportunists during short-term returns to oxic conditions, a hypothesis supported by Sigmolina rapidly colonizing after Mediterranean sapropel events (Kirki-Elmas et al., 2008).

6.3. Development of brackish meteoric lens: 4.2 to 1.6 ka

The BA biofacies indicates that bottom water became abruptly brackish from 4.2 to 1.6 ka, most likely in the salinity range of 9 to 18 psu. The BA biofacies is completely dominated by Physalidina simplex and Conicospirillina exleyi. In a low oligohaline (1.5 to 3.5 psu) setting, van Hengstum et al. (2008, 2009) observed abundant P. simplex living in brackish anichaline sinkholes and caves in Mexico, but not C. exleyi. In a mesohaline (5 to 18 psu) setting on the carbonate coast of Spain, Guillem (2007) found P. simplex living in multiple brackish ponds (salinity of 6.6 to 13.4), even when one pond became sub-oxic (1.12 ml/l), and C. exleyi lived in these ponds when salinity exceeded 9 psu. The modern brackish meteoric lens flooding Cliff Pool Sinkhole has a salinity greater than 24 psu (polyhaline), and although P. simplex and C. exleyi were indeed present, they were rare. In subfossil examples, P. simplex and C. exleyi were found in association with other brackish microfossils that characterized prehistoric brackish conditions in both Spanish lagoons and Mexican anichaline caves (Usura et al., 2002; Blázquez and Usura, 2010; van Hengstum et al., 2010). Other euryhaline species in the BA biofacies (M. simplex and T. earlandi) also suggest a brackish setting, however, the presence of Spirillina vivipara suggests that salinities were greater than 7 psu, the ecological threshold for this taxon (Bradshaw, 1961). Based on the evidence for P. simplex colonizing habitats in the salinity range of ~1.5 to 18 psu, and C. exleyi colonizing habitats when salinity exceeds 9, the most simple explanation is that the cave bottom water had a salinity of 9 to 18 psu (mesohaline) from ~4.2 to 1.6 ka.

Therefore, the groundwater flooding GBC rapidly shifted from saline groundwater (MA biofacies) to either a mixing zone or brackish meteoric lens (BA biofacies) at 4.2 ka. Considering coeval sea level was at approximately ~45 mbsl, there was a water depth of approximately 15 m between a prehistoric water table and the sediment-water interface colonized by the foraminifera. That volume of non-marine groundwater can only be reconciled by the emplacement of (i) a brackish meteoric lens, or (ii) a brackish mixing zone and a shallow freshwater lens (Fig. 2A). The largest freshwater lens currently in Bermuda is the Devonshire (Central) Lens, which is 15 m thick and has developed on a 2 km-width landmass. However, even when sea level was ~5 m below present at 4.2 ka, 2 km of land width would not be available near GBC (Vollbrecht, 1996). Furthermore, hydraulic conductivity of the bedrock in the Devonshire Lens region specifically promotes its development (Vacher and Wallis, 1992). The lithology in the GBC area is mostly the Belmont Formation (Vacher and Wallis, 1992), which is a more porous formation that is not as conducive to the formation of a 15 m thick meteoric lens. The most likely explanation for the brackish benthos in GBC involves considering the local paleohydrogeology within a regional hydrographic and climatic setting.

Based on a comprehensive stratigraphic analysis, Harrington Sound was a restricted pond from 4.2 to 1.6 ka because sea level had not yet breached Flatts Inlet to allow open hydrographic communication between Harrington Sound and North Lagoon (Vollbrecht, 1996). Stratigraphic markers in multiple sediment cores indicate that salinity in Harrington Sound was unstable, and in the polyhaline to marine salinity range during this time (18 to 35 psu; Vollbrecht, 1996). Aquifer recharge was also likely contemporaneously enhanced because regional temperature and potential evaporation was reduced and combined with increased precipitation. Local pollen reconstructions from Devonshire Marsh, Bermuda, indicate that cool and wet conditions existed from ~5.0 to 3.5 ka (Rueger, 2006), albeit Bermuda remained a tropical climate (Watts and Hansen, 1986), and the western Sargasso Sea was generally cool from 4.5 to 3.2 ka (Keigwin, 1996). These cooler and wetter conditions perhaps promoted a brackish cap in Harrington Sound, increased regional aquifer recharge on land, and expansion of the mixing zone along the periphery of Harrington Sound from 4.2 to 1.6 ka. This interpretation is consistent with evidence for a salinity-stratified Harrington Sound beginning at ~4 ka (Vollbrecht, 1996). The observation of thecamoebians (Centropyxis and Cyclopoxys) in the BA biofacies suggests that Cliff Pool Sinkhole was indeed nearly a freshwater pond flooded by an oligohaline meteoric lens, as these thecamoebians are common in Mexican oligohaline sinkholes and caves (van Hengstum et al., 2008). At this point, the exact volume of the meteoric lens that may have developed near GBC would be a challenge to estimate, but the most reasonable explanation for the microfossil evidence is that the benthos in GBC was flooded by a brackish mixing zone below an upper meteoric lens, which was perhaps oligohaline (see Fig. 1). An increased regional dataset will no doubt refine our spatial understanding of regional groundwater at this time.

6.4. Meteoric lens collapse at 1.6 ka with onset and amplification of tidal pumping

At 1.6 ka there was a systematic turnover from the brackish biofacies dominated by Physalidina and Conicospirillina to foraminifera indicative of marine conditions (Tables 2 and 3). The most dominant taxon in both cores in the LS assemblage is Rotaliella arctica, a deep sea taxon known only from the Lomonosov Ridge off northeast Greenland in the Arctic Ocean (1980 mbsl, Scott and Vilks, 1991), and the Bermuda Rise in the Sargasso Sea (4450 mbsl, Pawlowski, 1991). The BFOI index from the LS biofacies indicates a return to low oxic saline groundwater in GBC based on the dominance of bolivinid taxa: B. paula, B. pseudopunctata, and B. variabilis (Kaiho, 1994; Bernhard and Sen Gupta, 1997; Bernhard et al., 1997). Bolivina variabilis can also thrive in eutrophic environments (Kuhn et al., 2007; Abu-Zied et al., 2008), but this is an unsatisfactory explanation for conditions in GBC at this time because the C:N ratio indicates that the organic matter quality is actually poorer in the LS biofacies than the CS biofacies, but the organic matter quantity is consistent between the two biofacies.

Only in the LS biofacies do R. nana and R. scottii each represent greater than 1% of the assemblage, along with Trochammina (Table 3). Both these Reophax genera are known from coastal environments with high-productivity and decreased dissolved oxygen (Scott et al., 2001). In a cave–specific modern analog, R. nana and R. scottii are presently living in Crustacea Cave, an anichaline cave in Mexico flooded by saline groundwater that has only 0.6 ml l−1 dissolved oxygen (van Hengstum and Pakes, unpublished data). Reophax and Trochammina are also pioneering fauna when new open ocean habitat becomes available (Fig. 7; Alve, 1999). Lastly, the low milio lith population in the LS biofacies is also indicative of low-oxygen levels (den Dulk et al., 2000).
Table 3

Summary of foraminiferal biofacies and their hydrogeological implications. See van Hengstum et al. (2011)

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</tbody>
</table>
| Littoral: 7.7 to 7.3 ka | Oligotrophic Littoral        | Calcite rafts   | Sea level riseDecorated case ceiling, intermittent low-oxygen saline groundwater floods GBC, GBC saturated by oxic saline groundwater, saline groundwater actively circulating through GBC where cores 5 and 9 were collected. Since all the foraminifera colonizing the cave at 1.6 ka are marine, adapted to sub-optimal oxygen conditions, and known pioneers, then a rapid return to marine conditions with reduced oxygenation of the saline bottom water is the most likely environmental conditions characterizing the beginning of the submarine cave environment (LS biofacies). Based on the trend from low to high BFOI, saline groundwater circulation was likely initially sluggish, but increased in vigor and strength over the last 1600 years with increased tidal pumping through the submarine cave entrance (Table 3). The implication of these results is that the meteoric lens that persisted from 4.2 to 1.6 ka abruptly collapsed at 1.6 ka, and GBC was immediately re-flooded by saline groundwater. Harrington Sound is the most isolated lagoon in Bermuda due to its restricted entrance at Flatts Inlet (Fig. 2). Based on a Holocene paleogeographic reconstruction, Harrington Sound did not achieve its connection with North Shore Lagoon through Flatts Inlet until the latest Holocene (Vollbrecht, 1996), which initiated active circulation between Harrington Sound and saline groundwater flooding GBC through the submarine cave entrance (Fig. 3B), in turn collapsing the paleometeoric lens (Fig. 2). These results indicate that a SL rise of less than 1 m rise can have profound impacts on coastal groundwater, when coastal geometry and circulation are considered.

5. Conclusions

This study provides the first Holocene-scale reconstruction of prehistoric groundwater and its response to regional sea-level and climate change. This was achieved by using foraminiferal paleoecology as a groundwater proxy in underwater caves, which provides a new technique for investigating the response of prehistoric groundwater to ocean-atmospheric forcing. There is little doubt that our understanding of global prehistoric groundwater will be re-defined. Since all the foraminifera colonizing the cave at 1.6 ka are marine, adapted to sub-optimal oxygen conditions, and known pioneers, then a rapid return to marine conditions with reduced oxygenation of the saline bottom water is the most likely environmental conditions characterizing the beginning of the submarine cave environment (LS biofacies). Based on the trend from low to high BFOI, saline groundwater circulation was likely initially sluggish, but increased in vigor and strength over the last 1600 years with increased tidal pumping through the submarine cave entrance (Table 3). The implication of these results is that the meteoric lens that persisted from 4.2 to 1.6 ka abruptly collapsed at 1.6 ka, and GBC was immediately re-flooded by saline groundwater. Harrington Sound is the most isolated lagoon in Bermuda due to its restricted entrance at Flatts Inlet (Fig. 2). Based on a Holocene paleogeographic reconstruction, Harrington Sound did not achieve its connection with North Shore Lagoon through Flatts Inlet until the latest Holocene (Vollbrecht, 1996), which initiated active circulation between Harrington Sound and saline groundwater flooding GBC through the submarine cave entrance (Fig. 3B), in turn collapsing the paleometeoric lens (Fig. 2). These results indicate that a SL rise of less than 1 m rise can have profound impacts on coastal groundwater, when coastal geometry and circulation are considered.

The final faunal transition from the LS to CS biofacies demarcates the onset of present-day foraminiferal assemblages and modern hydrogeological conditions in GBC (Fig. 4, van Hengstum and Scott, 2011). The CS biofacies contains abundant Triloculina oblonga, Quinqueloculina, and other mioloids, which are indicative of high-oxygen saline groundwater actively circulating through GBC where cores 5 and 9 were collected. Because the exact horizon of this biofacies transition is not dated, one could argue that the final LS to CS biofacies shift relates to anthropogenic modification of Flatts Inlet, which in turn amplified tidal currents entering Harrington Sound, and tidal pumping throughout GBC. However, if one assumes exponential sedimentation rates between the 14C dates in the submarine facies from cores 5 and 9 (r² = 0.98, n = 4, origin is 1950 AD) this biofacies shift occurred ~650 years ago (~1350 AD), predating the colonization of Bermuda in 1609 AD from the Sea Venture shipwreck. The long-term increasing trend in the BFOI (increasing oxygenation) and marine organic matter deposition (C:N, 813Corg, Fig. 7) provides further evidence that an ecosystem threshold was not breached from some environmental change after 1609 AD, but rather there was a long-term shift to more favorable environmental conditions in GBC.

7. Conclusions

This study provides the first Holocene-scale reconstruction of prehistoric groundwater and its response to regional sea-level and climate change. This was achieved by using foraminiferal paleoecology as a groundwater proxy in underwater caves, which provides a new technique for investigating the response of prehistoric groundwater to ocean-atmospheric forcing. There is little doubt that our understanding of global prehistoric groundwater will be re-defined since the significance of sediment records in underwater caves is now being realized.

Based on the results from GBC, sea-level controls the boundary conditions where upon the ocean-atmospheric system can act to develop groundwater. Although this result may appear intuitive, it is amazing how responsive the foraminifera were to even subtle groundwater changes through the Holocene. Foraminifera indicate that rising sea and groundwater levels flooded GBC with saline...
groundwater at 7.7 ka. This saline groundwater became sub-oxic from 7.4 to 4.2 ka, either from reduced saline groundwater circulation or increased upwelling of anoxic groundwater. A brackish meteoric lens then flooded GBC from 4.2 to 1.6 ka, which was most likely related to coeval hydrographic conditions in Harrington Sound. Importantly, relative sea-level rise flooded the sill in Flatts Inlet at 1.6 ka, caused by a sea-level rise of less than 1 m (Figs. 2 and 6). This event facilitated open circulation between the North Shore Lagoon and Harrington Sound, and activated modern tidal pumping of sea-water into GBC through the submarine cave entrance. This new pattern of coastal circulation collapsed the meteoric lens that was previously flooding GBC within a geologic instant, and has since precluded a meteoric lens from reforming near GBC. This is despite only minor sea-level rise since then, and other intervals of increased regional precipitation or hemispheric warming (e.g., Medieval Warm Period).

These results validate previous numerical evidence that small sea-level variations (<1 m) may destabilize coastal groundwater masses (Bobba et al., 2000). As such, coastal geometry and circulation patterns should be incorporated into groundwater numerical simulations to accurately model the response of coastal groundwater to future climate change, in addition to the forecasts of relative sea-level change.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.marmicro.2012.02.007.

References


Heron-Allen, R., Earland, A., 1928. On the...


Kuht, T., Schmiedli, G., Ehrmann, W., Hamann, Y., Hemberle, C., 2007. Deep-sea ecosyste...