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Sea level controls sedimentation and environments in coastal caves and sinkholes

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ABSTRACT

Quaternary climate and sea-level research in coastal karst basins (caves, cenotes, sinkholes, blueholes, etc.) generally focuses on analyzing isotopes in speleothems, or associating cave elevations prior sea-level highstands. The sediments in coastal karst basins represent an overlooked source of climate and sea-level information in the coastal zone, but to accurately interpret these sediments first requires an understanding of the forcing mechanisms that emplace them. In this study, we hypothesize that coastal karst basins transition through vadose, littoral, anchialine, and finally into submarine environments during sea-level rise because groundwater and sea level oscillate in near synchrony in the coastal zone, causing each environment to deposit a unique sedimentary facies. To test this hypothesis, the stratigraphy in twelve sediment cores from a Bermudian underwater cave (Green Bay Cave) was investigated and temporally constrained with twenty radiocarbon dates. The results indicate that we recovered the first succession spanning the entire Holocene from an underwater cave (~13 ka to present). The sediments were characterized with X-radiography, fossil remains, bulk organic matter, organic geochemistry ($\delta^{13}C_{org}$, C:N), and grain size analysis. Four distinct facies represent the four depositional environments: (i) vadose facies (>7.7 ka, calcite rafts lithofacies), (ii) littoral facies (7.7 to 7.3 ka: calcite rafts and mud lithofacies), (iii) anchialine facies (7.3 to 1.6 ka: slackwater and diamict lithofacies), and (iv) submarine facies (<1.6 ka: carbonate mud and shell hash lithofacies). The onset and duration of these sedimentary depositional environments are closely linked to Holocene sea-level rise in Bermuda, indicating that sea level controls environmental development in coastal karst basins. Finally, we present a conceptual model for interpreting the sediments and environments in coastal karst basins as a result of sea-level change.

1. Introduction

In general, cave-based reconstructions of Quaternary climate and sea levels can be organized into two areas of research. Most commonly, isotopes (e.g., $\delta^{13}C$, $\delta^{18}O$) preserved in speleothems like stalagmites or flowstones provide climate proxies (Yuan et al., 2005; Wang et al., 2008; Medina-Elizalde et al., 2010), or interrupted growth patterns or worm-encrusted layers on speleothems provide a surrogate for cave flooding and sea-level highstands (e.g., Harmon et al., 1981; Richards et al., 1994; Surić et al., 2005; Dutton et al., 2009; Dorale et al., 2010). Alternatively, cave elevations are related to prior sea-level highstands because caves often develop at the mildly acidic halocline or mixing zone in the groundwater, which oscillates in near synchrony with sea level in the coastal zone (Mylroie and Carew, 1988; Mylroie and Carew, 1990; Florea et al., 2007; Mylroie, 2008). The term *coastal karst basins* refers to the myriad of basin-like features that develop from long-term dissolution processes (speleogenesis) on carbonate platforms, such as sinkholes, cenotes, blueholes, and caves, all of which have been repeatedly flooded and drained by oscillating Quaternary sea levels. Sediment records are the primary targets of sea level and climate information in other coastal environments, yet the sediments in coastal karst basins are an over looked resource of climate and sea level information. However, sedimentation in coastal karst basins remains poorly understood, and has yet to be related to a broader forcing mechanism.

The environments that exist within coastal karst basins are not arbitrary. In contrast, their environments can be systematically divided into different groups, depending first on whether the cave is in the vadose (unsaturated) or phreatic (saturated) zone. Any coastal karst basin in the vadose zone can be described as being a *vadose* environment. Continuing below the groundwater table into the phreatic zone, Stock et al. (1986) originally classified modern phreatic coastal caves as littoral, anchialine, or submarine. These definitions were subtly expanded by van Hengstum and Scott (2011) so that different cave environments could be quantitatively distinguished based on sedimentary and microfossil characteristics. It is important to consider that all aquatic coastal karst

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basins are open-systems with subterranean connection to the ocean, unless empirically proven otherwise in individual cases. This is because porous karst allows for uninhibited circulation of groundwater through coastal karst basins, and the groundwater itself can be divided into two general watermasses: the upper meteoric lens versus the lower saline groundwater.

Littoral environments exist when the groundwater table or sea level is within the cave passage (Fornós et al., 2009; Dorale et al., 2010). *Anchialine* environments are dominated by terrestrial influences, such as the influx of terrestrial sediment or hydrogeologically by a meteoric lens (Schmitter-Soto et al., 2002; van Hengstum et al., 2010). Saline groundwater or seawater floods *submarine* environments, which cause marine processes to dominate the environment, and any physical exits that open into the ocean will obviously be flooded by sea level (e.g., Airoldi and Cinelli, 1996; Yamamoto et al., 2010). This classification scheme is independent of speleogenesis, and focuses solely on environmental conditions within coastal karst basins. All these environments can be observed with respect to the modern position of sea level on coastal karst platforms, but they have not been linked in succession.

Three critical ideas have been proposed for coastal karst basins. First, as introduced above, discrete environments exist in these basins, each with individual environmental and hydrogeological characteristics (Holthuis, 1973; Stock et al., 1986; van Hengstum and Scott, 2011). Second, these basins provide accommodation space for sediments, and their deposition is not yet related to a broader forcing mechanism or incorporated into a unifying theory (Ford and Williams, 1989; Teeter, 1995; Alverez Zarikian et al., 2005; White, 2007; Gischler et al., 2008; van Hengstum et al., 2010; Yamamoto et al., 2010). And third, sea-level change causes a concomitant change in the position of the coastal aquifer, which causes environmental change in caves and sinkholes themselves (Shinn et al., 1996; Ginés and Ginés, 2007; Mylroie, 2008; Gabriel et al., 2009; van Hengstum et al., 2009a). We argue that all these separate ideas are inextricably linked.

We hypothesize that glacioeustacy controls environmental evolution and sedimentation patterns within coastal karst basins (Fig. 1). More specifically, sea-level rise will force coastal karst basins to systematically transition from vadose environments during a low-stand scenario, into littoral, then anchialine, and finally into submarine environments during a sea-level highstand. This framework allows each environment to retain the spatially variable sedimentary and environmental patterns that are observed along modern coastlines, yet sea level becomes the external force driving sedimentary and environmental development in coastal karst basins over time. The purpose of this study is to test this hypothesis in a modern phreatic coastal cave, which has been flooded by eustatic sea-level rise during the Holocene.

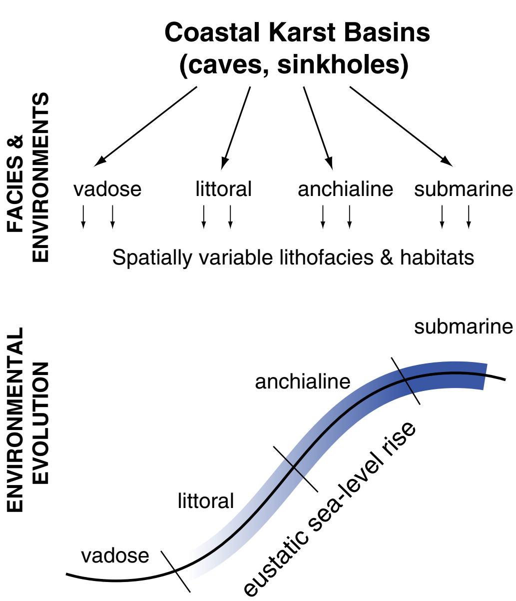

Fig. 1. Environments and facies in coastal karst basins, and their evolution during a transgressive systems tract.

2. Regional setting

Bermuda contains a basalt core overlain with karst, characterized by alternating eolianites (~90%) and paleoesols (~10%) that developed during late Quaternary sea-level highstands and low-stands, respectively (Bretz, 1960; Land et al., 1967; Vacher et al., 1989; Mylroie et al., 1995b; Vacher et al., 1995). This stratigraphy is a Carbonate-Cover Island according to the Carbonate Island Karst Model (Mylroie and Mylroie, 2007). Caves are common in Bermuda, but are most abundant on the isthmus between Castle Harbor and Harrington Sound in the diagenetically-mature Walsingham Formation (Land et al., 1967; Mylroie et al., 1995b). It is generally thought that Bermuda's caves formed through three processes: (a) phreatic dissolution in a paleo-meteoric lens during sea-level highstands, (b) vadose dissolution concentrated at the basalt–eolianite contact during sea-level lowstands, and (c) subsequent modification by collapse events (Palmer et al., 1977; Mylroie et al., 1995b). These processes have created large cave chambers connected by fissures, with sediment accumulating in structural depressions on cave floors.

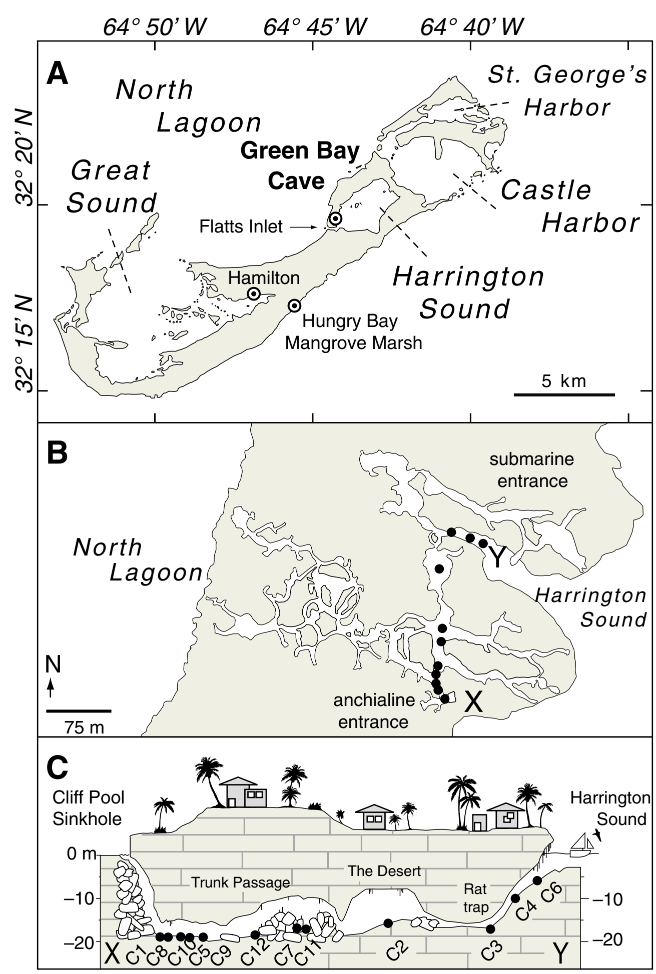

Fig. 2. A: Regional map of Bermuda with location of GBC. B: Primary cave passages and location of transect X to Y in GBC. C: Location of cores collected on SCUBA along the X to Y transect.