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ORIGINAL ARTICLE

A qualitative and quantitative model for climate-driven lake formation on carbonate platforms based on examples from the Bahamian archipelago

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Abstract Lakes on carbonate platform islands such as the Bahamas display wide variability in morphometry, chemistry, and fauna. These parameters are ultimately driven by climate, sea level, and carbonate accumulation and dissolution. The authors propose a model that integrates climatological, geomorphological, and stratigraphic frameworks to understand processes of carbonate-hosted lake formation and limnological characteristics in modern day environments, with applications to carbonate lake sedimentary records. Fifty-two lakes from San Salvador Island and Eleuthera, Bahamas, were examined for water chemistry, basin morphology, conduit development, conductivity, and major ions. Using non-metric, multi-dimensional scaling ordination methods, the authors derived a model dividing lakes into either constructional or destructional formational modes. Constructional lakes were further divided into pre-highstand and highstand types based on whether their formation occurred during a marine regressive or transgressive phase. Destructional lakes are created continually by dissolution of bedrock at fresh/saline water interfaces and their formation is therefore related to changing climate and sea level. This model shows that lake formation is influenced by the hydrologic balance associated with climatic conditions that drives karst dissolution as well as the deposition of aeolian dune ridges that isolate basins due to sea-level fluctuations. It allows for testing and examining the climatic and hydrologic regime as related to carbonate accumulation and dissolution through time, and for an improved understanding of lake sensitivity and response to climate as preserved in the lacustrine sedimentary record.

Keywords Bahamas · Lakes · Carbonates · San Salvador · Eleuthera · Saline

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Introduction

Lake basin formation on carbonate platforms is driven by sediment accumulation and dissolution, which in turn are forced by hydrostatic conditions, sea-level fluctuations, and groundwater interactions. Such lakes range widely in chemistry from fresh to hypersaline and can be large or small landscape features of varying morphometries in a variety of geomorphic expressions. To understand the complex feedbacks within this system, a model is needed that can explain the connections between lake formational processes, paleoclimate and sea-level changes, and resulting limnological characteristics.

The linkages between depositional processes and basin formation allow lakes on these platforms to be used as means by which to understand high and low sea-level stands in response to climate change. Carbonate systems have their highest rates of sediment supply (or production) during rising relative sea level and there is a strong linkage between the progradation of dunes and the development of lake basins on carbonate platforms. The development of lake basins is therefore related directly to climate by both the aggradation of dunal ridges during lowstands and karstification dissolution during dry periods.

In the Bahamas, the limestone bedrock controls the type and size of the freshwater lens (Mylroie et al. 1995a). Freshwater recharge infiltrates the porous rocks and is perched upon and displaces saline ground water below because of the difference in water densities. Located at or near sea level, and interacting with relatively fresh groundwater systems, water balance, chemistry, and flora and fauna in these lakes can respond quickly to subtle changes in sea level or local climate. This rapid response is thought to be driven by the high hydraulic conductivity of the aquifer and the low hydraulic gradient (Vacher 1988; Budd and Vacher 1991; Mylroie et al. 1995a). Most lakes on carbonate platforms are isolated from surficial marine contact, but many are connected to the ocean via conduits and high matrix porosity (Smart et al. 1988; Vogel et al. 1990; Mylroie and Balcerzak 1992; Bottrell et al. 1993; Vacher and Mylroie 2002). Their salinities are controlled not only by the seepage of seawater through the porous carbonate bedrock, but also seasonal rainfall and evaporation (Vacher and Mylroie 1991; Mylroie and Carew 1995).

Some carbonate platform lakes have yielded important records of Holocene climate change (Kjellmark 1996; Dix et al. 1999; Park 2012), offering improved temporal and stratigraphic resolution of paleoclimatic variation that complements existing island and marine shelf geology (Chen et al. 1991; Carew and Mylroie 1995). Their utility as sedimentary archives of past climates and past sea-level position can be strengthened by understanding different lake types' relative sensitivity to various hydrologic and geochemical processes due to their differing hydrology, landscape position, morphometry, and chemistry.

Study area

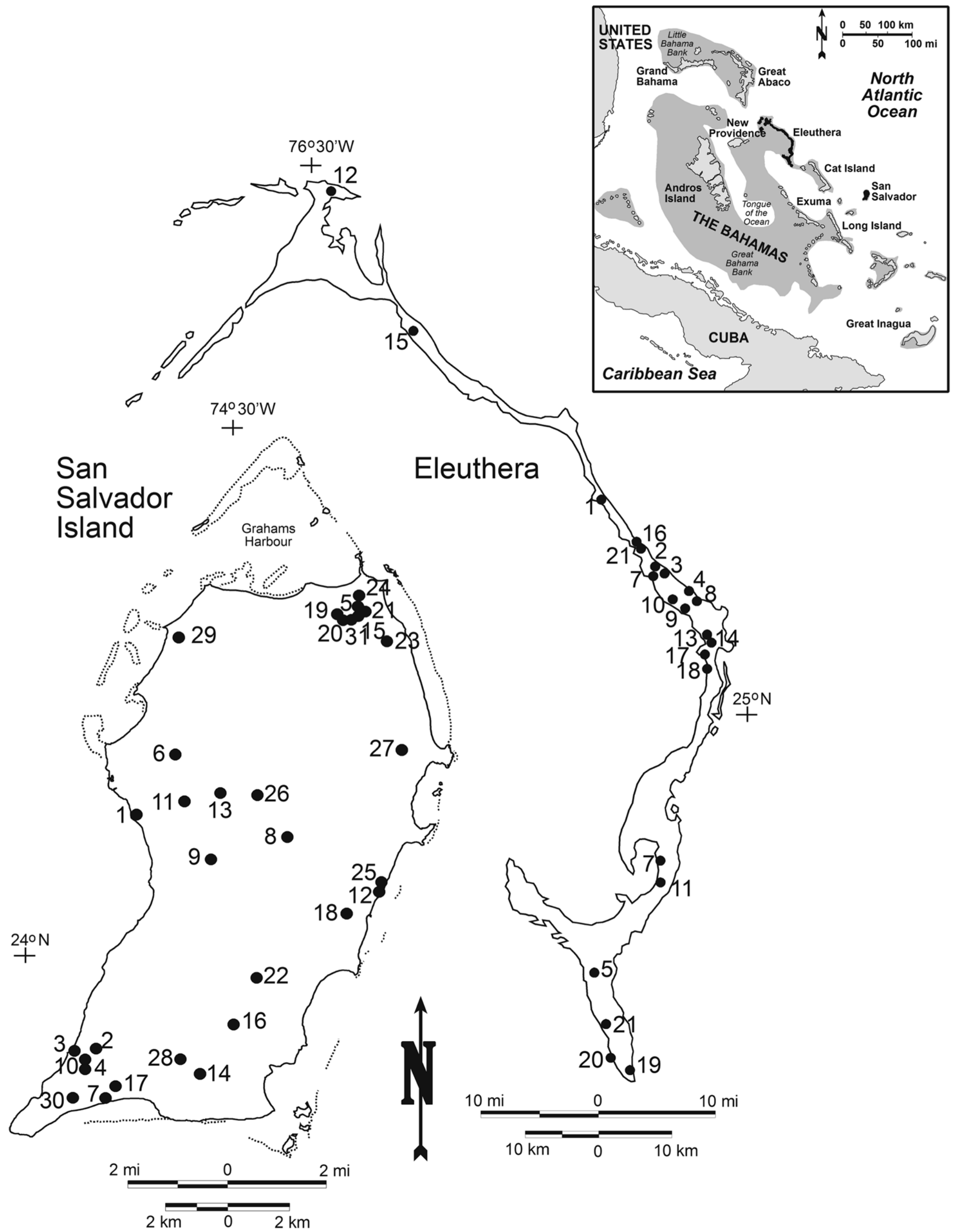
The Bahamian archipelago extends for 1,000 km NW–SE with Florida to the west and Cuba to the south. The northwestern Bahama islands project above sea level from two larger carbonate platforms, the Great Bahama Bank and Little Bahama Bank, separated by the Tongue of the Ocean, which is ~2 km deep (Fig. 1). To the southeast, the Bahamas comprise small isolated platforms capped by islands that cover a significant portion of the available platform area. The Bahamian platforms have been sites of carbonate deposition since the Cretaceous (Lynts 1970; Carew and Mylroie 1995). The islands are influenced by two major geologic processes, the aggradation of dunal ridges and the dissolution of the carbonate bedrock by karst processes. Both processes are related to sea-level change: during pre-highstands and highstands, dunes prograde as platform flooding occurs and carbonate sediment is produced; dissolution occurs continually but is enhanced during dry or lowstand periods. Depositional sequences can be viewed as individual packages controlled by sea-level highstands and separated by erosional unconformities that are typically marked by a *terra rossa* paleosol (Carew and Mylroie 1991; Boardman et al. 1995; Kindler and Hearty 1997). Each depositional package consists of three parts—transgressive, stillstand, and regressive phases—which contain a subtidal, intertidal, and aeolianite component (Carew and Mylroie 1995; Aalto and Dill 1996; Mylroie 2008). Because Holocene sea level is sufficiently high at present, the only marine deposits exposed today are those associated with the higher stillstand phase of marine isotope substage 5e (MIS 5e) about 131,000–119,000 years ago. At its maximum, the MIS 5e was about 6 m higher than at present, suggesting that the transgressive and regressive marine deposits of substage 5e are below modern sea level and the stillstand, subtidal deposits of sea-level highstands prior to 5e are not visible (Carew and Mylroie 1995; Mylroie 2007).

San Salvador Island and Eleuthera

The two islands used in this study, San Salvador and Eleuthera, were chosen because they are climatologically similar to each other and are rich in various types of lakes (Fig. 1). San Salvador is a small island (20 × 10 km) that lies on the northeastern edge of the Bahamas on a small isolated platform (Fig. 1). Grahams Harbour at the north end of the island has the widest shelf and is partially protected by marginal island cays. The oldest lithologic unit is the Owl's Hole Formation (MIS 7) which is made of large aeolian dunes and beach ridge deposits dated at 220 ka (Carew and Mylroie 1995). The Grotto Beach Formation, formed during the MIS 5e interglacial highstand is well exposed on the island, as is the Holocene Rice Bay Formation (MIS 1). The stratigraphy of the coastal areas of San Salvador is well established, but controversy still exists as to the geochronology of the island's interior (Carew and Mylroie 1995).

In contrast to San Salvador, Eleuthera is an elongate and narrow island (140 × 25 km) that is located on the northeastern and windward margin of the Great Bahama Bank (Fig. 1). The eastern side of Eleuthera is characterized by a steep marginal escarpment that extends down to the abyssal ocean floor at depths of over 1 km (Kindler and Hearty 2000). The eastern coast of northern Eleuthera contains high cliffs (>20 m) that are composed of

Fig. 1 Location map. Numbers refer to lakes in Table 1



vertically stacked carbonate units and paleosols (Kindler and Hearty 2000; Kindler et al. 2006). Lithologic units seen on Eleuthera correspond with interglacial sea-level highstands and potentially correlate with isotope stages 5e, 7 and 9 (Kindler and Hearty 2000). Determination of the age relationships between the rocks on Eleuthera and the stratigraphy from other islands, namely San Salvador, is still being investigated (Kindler et al. 2006). The western side of the island is a shoaling margin (<30–40 m) and is characterized by anastomosing tidally influenced creeks at the island's margin. The island has numerous cays to the north and southwest.

The lakes on San Salvador and Eleuthera differ in area, morphology, depth, and connectivity to the ocean. Identifying the similarities and differences that exist between lakes related to various physical and chemical parameters is a fundamental step necessary for creating a predictive model that relates lake formation and morphometry to limnological characteristics. This model should be able to explain how the various lake types are related to climate change and sea-level fluctuations on the Bahamian platform and whether or not there is a correlation between lake type, lake fauna, and lake chemical properties.

Research methods

Fifty-two lakes were described and sampled for water chemistry and physical characteristics (Online Resource 1). Surface water samples (0.5 m below the water surface) were collected within 10 m of the lake shore using sterile, acid-washed Nalgene jars and were analyzed for the concentration of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) using a Perkin Elmer Analysis 700 atomic absorption (AA) spectrometer, and for major anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}) using a Dionex DX-120 ion chromatograph, both at the University of Akron. Conductivity and water temperature were determined in the field with a YSI model 556 field meter.

Lake area was determined on San Salvador using the San Salvador GIS database (Robinson and Davis 1999), while lake area on Eleuthera was determined using peripheral estimates of the topographic maps. Depth profiles were conducted at stations along a 50-m transect into the lake. Conduit presence/absence was determined from field observations of tidal lake level fluctuations.

Non-metric (or non-parametric) multi-dimensional scaling analysis (NMDS; Hammer et al. 2001; Hammer and Harper 2006) was conducted on datasets from 31 lakes on San Salvador Island and 21 lakes on Eleuthera. NMDS attempts to ordinate the data in a low-dimensional space so that observed distances are preserved. NMDS transforms the distances into their ranks and compares these ranked distances with the rank of the Euclidean distances in the ordination plot so that absolute distances are discarded.

Results

Physical variability

Lakes on these islands are highly variable with respect to depth, size, area, and shape. On both San Salvador and Eleuthera, the smallest, deepest lakes (400–3,700 m^2 in area and 6–60 m depth) are the blue holes, dissolution lakes that typically have conduits that connect them to the ocean; they can have diurnal tidal ranges of 20–30 cm. Other lakes that are larger are typically shallower. Most lakes in the next size category range in depth from 0.5 to 1.5 m and vary in area from 5,730 to 105,000 m^2. These lakes may or may not have conduit connections, but if they do, they are typically near the shore. Larger lakes on both islands range in depth between 1 and 2.5 m and can be large, between 2,260 and 586,410 m^2. These lakes tend to be elongate and arcuate and are often expressed as features parallel to the shoreline.

Chemical variability

Conductivity in lakes on carbonate platforms can vary as much as their morphology. For example, blue holes are fresh to brackish (5–50 mS/cm), while the largest lakes may be hypersaline (53–300 mS/cm). Many of the mid-size lakes are in the marine window, between 47 and 53 mS/cm. Bicarbonate ion varies between 50 and 300 mg/L and pH tends to be slightly alkaline in all lakes, between 7.3 and 9.1. Blue holes have near neutral pH and the hypersaline lakes typically have higher pH values, between 8 and 9. Major ion chemistry shows deviations from simple evaporative concentration in ions that participate in biogeochemical processes, such as Ca^{2+}, Mg^{2+}, and SO_4^{2-} (Fig. 2). Conservative ions covary with salinity as expected.

Biota

Biota found within lakes vary tremendously and include microbial mats, molluscs, and fish. Microbial mats and stromatolites are present primarily in hypersaline lakes often associated with coastal settings (Myshrall et al. 2010; Glunk et al. 2011; Puckett et al. 2011). Microbial mats and stromatolites have been well studied in Storr's Lake and Salt Pond on San Salvador Island (Paull et al. 1992; Paerl et al. 2003; Yannarell et al. 2006) and in Big Pond on Eleuthera (Glunk et al. 2011). Algal mats often occur at the margins of these lakes and can have lateral zonation. Based on our observations, and contrary to conventional wisdom, grazers do occur in some of these lakes, including species of the gastropods *Cerithium*, *Cerithidea*, *Heleobops*, *Sayella*, and *Truncatella*, and the bivalves *Polymesoda* and *Anomalocardia*.

Quantitative modeling using NMDS

San Salvador Island

Non-metric multi-dimensional scaling analysis on 31 lakes from San Salvador yielded a distribution of pre-defined lake types into three separate point clusters as seen plotted in Fig. 3a, where Coordinate 1 contains most of the variability in lake size and Na^{+} concentration. The main outlier along this axis is Great Lake, which is the largest in size and has a high concentration of Na^{+}. The second axis, Coordinate 2, contains the variation in HCO_3^{-} as well as depth and Ca^{2+} and SO_4^{2-} concentrations. The overlapping fields of these pre-defined types indicate those lakes that might have hybridized formational processes, such as pre-highstand interdunal depressions that also experience karst dissolution within the basin.

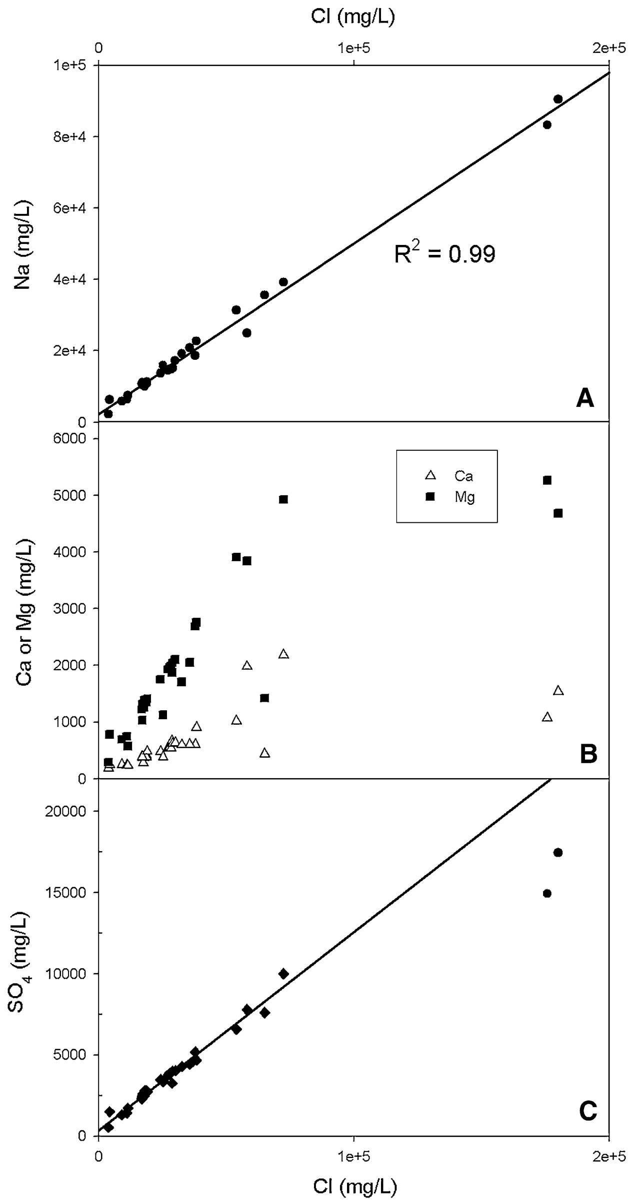


Fig. 2 Major ion geochemistry

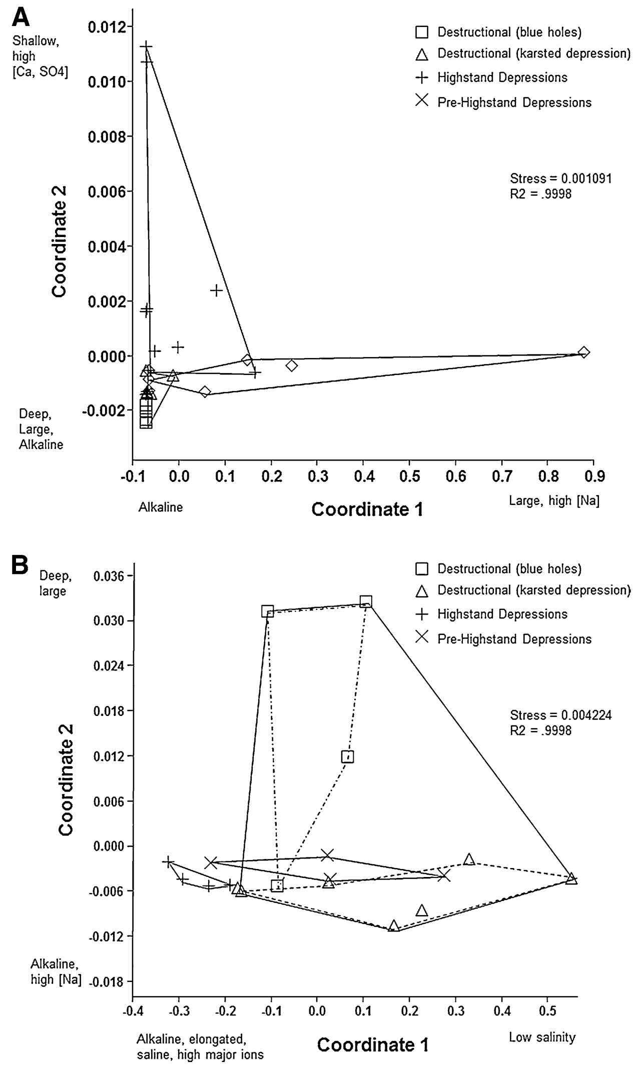


Fig. 3 **a** NMDSM model, **b** NMDSM model

Eleuthera

The NMDS model for the 21 lakes in the Eleuthera dataset show a similar separation along the pre-defined lake types (Fig. 3b). Coordinate 1 contains most of the conductivity variation as well as shape and alkalinity. Coordinate 2 contains the variation in alkalinity and depth. In this case, as seen in San Salvador, the lakes with multiple processes acting on them plot in the intersection of the defined domains. The destructional lakes are further separated into blue holes and 'karsted depressions.' The latter are shallow but broad features that often form between dunal ridges but are considered to be dissolutional because they are not strictly bounded by these dunes. The highstand cutoff lagoons with high alkalinity and high ionic strength, particularly in Na^+, are distinctive and cluster together.

Lake area and volume versus salinity

Two of the variables in the NMDS model with the greatest variability are area and conductivity; it might be posited that conductivity is strictly related to evaporative concentration and thus to lake area or area:volume relationships. However, plotting Log_{10} of lake area against salinity reveals no significant correlation ($r = 0.22$, $p = 0.193$) (Fig. 4a). Likewise, in plotting volume (Log_{10} area $\times$ depth) versus salinity, no significant correlation was determined ($r = -0.008$, $p = 0.962$) (Fig. 4b). Even if certain outliers were eliminated, no correlation was found.

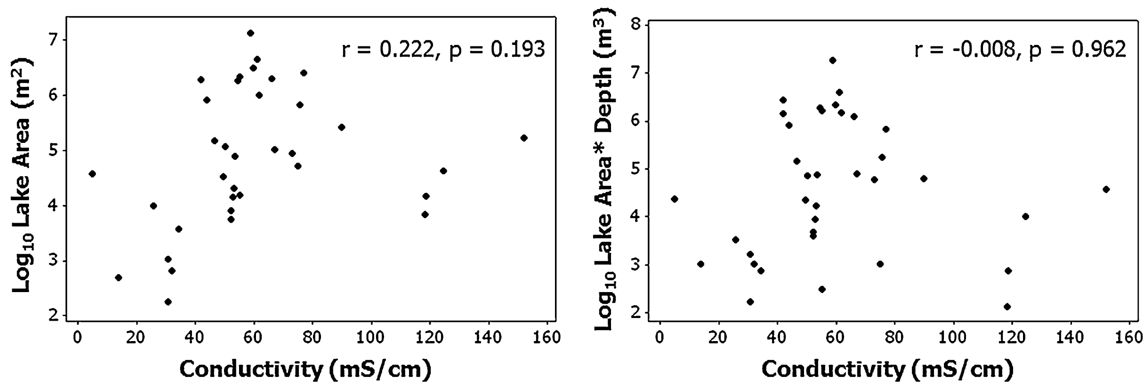


Fig. 4 Lake area and volume versus conductivity

Discussion

Lake Formation and limnological characteristics

Physical and chemical characteristics can be used to discriminate lakes into two general categories, constructional and destructional (Table 1). Constructional lakes are formed by aggradation and isolation and occur in response to sea-level fluctuations, while destructional lakes occur as dissolution and collapse features in immature eogenetic limestones (Fig. 5). Constructional lakes can be separated into two types: pre-highstand depressions, which are interdunal swales, and highstand depressions that form as cutoff lagoons by sedimentation along coasts (Table 1). Pre-highstand depressions are mostly broad, shallow lakes that are arcuate and elongate in shape and underlain by Pleistocene bedrock. Conduits typically are not present and conductivities tend to be within normal marine ranges (Table 1). Highstand depressions, in contrast, are also shallow and elongate, but run parallel to the coastlines. Conduits are not normally present. Salinities have the greatest variances, ranging from normal marine to hypersaline conditions. Both of these constructional lake types can occur in various phases of island development and it is not uncommon for pre-highstand depressions to have once been highstand depressions in a previous highstand sequence.

Destructional lakes are typically round or ovate in shape, and in the case of blue holes, they can be the deepest lakes on the islands. Conduits are typically present in these types of lakes and they have salinities that range from the lowest end of brackish conditions to the lower end of normal marine salinities. These are usually the oldest lakes and longest lived with continuous water present, particularly during lowstands (Table 1). Other, non-blue hole destructional lakes are much shallower and broader and have salinities that vary between near and normal marine waters. Both of these lake types form from dissolution of the bedrock through interactions with the groundwater table. These different styles of lakes can be readily identified using visual observations in the field and in mapview primarily by size, shape, and depth.

These different lake categories are affected differently by hydrologic processes. Pre-highstand and highstand lakes are less influenced by groundwater and more influenced by dunal aggradation and platform flooding due to sea-level fluctuations (Fig. 6). Destructional lakes are highly influenced by groundwater–atmosphere interactions and are often older and deeper than the pre-highstand and highstand lakes (Table 1). Often destructional lake-forming processes can be overprinted on top of constructional lakes.

The value of this conceptual model is threefold. First, it provides a way to classify and categorize lakes on carbonate platforms that is related to formational processes. This genetic approach allows us to describe different types of lakes with a better understanding of how their properties are related to their origins. Second, the model provides a qualitative and quantitative way to describe lakes and their attributes that corroborate one another. Third, the model could be used as a predictive tool for understanding faunal distributions, the effect of sea level on island geomorphology, and the effects of climate change on lake hydrology.

Application of the model on San Salvador and Eleuthera

Blue holes are the most distinct lake type on both islands, due to their limited morphological range (deep, round, and small). On San Salvador, cutoff lagoons are the most variable type of lake as their salinity and water chemistry are strongly affected by the presence and strength of conduits and their areas range from medium size to extremely large. Karsted and interdunal depressions on San Salvador are distinct groupings, but the variation within the model of interdunal depressions is similar to that of cutoff lagoons.

Table 1 Qualitative model

Lake type	Bahamas lake model		
	Constructional (occur in response to sea level fluctuations)		Destructional (occur all of the time)
	Pre-highstand depressions	Highstand depressions	Dissolution and collapse features including blue holes
Formational process	Form in between interdunal swales	Form as cutoff lagoons by highstand sedimentation along coast that cuts off coastal pond	Form from dissolution of diagenetically immature eogenetic limestones
Geomorphic expression	Most are broad, fairly shallow, often arcuate and elongated in shape	Are typically shallow, elongated features running parallel to coastline	Most are round or ovate in shape and, in the case of blue holes, can be the deepest lakes
Conduits	Not usually present	Not usually present	Usually present
Salinity and conductivity range	Normal marine	Normal marine to hypersaline	Normal marine to brackish
	30–35 ppt	30–120 ppt	4–30 ppt
	47–53 mS/cm	47–600 mS/cm	7.3–47 mS/cm
Microbial mats and stromatolites	Not usually present	Often present	Not usually present
Age of lake	Can be remnants of sea-level highstands of Pleistocene age and influenced by Holocene deposition	Typically youngest, often related to Holocene deposition and sea-level fluctuations	Are probably the oldest lakes and most likely served as freshwater sources during highstands
Examples on San Salvador	Little Lake, Great Lake, Long Lake, Flamingo Pond, Crescent Pond, Osprey Lake	Storr's Lake, Salt Pond, Granny Lake, Stout's Lake, French Pond, Clear Pond, Bamboo Pond, Triangle Pond, No Name Pond, Little Salt Pond, Nasty Pond, Peel Pond	Watling's Blue Hole, Ink Well, Blue Hole #5, Columbus Landing Blue Hole, New Blue Hole, Six Pack Pond, Moonrock Pond, Mermaid Pond, Oyster Pond, Pain Pond, Wild Dilly Pond, Reckley Hill Pond, Plantation Pond
Examples on Eleuthera	White Pond, Great Oyster Pond, Darnott's Pond, Ingraham's Pond, Turtle Pond	Great Pond, Charlow's Pond, Sweeting's Pond, Bannertown Wetlands	Duck Pond Blue Hole, Hut Bay Blue Hole, Rock Sound Blue Hole, Secret Blue Hole, Savannah Turtle Pond, Savannah Pond, Paw Paw Pond, Carey's Pond, Little Turtle Pond, Two Pines, Airport Pond

This might be due to the large range of salinities in the cutoff lagoons and the presence of conduits in some interdunal depressions.

On Eleuthera, blue holes and interdunal depressions have low within-group variability when compared to the other lake types due to their similarities in geomorphology, salinity, and water chemistry. On Eleuthera, cutoff lagoons display less variation than on San Salvador. This might be due to the type of conduit development and the extent of the carbonate platform. The cutoff lagoons on Eleuthera are not all hypersaline as they are on San Salvador and do not have the same amount of cyanobacterial mat development. Karsted depressions on Eleuthera display the largest amount of variation of any lake type on this island.

Lake formation and relation to groundwater

During times of sea-level lowstand, standing water will not be present in most shallow lakes. Only deeper blue holes would be likely to continue to have water (Mylroie et al. 1995b). Dissolution lakes, specifically blue holes, are likely to form during times of sea-level lowering, as the halocline between fresh rainwater and intruding ocean water decreases in elevation. In wetter regimes like Bermuda today, these processes can form depression karst that could have existed in the past when climate conditions were warmer and wetter (Mackenzie 1964).

Limnological characteristics across the lake types

Lake area and its potential for evapotranspiration may affect salinity in a localized way in individual basins, but there is no systematic relationship between lake area and conductivity (Fig. 4a), nor estimated lake volume when plotted against conductivity (Fig. 4b). The lack of a direct and simple relationship could be due to the presence of conduits and connections with the groundwater table. Highstand lakes are the most likely to be hypersaline and

Fig. 5 Cross section island

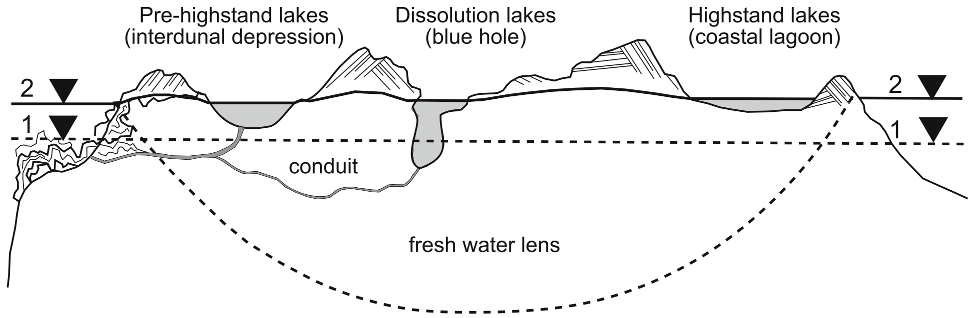
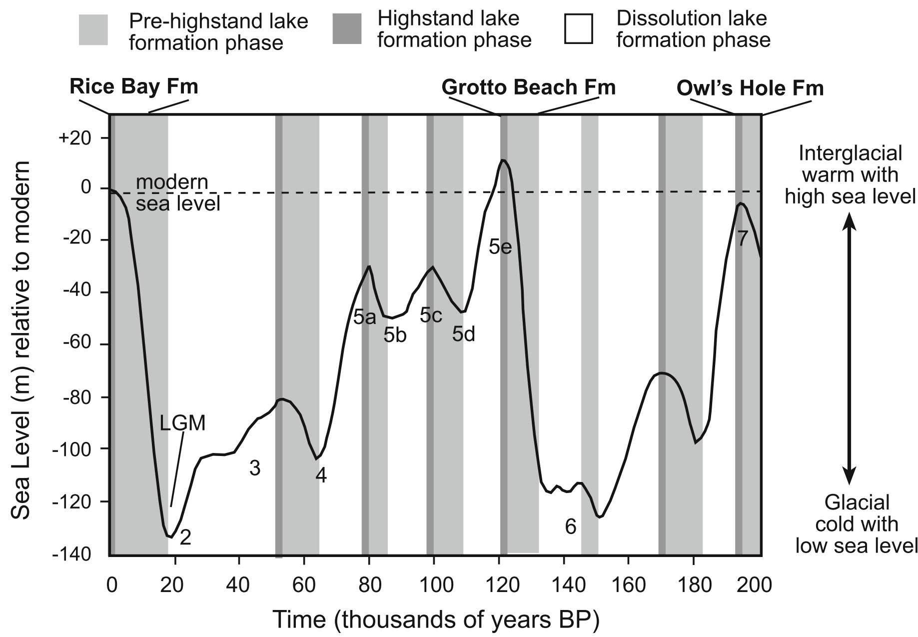


Fig. 6 Sea level and lake model



have algal mats and are potentially more influenced by evapotranspiration processes and area and volume ratios because they lack connection to either the groundwater table or marine water. This is because they are not formed by dissolution processes, but by cutoff and isolation of coastal basins due to progradation of dunes during highstands. Blue holes, on the other hand, are relatively small in area and are typically brackish, being a mixture of rainfall inputs and seawater moving through marine conduits. If all basins were closed, there would likely be a strong correlation between lake volume and salinity; however, because of the conduits and connectivity of lakes to the ocean and groundwater, there is a non-linear relationship between lake size and salinity.

Faunal and floral distribution

Faunal and floral elements can be seen to be distributed according to lake characteristics, and therefore lake type. The dominant green algae are *Batophora oerstedii* and *Acetabularia crenulata*, which live on hard substrates along the shores and contribute to the autochthonous organic sediment load of the lake (Yannarell et al. 2006; Yannarell et al. 2007). Stromatolites and thrombolites occur in hypersaline highstand lakes with little or no conduit connectivity. These are often coastal lagoons of mid- to late-Holocene age and are good examples of how lake type may influence species distribution. Attributes of these lakes include those faunal and floral elements best adapted to not just hypersaline conditions but to wide ranges of salinities, suggesting opportunism. These lakes are often highly productive and have simple trophic structures that are dominated by autotrophic organisms. Molluscs and other grazers live in the littoral margins. Few or no fish or other predators live in these lakes.

Examining molluscs further, their lacustrine assemblages typically are dominated by two bivalve species, *Polymesoda maritima* and *Anomalocardia auberiana*, and four gastropod species, *Cerithidea costata*, *Cerithium lutosum*, *Melampus coffeus*, and *Batillaria minima*. Lakes with constant normal marine salinities can also have several marine species of molluscs. Blue holes often contain a freshwater fauna depending on the range of salinities (Pilsbury 1930). How the fauna get from one lake to another is not well known. Speculation on movement via birds' feet or by flooding during highstands has been made, but no systematic study has been done to examine these mechanisms (Barnes 1988; Kjellmark 1996). Other organisms such as crustaceans, insects, amphibians, reptiles, and birds have been found in or near blue holes at varying abundances. Karsted depressions and interdunal lakes seem to have a much more varied faunal composition, which is not well understood (Godfrey et al. 1999).

Applications to paleolimnology

Sediment cores from lakes on carbonate platform islands (e.g., Kjellmark 1996; Dix et al. 1999; Park 2012) provide a long-term record of changes in hydrological and climatic parameters such as precipitation:evaporation ratio, hurricane frequency, and sea-level fluctuations, but are complexly overprinted by geomorphic parameters such as basin isolation and dune aggradation, and biological factors including floral and faunal history, and microbial mat development. Cutoff lagoons can be used to date dune emplacement, which alters the hydrology and thus salinity of the lagoon. Blue holes contain records of the changing balance between rain and seawater, and may be able to show conduit development over time. Salinity variations (with resulting sedimentary mineralogical and biotic indicators) related to climate change can be separated from those related to geomorphic development of the basin.

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