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INFILLED BLUE HOLES ON THE BAHAMA BANKS AS POTENTIAL POINT SOURCES FOR WHITING ORIGIN

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ABSTRACT. Blue holes are karst features that are found ubiquitously across the Bahamian archipelago. Blue holes are primarily formed by progradational collapse initiated in dissolutional voids and conduits at depth. Most blue holes are observed on islands (inland blue holes), or proximal to the coast in protected lagoons (ocean blue holes). It is assumed that blue hole distributions on islands today should represent blue hole distribution across the shallow banks. Most shallow-bank blue holes are likely covered by carbonate sediments produced on the bank during the current or an earlier sea-level highstand.

Ocean blue holes are tidally active features, with strong inflow and outflow currents. At depth, they are commonly linked to lateral conduits of fracture guided passages. We hypothesize that sediment-filled blue holes should also be connected to lateral conduits and be tidally active, such that water would be brought up by diffuse flow from deep within the banks. During subaerial exposure, island carbonates develop greater horizontal hydraulic conductivity (Kh) over time, however vertical hydraulic conductivity (Kv) decreases, so blue holes would act as preferential flow paths for water given their higher vertical permeability relative to the carbonate host rock. Deep water is cooler, and because of depth pressure, should contain additional CO_2 compared to bank surface water. Once this deep-seated water rises to the bank top, it would degas and warm, therefore driving precipitation of $CaCO_3$.

We hypothesize that this process might be the driving force in the formation of whitings. Whitings have been studied extensively over the past 60 years, and no satisfactory model has yet been established. Using three existing blue hole databases from Bahamian island and coastal locations, an extrapolation was done to estimate the number of sediment-filled blue holes on the shallow Bahama banks. Great and Little Bahama Bank should have 2250 infilled blue holes, with an average density of $0.05/km^2$ on these shallow banks. This number is a minimum estimate, as not all blue holes can be assumed to be in the database. The description of whitings as being point source in origin, the hydraulic and water chemistry constraints, and the blue hole number extrapolations implicate infilled blue holes as the potential cause of whitings.

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INTRODUCTION

This paper represents the authors understanding of whiting formation as of June 2012. This is an intermediary paper between an earlier abstract (Larson and Mylroie, 2012) and our most recent and current understanding of whiting formation in Larson and Mylroie (2014). This paper is valuable as it demonstrates the evolution of the authors' ideas regarding whiting formation.

Whitings in the Bahamas are a sedimentological enigma in the Bahamian archipelago in regards to their formation mechanism. Whitings are clouds of fine grained (<5μm) aragonite that are suspended in the water column on the Bahamian banks (e.g. Shinn et al., 1989). Whitings seem to originate from a point source, remain suspended for multiple days and are moved by the tides and currents on the banks (e.g. Shinn et al., 1989). Whitings have bulk ^{14}C ages of about 100-200 years on the Great Bahama Bank, and about 700 years on the Little Bahama Bank (Broecker and Takahshi, 1966; Bustos-Serrano et al., 2009; Shinn et al., 1989). ^{7}Be dating indicates that whitings have bulk dates of a few hundred days, and more significantly, the cores of the whiting grains are enriched with ^{7}Be, and their respective rims depleted with respect to ^{7}Be (Shinn et al., 2004). Whitings have been proposed to have formed through multiple mechanisms: resuspension of bottom material, direct precipitation from the water column, and biological mediation. Whitings in the Bahamas are the sole focus of this paper though they have been discovered in other places around the world (e.g. Black, 1933; Ellis and Milliman, 1985; Glenn et al., 1995; Shinn et al., 1989; Sondi and Juračić, 2010; Thompson et al., 1997).

Blue holes in the Bahamas also are poorly understood; especially with regard to the formation mechanisms involved for the creation of progradational collapse blue holes (Larson and Mylroie, 2012). These features however, allow for the integration of horizontal zones of permeability and act as quick flow paths for tidally pumped water (Dill, 1977; Vacher and Mylroie, 2002; Whitaker and Smart, 1997).

Previously Proposed Whiting Formation Mechanisms

Resuspension. Whitings were originally thought to be caused by resuspension by fish stirring up the bottom sediments (e.g. Shinn, 1985). Multiple studies have attempted to test this hypothesis with no success, by using explosives and poison in the whitings in an attempt to locate fish (Shinn et al., 1989). Furthermore, when divers have entered whitings, fish are rarely encountered (e.g. Shinn 1985). However, black tipped sharks have occasionally been found in whitings and it was hypothesized that they may stir up the bottom sediments to trap prey (Broecker et al., 2000).

Whitings have also been proposed to be caused by microturbulent flow regimes on the Bahamian banks (Boss and Neumann, 1993). Finally, Dierssen et al. (2009) proposed that whitings may be caused by Langmuir circulation on the banks.

Direct Precipitation. Whitings have long been thought to be formed from the precipitation of $CaCO_3$ from super saturated bank water (e.g. Black, 1933). Earlier work by Broecker and Takahshi (1966) and Morse et al. (1984) were unsuccessful in demonstrating that whitings were formed through the precipitation of $CaCO_3$ from the water column. However, Morse et al. (2003) developed the hip-hop'n (sic) model that allowed for the resuspension of bottom material and the precipitation of $CaCO_3$ onto the resuspended grains. Most recently Bustos-Serrano et al. (2009) demonstrated based on water chemistry changes in the Little Bahamas bank water that whitings were at least in part instantaneously precipitated from the bank water.

Biological Mediation. Recently it has been proposed that whitings are the result of precipitation of $CaCO_3$ from biological media, either through precipitation within the cell walls of algae (e.g. Yates and Robbins, 1998), or within the extracellular membrane substances of various planktonic organisms (e.g. Robbins and Blackwelder, 1992; Thompson, 2000). However, Macintyre and Reid (1992) demonstrated through scanning electron microscopy that whiting grains are morphologically different than the aragonite grains that are formed through biologic processes.

Blue Hole Formation in the Bahamas

Blue holes in the Bahamas are formed through four different mechanisms: 1) flooding of sinkholes, 2) phreatic dissolution along the halocline, 3) bank margin failure, and 4) progradational collapse (Mylroie et al., 1995). Of interest in this paper are blue holes that are formed through progradational collapse. These voids are formed at depth and as sea-level drops buoyant support is lost, allowing for cycles of collapse and removal of breakdown material, resulting in a positive feedback cycle until the void progradationally collapses to the surface. These progradational collapse blue holes act to vertically integrate the various zones of horizontal permeability in the Bahamian platforms (Vacher and Mylroie, 2002). Finally, blue holes can exhibit tidal pulses within themselves (e.g. Dill, 1977; Martin et al., 2012; Whitaker and Smart, 1997).

METHODS

Progradational collapse blue hole distributions in the Bahamas were calculated using three blue hole databases from the last three authors of this paper. The databases were culled for only progradational collapse blue holes and with the assumption that the blue holes in the database represent all those known on the islands and inshore areas, their spatial distribution was then extrapolated across the bank to estimate the total number of progradational collapse blue holes on the Bahamaian banks. These blue holes across the banks would be filled with carbonate sediments from the current sea-level high stand or a previous one and would be obscured from surface observation.

RESULTS

Based on extrapolation of the existing blue hole databases (from the last three authors of this paper), there should be about 2250 progradational blue holes on the Great and Little Bahama Banks, with an average density of 0.05/km^2 (Table 1). This distribution is a minimum estimate of the number of blue holes, as it is reasonable to assume that not every known progradational blue hole was in the three databases that were used and there is explorational bias. Furthermore, this database is continually being added to and modified so the data in the table represent a snap shot of the database as it stands currently (June 2012).

Bank	Area (km^2)	Density Bank (No. km^2)	Expected No. on Bank
Great Bahama	95800	0.0104	1000
Little Bahama	15500	0.0821	1273
Cay Sal	5500	1.3333	7333
Acklins-Crooked	2600	0.0276	72
Mayaguana	440	0.0231	10

Table 1. Extrapolation of progradational collapse blue hole numbers based on three cave divers' databases (the last three authors of this paper). Note that the high number of expected blue holes on Cay Sal Bank is due to the database only having three known features which are all found in very close proximity of each other.

DISCUSSION

The blue holes that are predicted by the extrapolations are on the Bahamian Banks, below present sea-level, and are likely filled in with sediment, obscuring them from surface observation. However, sediment-filled blue holes have been observed on Great Bahama Bank using seismic surveys, so it is reasonable to assume that these features are in fact on the banks, and as yet, not fully discovered (Beach, 1995; Hine and Steinmetz, 1984).

Based on the discussion of whitings above, and the existence of sediment-filled blue holes on the Bahamian Banks, there is evidence based on the high, sediment-filled blue hole distributions to suggest that whitings are a result of sediment-filled blue hole tidal pumping. The tides are pumped through the zones of high horizontal permeability and rise through the blue holes as they act to vertically integrate multiple zones of horizontal permeability. The degassing of CO_2 with the rise from depth, coupled with the warmth of the shallow surface water, promotes the sudden precipitation of fine-grained $CaCO_3$, producing the whiting. Water chemistry data collected by Iliffe from Four Shark blue hole off Andros Island demonstrates that the tidally pumped water is not just cooler, but is also more acidic, thus increasing the likelihood of carbonate precipitation when it mixes with the seawater (Figure 1). The whiting model proposed is a similar process to what occurs on the Bahamian Bank margins to form ooids (e.g. Davies et al., 1978; Simone, 1980/1981). Whitings are found in association with the sediment-filled blue holes and not open blue holes because the fluid flow through the sediment plug ensures that the water is supersaturated with respect to $CaCO_3$ before it reaches the surface (Figure 2).

The radiometric data from others is also supported by the infilled blue hole – whiting hypothesis. The rising of water through the sediment-filled blue hole would likely bring old carbon up from depth, explaining the 100-200 year dates for ^{14}C in the individual whiting grains (Broecker and Takahshi, 1966). The young ^{7}Be dates, and higher concentration of ^{7}Be in the core can be explained by the direct precipitation of the whiting material while depleting the ^{7}Be reservoir in the bank water (Shinn et al., 2004).

Future Work

Future work requires additional modeling of progradational collapse blue hole formation on the Bahamian Banks. Additionally, SONAR needs to be run over the banks to look for additional infilled blue holes to test the extrapolation model. Finally, sediment-filled blue holes need to be correlated to whiting events, which should be possible using satellite imagery (e.g. Robbins et al., 1997).

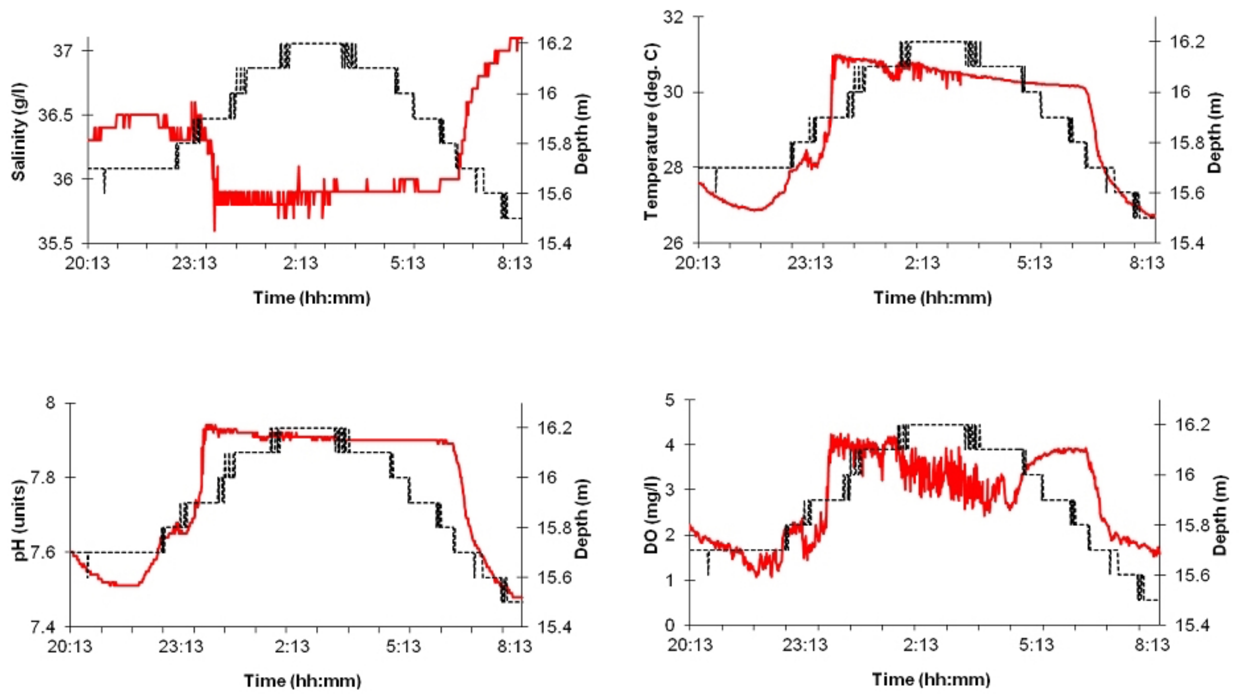

Figure 1. Plots of salinity, temperature, pH and dissolved oxygen (solid lines) and water depth (dashed line) over time in Four Shark Blue Hole, an ocean blue hole off the coast of South Andros Island, Bahamas. Water exiting the cave (blue hole) on the tidal outflow was more saline (by 1.2 ppt), cooler (by 4°C), more acidic (by 0.4 pH units) and with lower dissolved oxygen (by 2.75 mg/l) than the corresponding inflow water from the open ocean. This data is unpublished and were collected on 11 Aug. 1997 by T. Iliffe using a Hydrolab water quality analyzer suspended in the cave entrance shaft and programed to record data at one minute intervals for a period of 13 hours. These blue hole data are shown as an example of how the water column within an open blue hole is moved during tidal pumping.

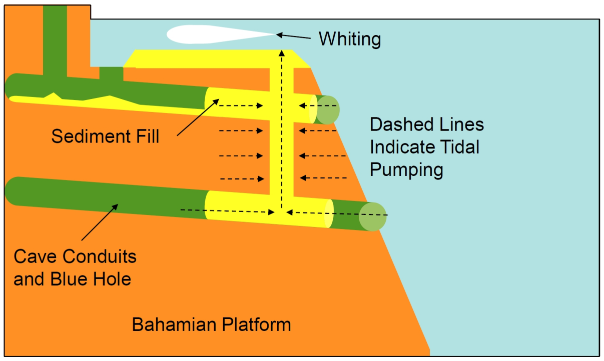

Figure 2. The sediment-filled blue hole model to explain whiting formation. Note that the dashed lines represent the flow of water along zones of high horizontal permeability to the blue hole where the water rises to the surface. When the water gets to the surface from the sediment filled blue hole, precipitation of $CaCO_3$ occurs, resulting in the formation of whitings.

CONCLUSIONS

With simple extrapolations of known progradational collapse blue holes, it can be shown that there is an abundance of sediment-filled blue holes on the Bahamian Banks. It is reasonable to assume that these blue holes also convey tidal pulses like non sediment-filled blue holes (e.g. Bustos-Serrano et al., 2009). The tidal pumping of water through these sediment-filled blue holes is hypothesized to result in the formation of whitings on the Bahamian Banks.

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