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BANANA HOLES AS SYNDEPOSITIONAL FLANK MARGIN CAVES WITHIN AN ADVANCING STRANDPLAIN AND THEIR PREDICTION USING FUZZY-BASED SPATIAL MODELING

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ABSTRACT. Banana holes are common karst features found within Pleistocene strandplains of San Salvador Island and throughout The Bahamas. Banana holes are typically meters to tens of meters wide, and one to six meters deep, ovoid in plan, and usually contain phreatic dissolution features. A study of banana holes was conducted to see if their origin could be better explained, and to determine if their locations could be predicted using remote sensing. A detailed banana hole investigation of the Line Hole, Jake Jones Road, Hard Bargain, and South Victoria Hill areas of San Salvador was conducted during field visits in December 2010, May 2011, and December 2011, locating 390 banana holes, 70 of which were mapped. Plotting banana hole locations in ArcGIS shows they follow linear trends and are associated with low inland ridges. Facies in banana hole wall rock show an upward progression from shallow subtidal (herringbone cross beds) to intertidal (laminar beds and or back-beach breccia blocks) to supratidal (eolian foresets) deposits, in agreement with a prograding beach environment. The flat topography of low, coast-parallel ridges mimics modern strandplains. Dissolution features found in banana holes include wall cusps, blind passages, bell holes, and thin wall partitions. These observations suggest that banana holes form at the lens margin within a prograding strandplain. As the strandplain advances the lens margin follows, creating syndepositional voids at the dissolutionally aggressive lens margin. This sequence of dissolution and abandonment creates rows of voids that represent paleo-shoreline positions. Comparison of banana hole and flank margin cave morphometry based on cave area versus enclosing rectangle area, shows an overlap, indicating a common dissolutional origin. This new model for banana hole formation requires that the term "banana hole" be used to describe flank margin voids formed within progradational facies, instead of a unique upper-lens dissolutional mechanism as previously proposed.

In an attempt to predict banana hole locations, spatial models with unsupervised image classifications (Digital Elevation Model, ASTER 1a and Landsat 5 TM) were generated using different predictors: Normalized Different Vegetation Index (NDVI), Normalized Different Water Index (NDWI), Carbonate-Chlorite Index, Dolomite Index, and Slope. Most of the predictors had a strong capability to locate island karst features when combined with slope and elevation as the parameters; NDWI, NDVI, Carbonate-Chlorite Index, and elevation had the highest capability compared to other predictors. By using the fieldwork data from Dec 2010 and May 2011 as the validation dataset, the model showed a 95% percent correct, 0.4% false alarm ratio, 1% probability of false detection, and 93% critical success index. By using logistic regression to validate the model, it showed that Akaike's Information Criterion (AIC) is 10. By using geographic weight regression to validate the model, 91.5% of the validation data fell into standard deviation residual between -1 and 1, indicating that the model was accurate and had the ability to predict karst features such as flank margin caves and banana holes in the future.

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INTRODUCTION

The purpose of the project reported here was to do a thorough inventory and examination of banana holes on San Salvador Island, Bahamas, to see if the Mylroie et al. (2008) hypothesis was correct. Additionally, the inventory would provide a database that could be examined to provide groundtruth for a remote sensing analysis, to see if banana holes could be mapped from space.

The Bahama Islands are a carbonate archipelago that has been in existence for over 100 million years, but whose surface expression consists of carbonates that are only hundreds of thousands of years old (Carew and Mylroie, 1995; 1997). While islands large (Andros) and small (New Providence) exist on the large Bahamian banks, islands like San Salvador exist on small, isolated banks not much bigger than the island itself. Due to such conditions of small size and limited rock age, all geologic features, including karst, must have formed under tremendous constraints of time and space. San Salvador is an excellent natural laboratory in which to study both depositional and dissolutional phenomena because of these constraints. The surficial geology of the Bahamas is reviewed in detail by Carew and Mylroie (1995, 1997). Recent updates of that basic model are available in Mylroie et al., (2012). A simple review of the aspects of Bahamian surficial geology relevant to this paper follows.

The exposed rocks of The Bahamas are all mid to late Quaternary carbonates, dominated by eolian calcarenites or eolianites (fossilized carbonate sand dunes) and subtidal facies (including fossil reefs) at low elevations; and solely by eolianites at elevations above 8 m. The highest elevation in the Bahamas is 63 m on Cat Island. Paleosols can occur at all elevations. The glacio-eustatic sea-level changes during

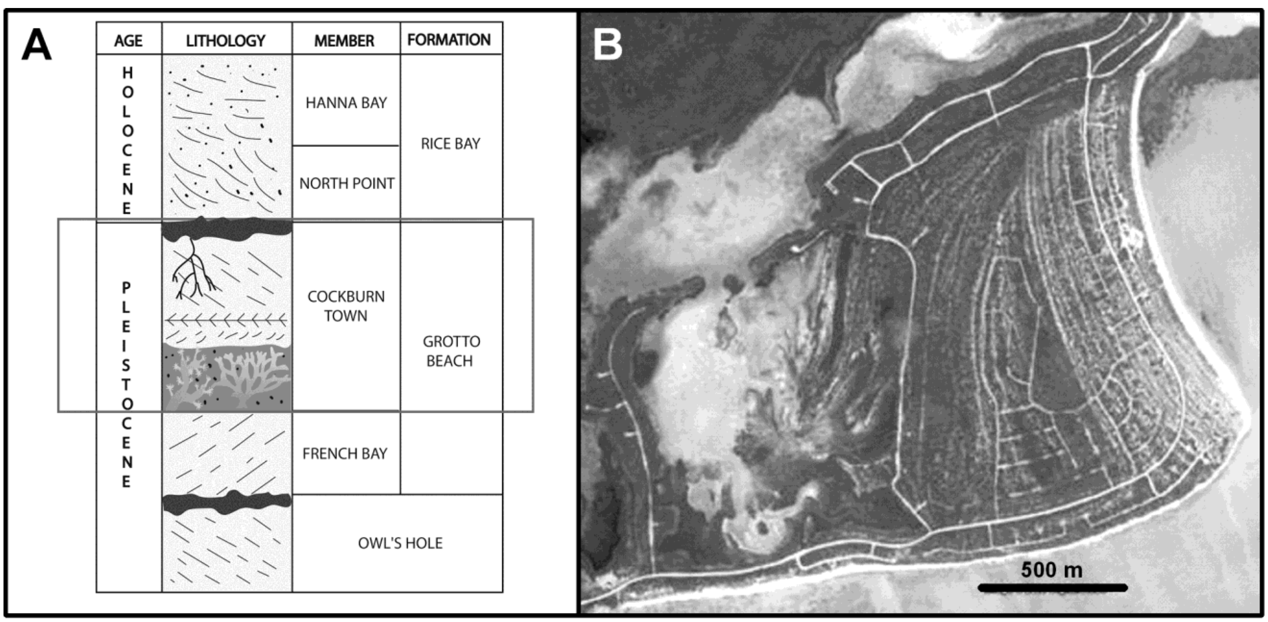

Figure 1. A) Simplified stratigraphic column for San Salvador, and by extension, the entire Bahamas. Subdivisions of the Owl's Hole Formation, visible in the field on Eleuthera Island, and pre-Pleistocene carbonates from Mayaguana, not included. The box highlights the Cockburn Town Member of the Grotto Beach Formation, within which Bahamian banana holes are found. Modified from Carew and Mylroie, 1995. B) Sandy Hook, southeastern end of San Salvador Island, Bahamas, north to the top. Pictured in this Google Earth image is a prograding Holocene strandplain, a model for the fossil Pleistocene strandplains found on San Salvador and throughout the Bahamas. Note the low beach ridges sweeping in an arc from west to east; each represents a separate progradation event within the last 5,000 years.

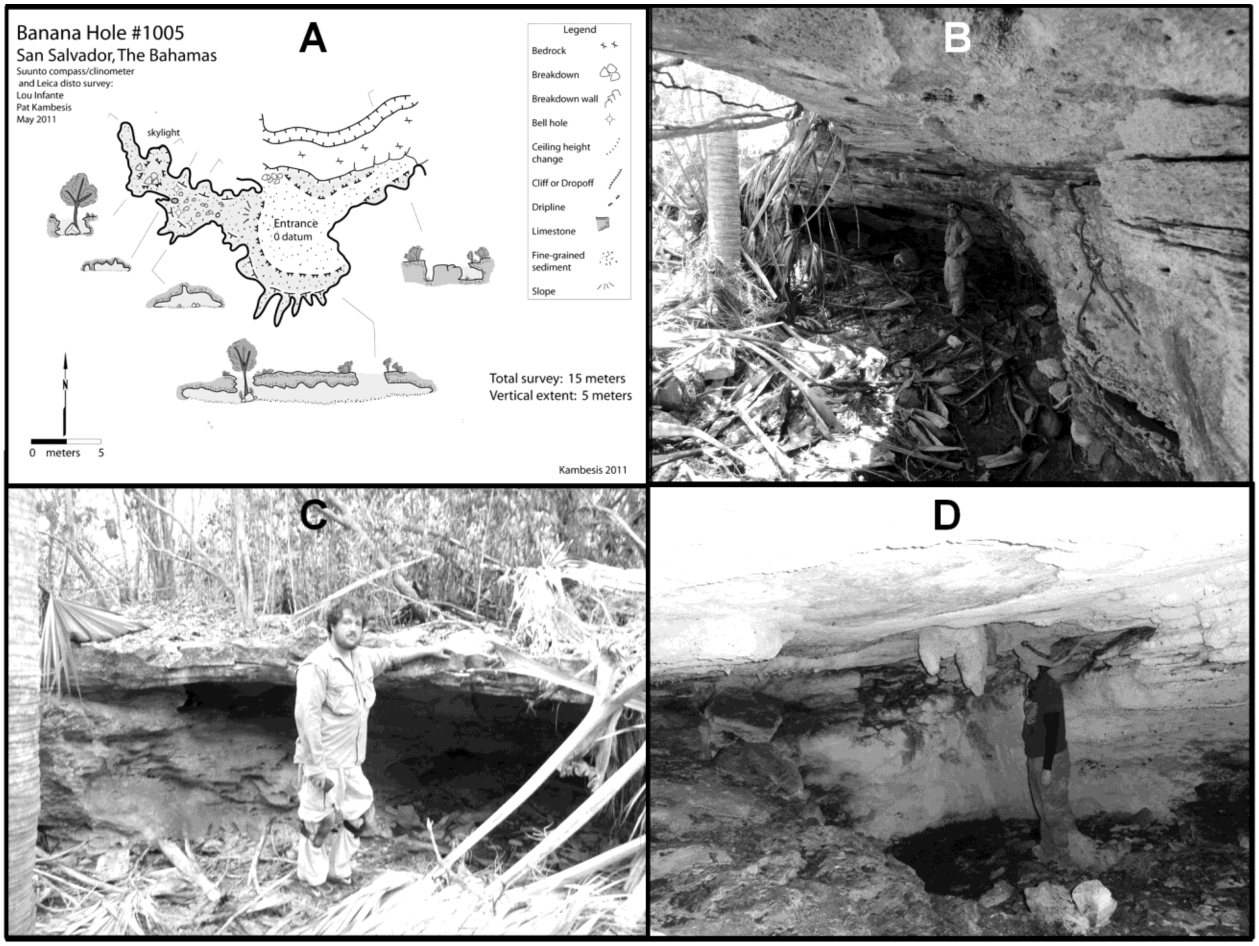

Figure 2. Map and images of banana holes from San Salvador Island, Bahamas. A) Map of a partially collapsed banana hole, showing passage complexity commonly found in flank margin caves. B) Large, partially collapsed banana hole with 2 m of wall exposure. C) Small, partially collapsed banana hole, partly infilled with collapse and soil, such that the lowermost rock units are not visible. D) Intact banana hole chamber.

Quaternary time alternately have flooded and exposed the Bahamian platforms, subjecting them to cycles of carbonate deposition and dissolution, respectively. Significant carbonate deposition occurred in the past only when the platforms were flooded, as is the case today.

The carbonate sequences of the Bahamas can be viewed as individual packages deposited on each sea-level highstand, separated by erosional unconformities (usually marked by paleosols) produced by each sea-level lowstand (Carew and Mylroie, 1995; 1997). The oldest unit on all Bahamian Islands, except Mayaguana (Kindler et al., 2011), is the Owl's Hole Formation (Figure 1A), consisting entirely of eolianites. Overlying the Owl's Hole Formation and separated from it by a paleosol or other erosion surface is the Grotto Beach Formation, which developed during the last interglacial, Marine Isotope Substage 5e (or MIS 5e), 124,000 to 114,000 years ago (Mylroie et al., 2012). The last interglacial was about 6 m higher than present sea level, so subtidal deposits, such as fossil reefs and lagoons, are found above sea level in this unit. Two members occur in the Grotto Beach Formation, the French Bay Member, and the Cockburn Town Member, representing the transgressive (French Bay), and stillstand and regressive episodes (Cockburn Town) of the last interglacial sea-level highstand. There are numerous karst caves developed in the unit, which formed during and immediately after the deposition of the rock, which is about as fast as caves can form following limestone deposition. The Cockburn Town Member rocks have many fossil strandplains throughout the Bahamas.

Overlying the Grotto Beach Formation and separated from it by a paleosol or other erosion surface are the rocks of the Rice Bay Formation, deposited during Holocene time. This unit is made up of eolian and beach deposits. The Holocene units also contain strandplains that are actively growing (Figure 1B) and serve as models for the fossil Pleistocene strandplains.

Karst features are abundant in the Quaternary limestones including blue holes, pit caves, flank margin caves, and banana holes as well as a variety of surface karren (see Mylroie and Mylroie, 2007, for a full discussion). Blue holes are polygenetic features and not relevant to this discussion. Pit caves result from vadose fast flow from the surface to the water table. The key aspect of carbonate islands and coasts are the caves produced by the fresh-water lens. Caves develop most favorably in the distal margin of the lens, under the flank of the enclosing landmass (hence their name, *flank margin cave*). They form in this location as a result of the superposition of three phenomena: mixing dissolution at the halocline, oxidation of organics trapped at the density interface of the halocline, and the increased flow velocities at the lens margin. They can be small chambers with dimensions of only a few meters, ranging upward to large caves with over 3,000 m^2 of floor area. Because they develop at the thinning margin of the fresh-water lens, they are commonly restricted to a vertical range of only 1 to 6 m. For a full treatment of flank margin caves, see Mylroie and Mylroie (2007).

Banana holes are sinkhole-like features commonly a few meters to a few tens of meters in horizontal extent, circular to oval in plan, one to six meters deep, and appear in a variety of conditions from totally roofed to totally unroofed (Figure 2). The name “banana hole” comes from the Bahamian inhabitants, based on the use of the unroofed holes as a place to grow specialty crops such as papaya, breadfruit, and of course, bananas (Neuendorf et al., 2005, p. 51). The holes provide a collection point for in-washed soil, and their floors are closer to the water table and are consistently moist, providing a superior plant growth setting compared to the relatively barren karst land surface above. The history of the use of the term, and a discussion of previous models, is available in Harris et al. (1995).

At the time of this study, the accepted model for banana hole development was that they formed at the top of the fresh-water lens as a result of vadose and phreatic fresh-water mixing (Harris et al., 1995). This model apparently explained why banana holes were commonly found more than a kilometer inland, and in great numbers over broad areas, a distribution at odds with a flank margin cave origin. Because banana holes could be found in partially roofed and completely roofed conditions, they were not simple sinkholes or dolines as proposed by some earlier workers (e.g. Smart and Whitaker, 1989). Mixing of fresh waters at the top of the lens appeared to meet the distribution evidence, as this environment would exist over the entire lens footprint. Almost all banana holes were developed in flat plains in the range of 6 to 10 m above sea level. It was felt that the development of mixing dissolution voids under these broad, low plains would create thin roofs, making the voids prone to collapse, and create the many sinkhole-like features observed today as banana holes.

The Harris et al. (1995) model has some problems. Banana holes are rarely found in other carbonate island settings, such as the Mariana Islands, or Isla de Mona, Barbados, and Curaçao. This absence was in part explained by the thicker limestone overburden of these other carbonate islands, which would have inhibited collapse and the surficial expression of what were thought to be many small, isolated dissolution voids at depth. Another problem was that analysis of water at the

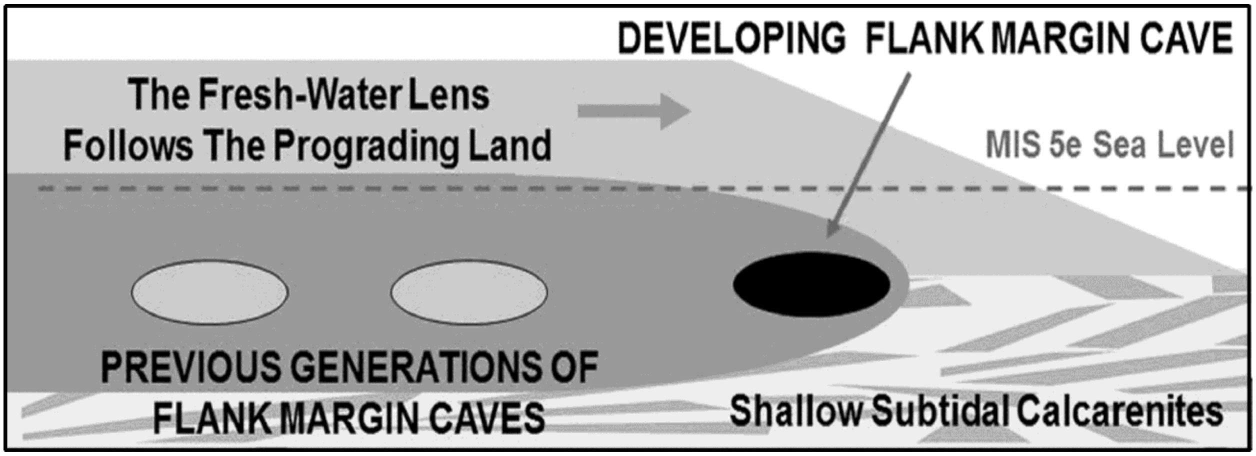

Figure 3. Schematic of the prograding strandplain model for banana hole formation. During MIS 5e, as the strandplain progrades into the lagoon, the fresh-water lens margin follows, creating and abandoning small, immature flank margin caves.

top of the lens was not dissolutionally aggressive as proposed by the Harris et al. (1995) model, in fact, it was commonly supersaturated as a result of CO_2 degassing at the top of the lens.(e.g. Whitaker and Smart, 1997).

Work on San Salvador (e.g. Pace, et al., 1993) had reported that many banana holes had subtidal lagoonal facies in their wall rock. Later field work by the senior author on Long Island, and later on Eleuthera Island, Bahamas, noted the same subtidal facies presence in banana holes there. During field work on New Providence Island in 2006 (Mylroie et al., 2008) a similar pattern was observed, and this time, a more detailed analysis was done. It became evident that all banana holes and related features in the New Providence field area were in subtidal lagoonal facies that graded upward into beach and back beach facies. It is important to note that reef facies were *not* present in the banana hole wall rock.

The presence of subtidal facies above modern sea level, as observed in banana holes throughout the Bahamas requires that the rock unit be the Cockburn Town member of the Grotto Beach Formation (Figure 1A). Mylroie et al. (2008) proposed that the banana holes were developed in a prograding strandplain formed during the last interglacial sea-level highstand (MIS 5e). Similar strandplains (Figure 1B) have formed in Holocene sediments throughout the Bahamas (e.g. Carney and Boardman, 1993), and Pleistocene strandplains from MIS 5e seem very abundant as well. Gerhardt (1983) and Aurell et al. (1995) provide detailed studies of Pleistocene strandplains on Grand Bahama Island and New Providence Island, respectively.

In their interpretation, Mylroie et al. (2008) explained that as the strandplain prograded seaward into a shallow lagoon, it created a new land surface. That land would be invaded by the existing fresh-water lens of the island. In that setting, strandplain progradation is episodic (Carney and Boardman, 1993), such that the leading margin of the fresh-water lens would pause and hold position for a period of time before progradation began anew (see Figure 1B). The pause in the lens margin position allowed the flank margin model of dissolution to take effect, creating dissolutional voids. As the lens margin advanced, these voids were left behind and new ones developed at the new lens margin (Figure 3).

This new model apparently solved all the original problems with the Harris et al. (1995) model. The absence of banana holes on other carbonate archipelagoes was because they were coral limestones, formed entirely in the subaqueous environment, and did not see a fresh-water lens until sea-level change brought them into the subaerial environment. The strandplain hypothesis creates a terrestrial environment during the sea-level highstand, allowing the fresh-water lens to be at the elevated position of the strandplain. The problem with the dissolutional aggressivity of the top of the fresh-water lens was resolved as the dissolution was actually occurring at the lens margin. The progradation of the strandplain caused the widespread pattern of banana holes, and their presence at significant distances inland. The small size of banana holes relative to many flank margin caves was the result of the banana holes being abandoned by the moving lens margin. In other words, banana holes are immature flank margin caves. This development of dissolutional caves in carbonates while they are being deposited has been labeled *syndepositional cave* development (Mylroie and Mylroie, 2009). It implies that carbonate cementation occurs rapidly enough that voids can form with stable roofs. Many of these roofs collapsed after sea level fell at the end of MIS 5e and buoyant support was lost. Collapse continued during the entire sea-level lowstand from the end of MIS 5e to the present highstand.

METHODS

The Line Hole, Jake Jones Road, Hard Bargain, and South Victoria Hill areas of San Salvador (Figure 4) were selected for this study and were examined in December 2010, May 2011, and December 2011. The Line Hole-Jakes Jones Road area was selected as it was known to have abundant banana holes, and had been the site of previous studies by Pace et al. (1993) and Harris et al. (1995). The Hard Bargain-South Victoria Hill areas were selected to provide a compare-and-contrast situation to the work in the northern end of the island.

Field work was simple and direct. Transects were run in the field areas. Each banana hole position was fixed using GPS, photo documentation was done, and selected banana holes were mapped, and some had rock samples taken. The rock samples were impregnated with blue epoxy and thin-sectioned commercially and analyzed at Mississippi State University by petrographic microscopy. Cave map data were collected using Suunto® compass and a Disto® laser rangefinder, assisted by fiberglass tape when light conditions prevented laser use. The data were reduced by Compass® software, and the maps were drawn on Adobe Illustrator®. The location data underwent spatial examination by Nearest Neighbor analysis and Ripley’s K Function. For a full treatment of the methodology, see Infante (2012).

The remote sensing portion of the study was conducted with imagery available in the public domain, and from an ASTER image available to researchers at the Gerace Research Centre on San Salvador Island. ASTER 1A is a satellite image set with 14 spectral bands. Based on the properties of multi-thermal bands and multi shortwave infrared (SWIR) bands, ASTER has the capability to explore for minerals. ASTER is also relatively cheaper than LIDAR and airborne-based hyperspectral images, and has a global geographic extent. The low cost and large geographic coverage of ASTER images can solve problem of field site accessibility and fieldwork costs (Ho, 2012a; Kokalj and Oštir, 2007). In order to develop an accurate fuzzy-based spatial model, a digital elevation model (DEM) was also used as raw data in this study. Island caves usually developed on the fresh-water lens margin, a topography-driven characteristic of island karst, where the caves such as flank margin caves and banana holes (now known to be a subset of flank margin caves) are usually found at the elevation of paleo-sea level on these carbonate islands. Therefore, topography became an important factor to predict island karst cave distributions. The DEM was used to generate topographic parameters for the fuzzy-based spatial model development. This DEM was rebuilt from the 1972 Bahamian

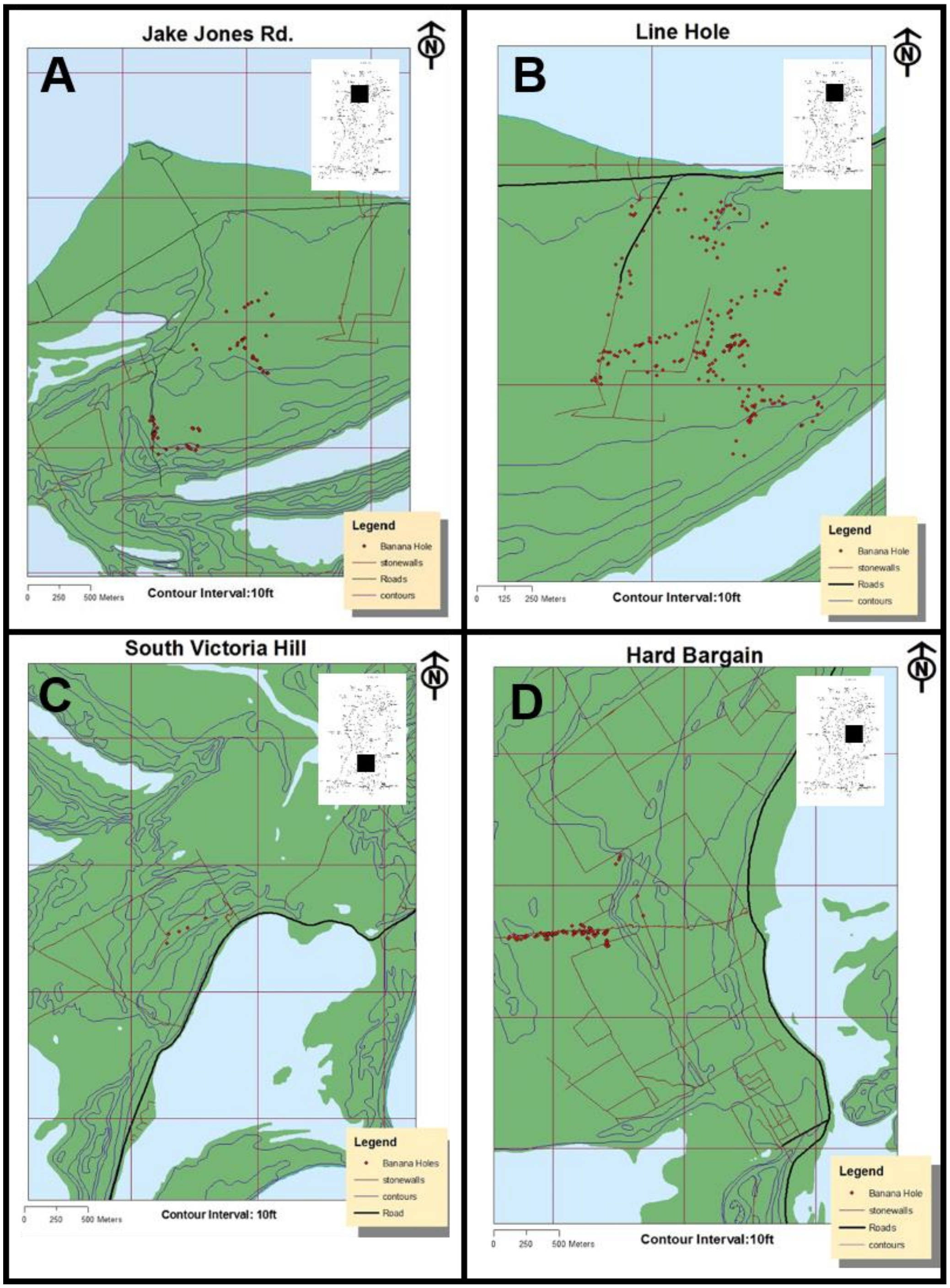

Figure 4. The four study areas on San Salvador: Jake Jones Road (A) and Line Hole (B) at the north end of San Salvador, and South Victoria Hill (C) and Hard Bargain (D) at the east central part of San Salvador. Locations of 390 banana holes shown as dots.

governmental topographic map and was interpolated into a raster layer with 10 meters resolution.

The first stage of this model was to examine the distribution of banana holes on San Salvador Island. This fuzzy-based spatial model was developed with six main components: elevation, slope, Normalized Difference

Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), carbonate-chlorite index (CCI) and dolomite index (DI). Based on the field evidence, it is believed that banana holes are usually found at +4 to +7 meters elevation (the sea level of the highstand during MIS 5e). Field records also showed that banana holes are usually extensively found in relatively flat areas. Therefore, +4 to +7 meters elevation and a slope less than 10 degrees were set as the unsupervised parameters of this model.

Based on the particular island karst landscape, NDVI and NDWI were used to assess the characteristics of vegetation cover, vegetation moisture, and soil moisture into the model. NDVI, [(Near Infrared – Red)/(Near Infrared +Red)], is a common vegetation index (Gao 1996). It has the ability to detect the vegetation type, vegetation cover change, and vegetation health. NDWI, [(Mid Infrared – Near Infrared)/(Mid Infrared + Near Infrared)], is a common moisture index (Gao, 1996). Its ability includes detecting vegetation and soil moisture. Landsat TM 5 satellite imagery was used to generate the NDVI and NDWI raster layers as the parametric inputs in the model.

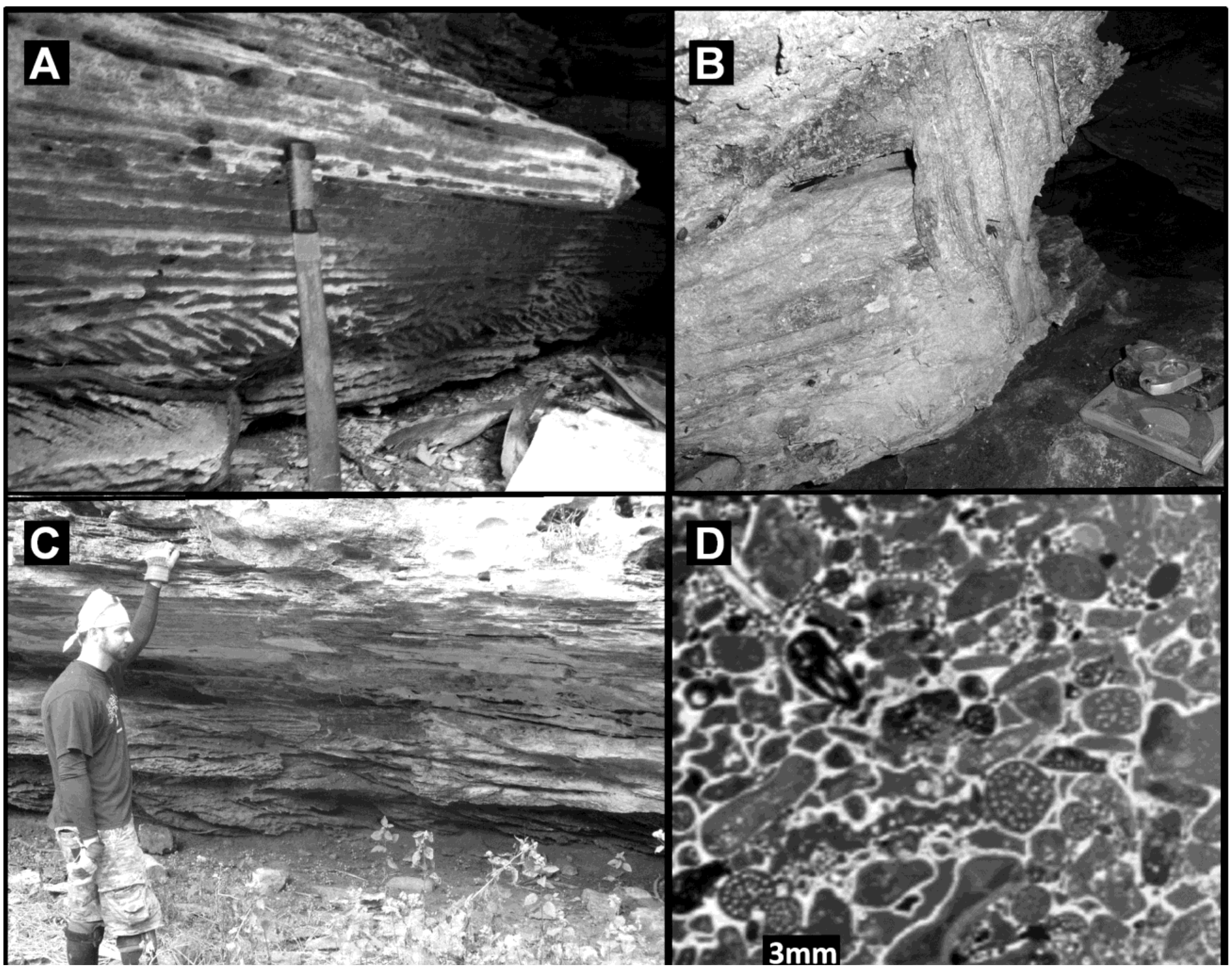

Figure 5. Facies found in the wall rock of banana holes in the Line Hole area (Figure 4B). A) Herringbone cross bedding. B) Back beach rubble facies. Notebook in lower right 20 cm long for scale. C) Upward facies change from subtidal to planar beach facies. D) Epoxy-impregnated thin section of subtidal facies.

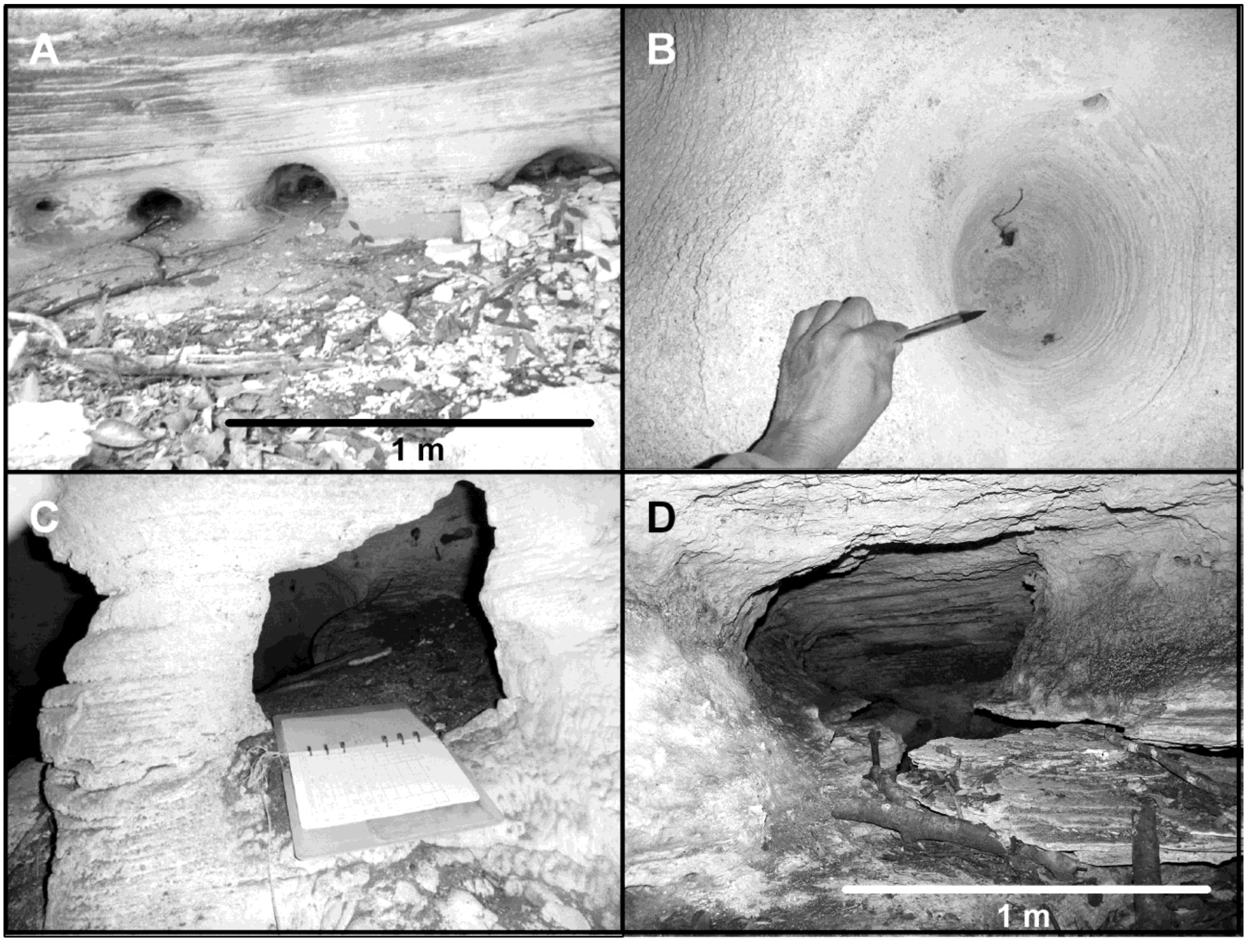

Figure 6. Phreatic surfaces from banana holes in the Line Hole area. A) Dissolution cusps. B) Bell hole (view looking upwards). C) Dissolution hole in a thin bedrock partition. Notebook 20 cm wide for scale. D) Blind (dead-end) passage.

CCI, [(ASTER band 7 + ASTER band 9)/ASTER band 9], was developed to explore carbonate minerals; DI, (ASTER band 6 +ASTER band 8)/ASTER band 7, was an index to detect dolomite minerals (Rowan and Mar, 2003). Both indices were calculated by the SWIR bands in the ASTER image, and were applied to investigate the maturity of carbonate rock on San Salvador Island in this study. It is believed that carbonate sediments from the Holocene and the Pleistocene should have different percentages of magnesium ions. The abilities of Holocene and Pleistocene sediments to reflect SWIR waves should not be the same. By using the combinations of SWIR bands in ASTER image, raster layers of CCI and DI were generated as the parametric inputs of the fuzzy-based spatial model. For a full treatment of these remote sensing methods, see Ho (2012b). The remote sensing results were compared to the field data for groundtruth and validation.

RESULTS

Figure 4 shows the plots of banana hole locations at the four study areas. A total of 390 banana holes were located, 70 of which were mapped (e.g. Figure 2A), the maximum that could be done in the time available. The Line Hole and Jake Jones Road area received most of the field work (Figure 4A and 4B). Only a few trips were taken to South Victoria Hill and Hard Bargain, as shown by Figure 4C and 4D, which reflects a single transect for South Victoria Hill, and the bias introduced at Hard Bargain by keeping near the

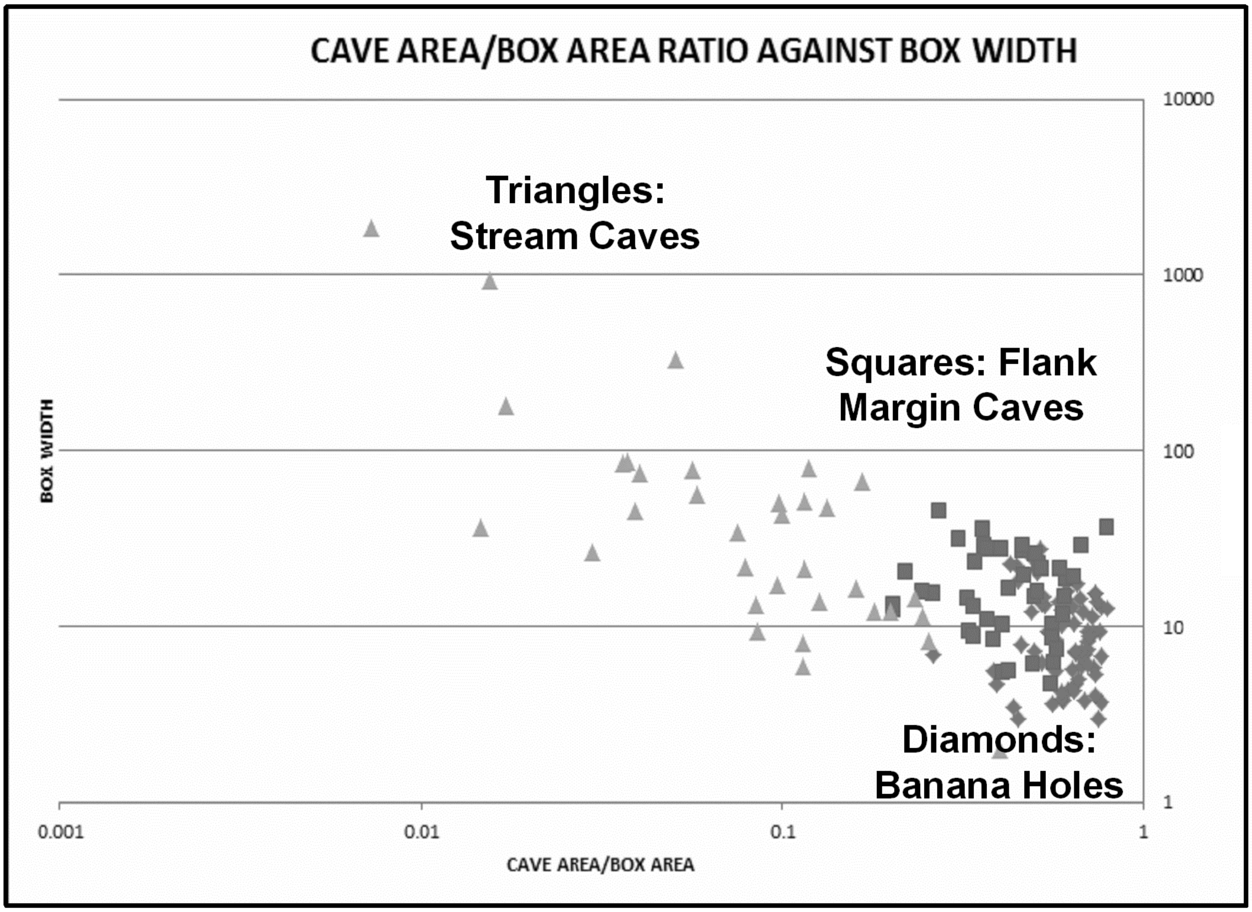

Figure 7. A plot of cave area/enclosing box area ratio versus box width, a cave map morphometric analysis tool that separates turbulent-flow stream caves typical of continental interiors from laminar-flow flank margin caves (Roth et al., 2006). The plot demonstrates that banana holes fall within the field for flank margin caves and outside the field for stream caves.

main trail through the area. Nearest Neighbor analysis at the Jake Jones/Line Hole area (the area least influenced by roads and trails), gave a Z-Score of -12.3412, indicating a significant degree of clumping of the banana holes. Riplye's K Function gave values that all plotted within the significant field for clustered behavior (see Infante, 2012, for a full treatment). Rock sample porosity values ranged from 1.3% to 46%, with a mean value of 28%, consistent for eogenetic carbonate rocks (e.g. Owen et al., 2010). The banana hole wall rocks displayed a variety of subtidal facies indicators (e.g. Figure 5), which graded upward into beach and back beach facies. The facies observed in banana hole wall rock progressed from shallow subtidal (herringbone cross beds) to intertidal (laminar beds and/or back-beach breccia blocks) to supratidal (eolian foresets) deposits. These features were present in almost all banana holes that were not partially infilled by surface debris. Dissolutional surfaces indicating phreatic development were also abundant (Figure 6). Morphological analysis of the cave maps indicated that banana holes plotted in the smaller end of the flank margin cave field (Figure 7), quite different from the field plot for stream caves as found in continental interiors (stream caves are turbulent-flow cave conduits; flank margin caves and banana holes form under laminar-flow conditions, see Roth et al., 2006). See Infante (2012) for all maps and data related to this study.

The first fuzzy-based spatial model was developed with the six parameters previously discussed. It aimed to generate a logical map of island karst cave predictions. Correlation analysis was applied to develop the parameter of logical mapping. By using 205 GPS records from the fieldwork accomplished in Dec 2010 and May 2011, it showed that banana holes were highly correlated with the model outcomes between 0.0 - 0.25. Therefore, pixel value of the raster output between 0.0 - 0.25 was used as the parameter of logical mapping. The predictions from logical map were validated with 341 records of banana holes and non-banana hole areas. This forecast validation showed that the prediction had 220 hits and 97 correct rejections. The percent correct, false alarm ratio, probability of false detection, and critical success index were about 93%, 1%, 3%, and 90%, respectively. The validation indicated that model predictions were highly accurate and had low error rates.

To improve the model statistically, a stepwise regression modeling was applied to rank the six parameters. According to the regression, the best parameters for the fuzzy logic classification were NDWI, NDVI, elevation, and DI. Therefore, a new model with same fuzzy logic structure was developed by these four parameters.

Kernel Density	High-High Correlation	Low-Low Correlation
NDVI	89.00%	100.00%
NDWI	59.00%	100.00%
Carbonate-Chlorite Index	87.00%	100.00%
Dolomite Index	88.00%	100.00%
Elevation	96.00%	100.00%
Slope	46.00%	100.00%

Table 1. A comparison of kernel density of each parameter. High-high correlation, which represents those areas with banana holes, is correlated with the parameters. Low-low correlation represented that area without banana holes, which are not correlated with the parameters.

Based on the correlation analysis, pixel values of the raster output between 0.0 - 0.25 were highly correlated to areas with banana holes. Thus, pixel values between 0.0 - 0.25 were used as the parameter of this model to reclassify the raster output into the logical map. The predictions from the new logical map showed that the percent correct, false alarm ratio, probability of false detection, and critical success index were about 95%, 0.4%, 1% and 93%, respectively, values much improved over the previous model. Stepwise regression did improve the fuzzy-based model.

Kernel density, a logistic regression model, and a geographic weight regression model were also applied to validate the model parameters and results. Akaike's Information Criterion (AIC) from the logistic regressions was used to compare the models. AICs of the basic model and the stepwise model were 14 and 10. The decline of AIC demonstrated that the stepwise model had a higher accuracy than the basic model. Modeling with geographic weight regressions, 88.6% of the standard deviation residual (STD residual) of the basic model were between -1 to 1. The STD residual of the stepwise model, which fell into -1 to 1, was about 91.5%. Compared to the basic model, the capability of the stepwise model to predict the island karst distribution, such as flank margin caves and banana holes, was significantly higher. Kernel density detected the sensitivities of six initial parameters. The results indicated that NDVI, CCI, DI, and elevation were highly correlated with the regions with banana holes (89%, 87%, 88%, and 96%, respectively) (Table 1). Conversely, the six parameters utilized in this study showed a low-low correlation to areas without banana holes. The kernel densities sufficiently demonstrated that the selected parameters were able to provide the fuzzy-based spatial models with sufficient input for a successful outcome.

A further assessment was also conducted to examine the abilities of fuzzy-based spatial models. Four basic unsupervised models were developed to compare with the fuzzy-based models (Table 2). None of the basic unsupervised models had a percent correct and critical success index higher than fuzzy-based models, and the false alarm ratio and probability of the basic models were relatively high. This approach also demonstrates a better performance of fuzzy-based models, and that the use of fuzzy models to predict island karst is appropriate. See Ho (2012b) for the complete data set.

DISCUSSION

The data on banana hole distribution and morphology are consistent with the prograding strandplain model for banana hole genesis. Banana holes on San Salvador are found exclusively in facies consistent with the subtidal-beach-backbeach transition found in both Holocene and Pleistocene strandplains. A few banana holes (<10%) were found that did not show subtidal facies, but these were shallow banana holes infilled with collapse material and soil, that did not extend deep enough to intersect the subtidal facies found in nearby banana holes (e.g. Figure 2C). The banana holes are not randomly or uniformly distributed, as would be expected if dissolution were occurring due to fresh-water vadose and phreatic mixing at the top of the lens. The clustered distribution reflects the episodic positional changes of the discharging fresh-water lens as the strandplain prograded during MIS 5e time in the late Pleistocene. Where a linear arrangement of banana holes exists, that line is parallel to the strike of the strandplain beach ridges (Figure 4B). Macroscopic features such as back-beach breccia block facies and herring bone cross beds, as well as thin section analysis, and phreatic dissolutional features such as cusps, blind passages, bell holes, and thin wall partitions, clearly demonstrate that banana holes originate by phreatic dissolution in subtidfal facies, and extend partly upward into beach and back-beach facies. Some of this upward extension, especially into the back-beach dune facies, is caused by collapse, and no original dissolutional surfaces exist high in such banana holes, as those regions would have been above the top of the fresh-water lens during MIS 5e time.

	Percent Correct	False Alarm Ratio	Probability of false detection	Critical Success Index
NDVI Model	89.00%	0.00%	0.00%	85.00%
NDWI Model	92.00%	1.00%	2.00%	89.00%
Carbonate-Chlorite Model	89.00%	5.00%	11.20%	85.00%
Dolomite Model	93.00%	6.00%	15.00%	90.00%
Fuzzy Logic Model (ALL variables)	93.00%	1.00%	3.00%	90.00%
Fuzzy Logic Model (Stepwise)	95.00%	0.40%	1.00%	93.00%

Table 2 – A comparison of fuzzy logic models and basic supervised models.

The strandplain model for banana holes explains their similarity to small flank margin caves. Banana holes begin their development as dissolutional voids, and then are abandoned to the lens interior, where dissolutional potential is low, as the strandplain progrades and the dissolutionally active lens margin follows. Flank margin caves, formed primarily in the sides of eolian ridges, developed in a fixed positional environment, as the lens was restricted to the eolian ridge. Therefore these caves developed to full size and maturity during the MIS 5e sea-level highstand. Banana holes were formed in a much smaller time window, and did not have time to get large and complex before the advancing lens margin sent them into senescence while they were still small. The degradation of banana holes from intact flank margin caves into the sinks and exposed holes we see today probably began early in their history. A major event would have been the lowering of the fresh-water lens as sea level fell at the end of MIS 5e. Loss of buoyant support could have triggered a number of collapse episodes in the banana holes. During the next 100 k plus years, surface denudation, pit cave development, and rock fatigue would have gradually caused banana hole collapses to occur and expand. The state of the banana holes today, in which most are open to the sky and many are degraded to simple sinkholes, reflects this continuous decay.

The presence of banana holes is therefore a facies indicator of the existence of a fossil strandplain. The strandplain model also indicates that soon after deposition, carbonate sediments gain enough cementation to support the roof of a dissolutional void. Because the top of these voids are in the back beach region, the cementation there may be a mix of phreatic and vadose cements, a topic for future investigation. Banana holes are therefore an example of syndepositional caves, voids that form soon after carbonate deposition, while that deposition is still occurring laterally near the site of dissolution. The strandplain model is an important indicator of the rapidity of geologic processes in carbonate environments. During the Quaternary, sea level has been high enough to flood the Bahama Banks and initiate carbonate deposition for about only 10% of the time (e.g. Carew and Mylroie, 1997). MIS 5e lasted about 10 k years. Within that small time window, time had to pass before carbonate sediment built up on the platform to amounts large enough to allow prograding strandplains to develop. While these strandplains were developing, they were cemented sufficiently to support a void, which itself had to form rapidly before the margin of the fresh-water lens migrated in response to further progradation. Syndepositional cave development requires that both rapid depositional and dissolutional events occur; the prograding strandplain model for banana hole genesis provides an outstanding example of such rapidity.

Using fuzzy-based spatial modeling to predict island karst features is an important aspect of island land-use study, given how many carbonate islands exist in the world. Future study may be able to use remote sensing for advanced investigative techniques applied to island karst features other than flank margin caves and banana holes. For a further progress of model development, Wide Dynamic Range Vegetation Index (WDRVI) can be introduced into a future model. WDRVI has been promoted as an index similar to NDVI (Gitelson, 2004), with less random error from atmosphere and wave spectrums. Future study should intend to examine the capability of WDRVI in relation to island karst cave predictions, with the evaluation of spectral angle mapping. Spectral angle mapping can obtain a high degree of spectral separability (separation of the various spectrums observed by the remote sensing satellite). The observation of spectral separability can design a better spectral range for unsupervised classification and reclassification (Narumalai et al., 2006). Banana holes are facies-specific karst features. The prediction of banana holes by remote sensing is also a tool for mapping of Pleistocene fossil strandplains in the Bahamas.

SUMMARY

Banana holes are flank margin caves. They are product of fresh-water lens margin processes which promote carbonate dissolution and the production of voids. Because they form in prograding strandplains, the fresh-water lens margin migrates, causing a field of banana holes to form as the strandplain grows. Banana holes are syndepositional immature flank margin caves. They are indicators of fossil strandplains. Their abundance makes them available to mapping by remote sensing. Because the banana holes are facies specific, this remote sensing application allows the Pleistocene strandplains that host them to also be mapped.

The strandplain model for banana hole development explains all known observations about banana holes in the Bahamas, and removes problems associated with earlier models. The banana hole work on San Salvador has provided data in sufficient quantity and quality to assist in testing the viability of the strandplain model.

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