PROCEEDINGS

OF THE

SECOND JOINT SYMPOSIUM

ON THE

NATURAL HISTORY AND GEOLOGY OF THE BAHAMAS

Edited by
Tina M. Niemi
and
Kathleen Sullivan Sealey

ORGANIZER:

Troy A. Dexter

Executive Director
Gerace Research Centre
University of The Bahamas
San Salvador, The Bahamas

2020

ISBN: 978-0-935909-67-8

VEGEMORPHS AS A MEANS TO DIFFERENTIATE TRANSGRESSIVE-PHASE FROM REGRESSIVE-PHASE QUATERNARY EOLIAN CALCARENITES, SAN SALVADOR ISLAND, THE BAHAMAS

John E. Mylroie, Andrew N. Birmingham, and Joan R. Mylroie

Department of Geosciences, Mississippi State University,
Mississippi State, MS 39762

ABSTRACT

During the start of Quaternary interglacial conditions, rising sea level flooded the top of the steep-sided carbonate platforms of The Bahamas, and carbonate sediment production was significant. This carbonate sediment was rapidly produced in large volumes within relatively small lagoons, and eolian calcarenites immediately developed on the remaining dry ground adjacent to their source beaches. As these dunes form as sea level is rising, they are referred to as transgressive-phase eolianites. Continued reef growth to wave base as the highstand stabilizes diminishes lagoon wave energy, and further dune production is modest until the end of the interglacial, when sea level begins to fall and surf zone processes pass through the platform lagoons, where stored carbonate sediments are remobilized into beaches and a second episode of dune production occurs. The resulting dunes are regressive-phase eolianites.

These two eolianite packages bracket the leading and trailing portions of individual sea-level highstands. Various criteria have been developed to identify transgressive-phase and regressive-phase eolianites; however, the one with the most potential is based on plant trace fossils, variously called rhizomorphs, rhizoliths, or vegemorphs. Vegemorphs is used herein as it refers to any plant structures, not just roots. Extensive field work has demonstrated quantitatively that vegemorphs are found preferentially in regressive-phase eolianites, and that the presence of vegemorphs disrupts the fine-scale eolian bedding. Transgressive-phase eolianites have notably fewer vegemorphs, and as a consequence, exhibit undisturbed fine-scale laminations. An average vegemorph spacing distance of 15 cm separates transgressive-phase eolianites (>15 cm) from regressive-phase eolianites (<15 cm). Vegemorph low abundance or high abundance is readily observable in outcrop, and so paleodunes exposed at sea cliffs, in quarries and road cuts, or in caves can be categorized as transgressive-phase or regressive-phase deposits, respectively.

INTRODUCTION

The Bahamian archipelago is a carbonate province where the subaerially exposed rocks and sediments have been produced by Quaternary glacioeustasy, with sea-level highstands creating lagoonal and eolian deposition, and sea-level lowstands dominated by surficial weathering and terra rossa paleosol production and almost no carbonate deposition (Carew and Mylroie, 1995a; 1997). The sole exception is Mayaguana Island, where minor tectonic activity has allowed lagoonal deposits dating back to the Late Miocene to be present at the surface (Kindler et al., 2010). Sea-level highstands in the Quaternary have a duration of ~10 ka, and the intervening lowstands have a duration of ~100 ka, within each glacial-interglacial cycle (Carew and Mylroie, 1995b). All subaerial carbonate deposits seen in The Bahamas today had to form within a geologically short time window when the steep-sided Bahamian platforms were flooded and the carbonate sediment "factory" (Carew and Mylroie, 1995a; 1997) was turned on and operating. In The Bahamas, almost all sediments above 7 m elevation are eolianites. From sea level up to 7 m, eolianites exist, but subtidal facies representing lagoons and former coral reefs are also present. The subtidal facies are almost exclusively from the last interglacial, or Marine Isotope Substage 5e (MIS 5e); tectonic subsidence and denudation have removed evidence of earlier highstand events (Carew and Mylroie, 1995b; Mylroie and Mylroie, 2017). Eolian deposits exist from the mid-Pleistocene, and represent at least three sea-level highstands prior to MIS 5e (Kindler et al., 2010) as they are high enough and massive enough to withstand both platform subsidence and denudation effects (Mylroie and Mylroie, 2017).

The eolianites of The Bahamas are difficult to place within a stratigraphy, as they contain almost no datable fossil material, and their patchy distribution means they are commonly not stacked one upon the other. In some locations, such as the Glass Window area of Eleuthera, the eolianites can be found stacked one upon the other to give an uncontestable field example showing eolianite production going back to the mid-Pleistocene (Kindler et al., 2010). The use of U/Th dating for eolianites is not possible as no coral fossils are present. Dating by amino acid racemization (AAR) has had some success in placing eolianites within a given interglacial episode, although the method has been controversial (Carew and Mylroie, 1995a; 1997; Kindler et al., 2010). Paleomagnetic studies have been successful using the paleomagnetic secular variation of terra rossa paleosols that separate the eolian units (Panuska et al., 1999), but these tests do not date the eolianite, they merely give the overlying terra rossa paleosol a unique magnetic fingerprint. This technique allows correlation in the field, but not an absolute age. Use of ^{14}C dating has been very successful in differentiating Holocene eolianites, but cannot be used on eolianites from MIS 5e or earlier. Electron Spin Resonance (ESR) analysis has been attempted, but with mixed success (Dealy et al., 2011). The problem using dating techniques to determine the stratigraphic position of a given eolianite is that the answer cannot be determined in real time in the field. The investigator must wait until the analyses have been completed in a laboratory somewhere other than in The Bahamas, often a year or more after sample collection. The techniques listed above also (with the exception of ^{14}C for Holocene rocks) cannot differentiate events within the eolianite deposits of a given interglacial highstand.

The simplified Bahamian stratigraphic model is shown in Figure 1 (Carew and Mylroie, 1995a; 1997) as it is most suitable for field investigations; for a more detailed stratigraphic column, see Kindler et al. (2010). The model postulates that when sea level is rising at the end of a glacial cycle, sediment production begins as soon as the sea water overtops the platform edge and begins to create lagoons on the platform top. Field evidence shows that even a small lagoon near the platform edge can produce sufficient carbonate allochems to allow almost immediate production of beaches on the remaining high ground of the platform, resulting in the deposition of eolianites sourced from those beaches. These eolianites are called *transgressive-phase eolianites* as they result from the initial transgression of the platform (Carew and Mylroie 1995a; 1997). Through time, sea-level rise will slow and stabilize. When this event occurs, reefs will grow up to wave base, and lagoons become quiescent compared to the early transgression. Eolian production continues, but produces dunes smaller than on the transgression as wave dynamics are less and sediment supply to the beach diminishes. At the end of the interglacial cycle, sea level regresses off the platform. In so doing, wave base passes through the accumulated lagoonal sediments, and another episode of eolianite production ensues, called *regressive-phase eolianites* (Carew and Mylroie 1995a; 1997). The transgressive-phase and regressive-phase eolianites therefore mark the beginning and end of each interglacial sea-level highstand, respectively.

It is important to bring up a cautionary note regarding regressive-phase eolianites. During the sea-level stillstand portion of a glacioeustatic sea-level highstand, strandplains can prograde into shallow lagoons, and eolianites can form on these strandplains. These are not true regressive-phase features, as sea level has not fallen. They are progradational. It can be difficult in the field to separate progradational eolianites from those formed by a true regression. In the first case, such eolianites

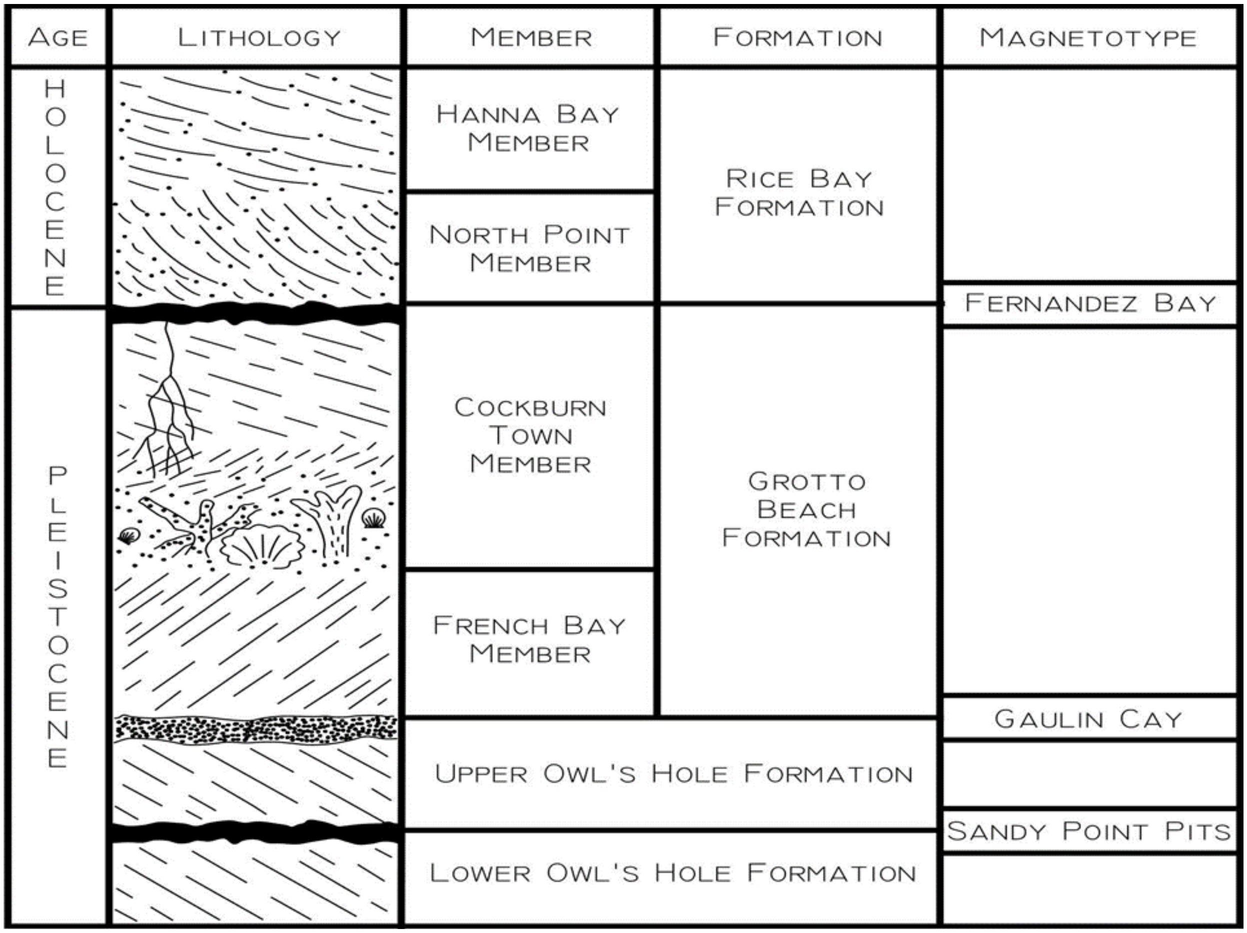

Figure 1: Simplified stratigraphic column for San Salvador, after Mylroie and Carew (2014). For a more detailed column, see Kindler et al. (2010).

will be found to overly beach sediments, which in turn overlie subtidal deposits, including coral reefs, with no evidence of a subaerial interval on top of the subtidal deposits. Such a progradational sequence can be seen at the Cockburn Town fossil reef on San Salvador Island. True regression would require evidence of a subaerial exposure between the subtidal facies and the entombing eolianite. Such evidence of regression can be seen at The Gulf on San Salvador Island. For these reasons, Carew and Mylroie (1995a; 1997) did not make a separate regressive-phase member within the Grotto Beach Formation, but included both progradational (sea-level stillstand) eolianites and regressive-phase eolianites (sea level falling) in the Cockburn Town Member, as only special field relationships can differentiate between the two. Such field relationships are rare, and the Carew and Mylroie (1995a; 1997) stratigraphy is designed to work in real time in the field.

Carew and Mylroie (1995a; 1997) developed a set of observational tools to determine if an eolianite was transgressive phase or regressive phase (Table 1). The top two of the criteria shown in Table 1 (inner dashed-line box in the table) are the degree of bedding disruption, and the abundance of vegemorphs. The term vegemorph is used here to indicate plant trace fossils such as root and stem casts. The terms rhizomorph and rhizolith are commonly used to identify these plant structures, but the term "rhizo" assumes a root origin, when stems and sometimes leaves are also preserved as trace fossils. The term vegemorph is inclusive and is used here, even though it is recognized that the

TABLE 1. PHASES OF DEPOSITION AND DIAGNOSTIC CHARACTERS

Transgressive Phase	Still-stand Phase	Regressive Phase
Fine-scale eolian bedding	Disrupted eolian bedding	Disrupted eolian bedding
Few vegemorphs	Abundant vegemorphs	Extensive vegemorphs
Penecontemporary cliffing and boulder paleotalus	Penecontemporary notching of beach and intertidal facies, and beach-face breccia facies	Lack of penecontemporary wave erosion
Penecontemporary sea caves	Rare sea caves	Lack of sea caves
Corals on wave-eroded benches	No corals on eroded benches	No penecontemporary benches
Lack of protosols	Protosols common	Protosols common
On lapped still-stand or regressive-phase deposits	Marine facies abundant	Commonly peleoidal/bioclastic
Predominantly eolianites, marine deposits rare	Ebb-tidal delta, lacustrine, and strand plain deposits	Eolianites overstepping marine deposits

most commonly observed plant trace fossil is from root structures, as would be expected from a preservational bias viewpoint. Carew and Mylroie (1995a; 1997) viewed the bedding disruption and vegemorph pattern as linked (Figure 2). If vegemorphs were abundant, then bioturbation of the eolian bedding by the root structures would occur high in the section, the trace fossils would form an ichnofabric (e.g. Drowser and Bottjer, 1989). The Carew and Mylroie (1995a; 1995b) model hypothesized that when the transgressive-phase eolianites formed, beaches had not yet had time to develop a full plant climax community (there had been no beaches on the platform for ~100 ka), and the dunes were only sparsely colonized by plants. When the regressive-phase eolianites formed, beaches had been present for ~10 ka, and the beach plant community was fully established. That plant community quickly colonized the regressive-phase eolianites, disrupting the upper section bedding and setting the stage for abundant preserved vegemorphs.

The Carew and Mylroie (1995a; 1997) list of criteria was solely observational and thereby somewhat subjective. No quantitative means for establishing an eolianite as transgressive phase or regressive phase had been established. The research presented here represents an attempt to create quantitative criteria to classify eolianites as transgressive phase or regressive phase based on the measurement of the actual vegemorph trace fossils present. The data presented here were developed as part of an unfinished master's thesis at Mississippi State University; the authors who all worked on the initial thesis project are using this venue as a means of placing the research into the Bahamian geologic community.

METHODS

Field work was conducted on San Salvador Island, The Bahamas in June and July 2008, and again during December 2008, and January 2009. During June and July 2008, numerous locations of outcrops throughout the island were investigated for the potential of measuring populations of plant trace fossils. After reconnaissance was complete, the plant trace fossils were measured at numerous locations throughout the island. These locations included both Pleistocene transgressive-phase and regressive-phase eolianites and Holocene transgressive-phase eolianites (there are as yet no regressive-phase Holocene eolianites in The Bahamas). All of the locations were examined thoroughly for the presence of plant traces prior to the determination of the best sites to retrieve data within a location. The fewest number of sites found to measure at a location was four at North Point. No less than four sites were measured at each location. The total number of measurements varied depending on the extent of the outcrop at a location and the presence of representative vegemorph populations. Further measurements were taken during December 2008, and January 2009. These measurements were primarily taken in order to fill any gaps in the data that were noticed during the preliminary analyses of the measurements from June and July 2008.

Two different types of plant traces were measured; casts and molds (Figure 3). The most abundant measurements were taken from the mold populations. These are 3-dimensional, bedding-plane penetrative traces that appear to most likely be root systems. They have been observed qualitatively to be most abundant in regressive-phase eolianite suites (Carew and Mylroie, 1995a; 1997). Casts (impressions in the bedrock) were also observed and measured at almost all of the studied locations. These are solely bedding-plane parallel and were observed to be relatively similar in abundance regardless of the depositional phase. It is most likely that these traces formed from the railroad vine, *Ipomoea pes-caprae,* or some similar species (Curran and White, 1987).

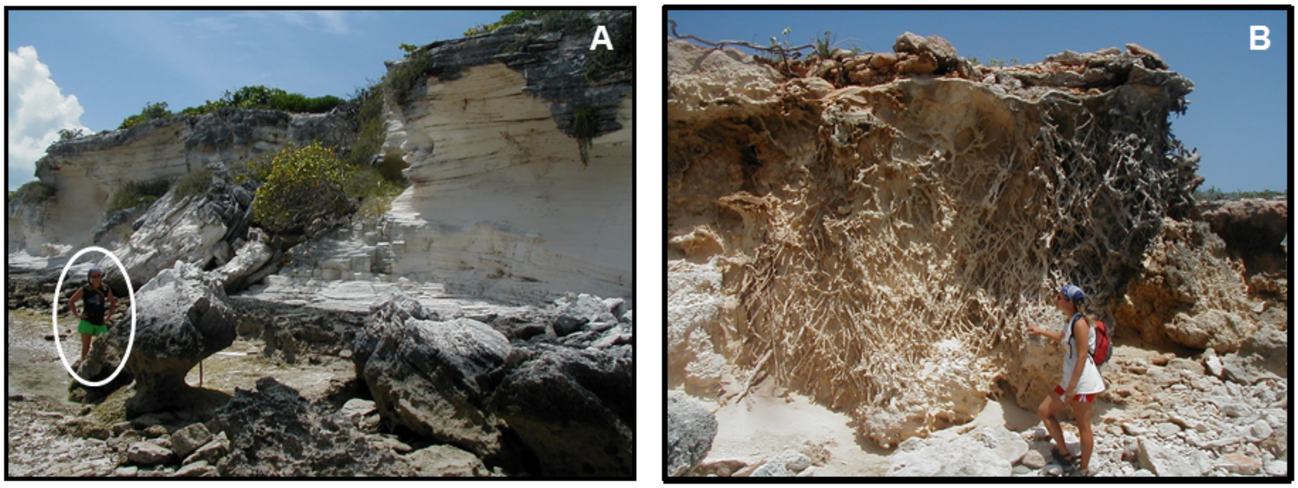

Figure 2: Comparison of transgressive-phase eolianites with regressive-phase eolianites, San Salvador Island, Bahamas. A) Holocene North Point Member of the Rice Bay Formation, Cut Cay. Fine-scale bedding can be followed from the water line up to the dune top, and vegemorphs are rare. These observations indicate a transgressive-phase eolianite (person on left in white oval for scale). B) Late Pleistocene Cockburn Town Member of the Grotto Beach Formation, Crab Cay. No bedding is visible, and vegemorphs are present though-out the entire outcrop exposure to create an ichnofabric. These observations indicate a regressive-phase eolianite (same person as in A for scale).

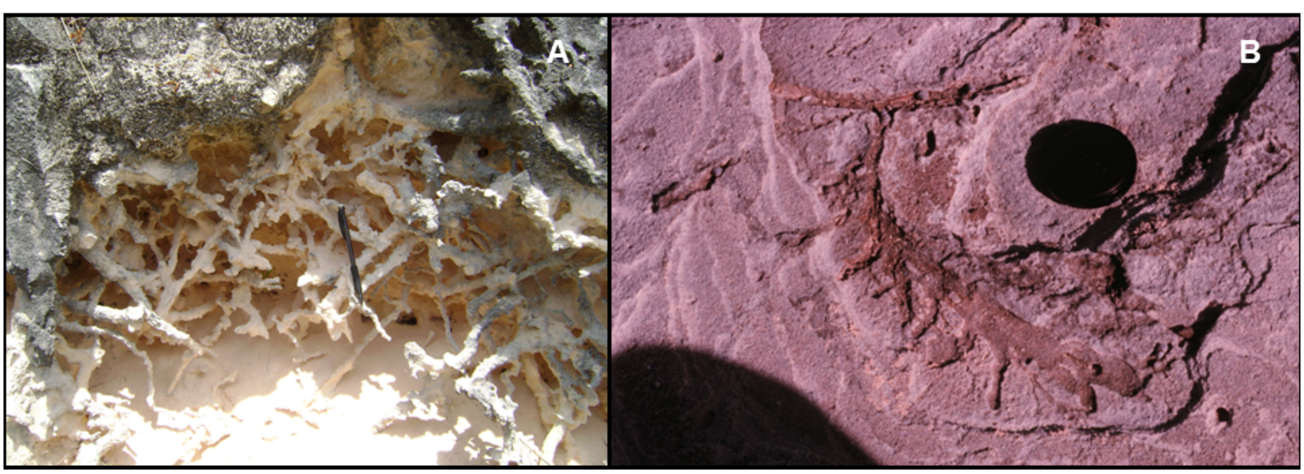

Figure 3: Vegemorph trace fossils, San Salvador Island, Bahamas. A) Molds of plant roots penetrating through bioturbated beds. Pencil, 13 cm long, for scale. B) Casts of plant stems, likely the railroad track vine, Ipomoea pes-caprae (Curran and White, 1987), along a bedding plane. Lens cap, 6 cm across, for scale.

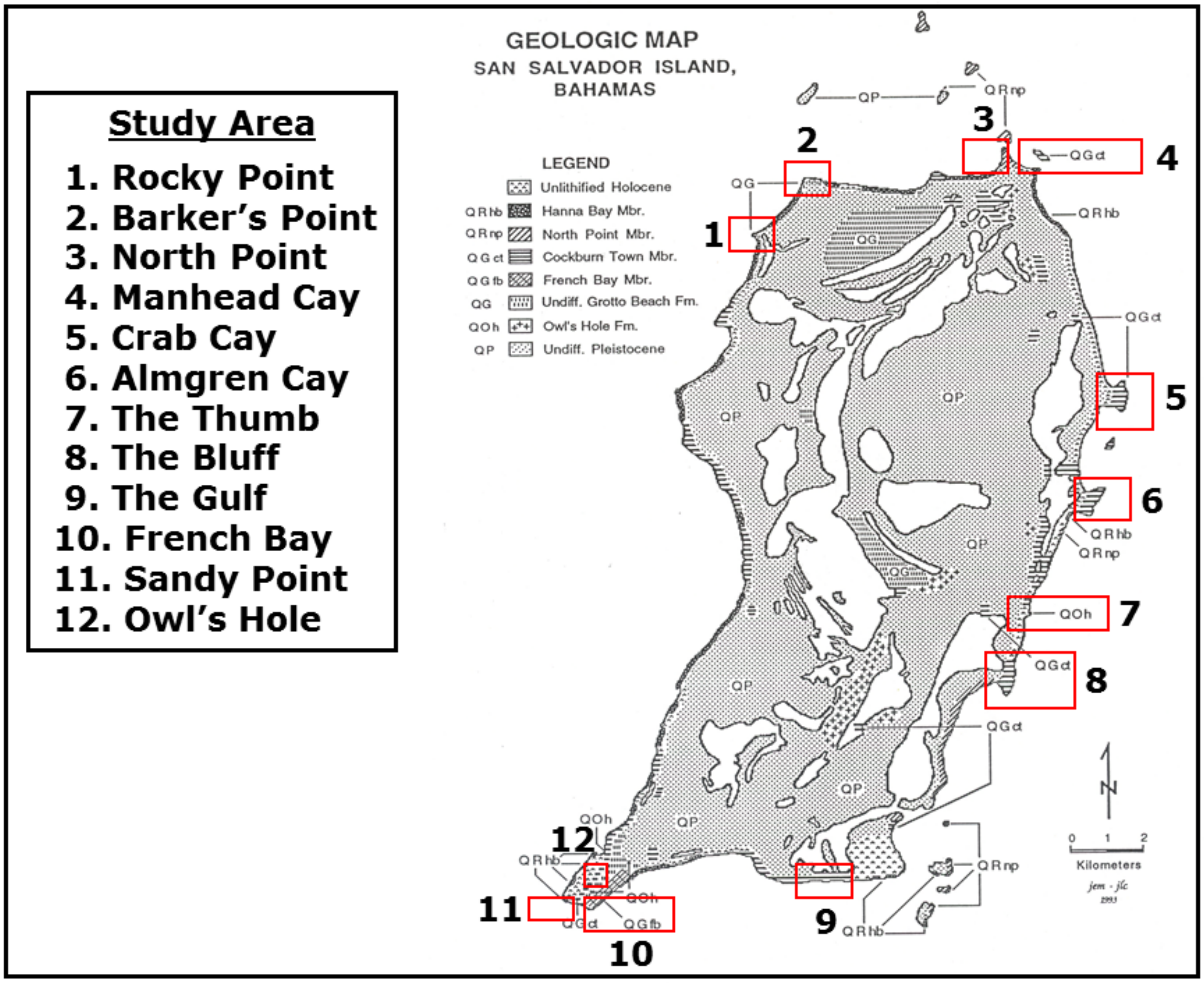

Figure 4: Map of San Salvador Island showing field locations for this study. Geology is based on Carew and Mylroie (1995a; 1997).

Study area

Data were collected from 12 locations on San Salvador (Figure 4). The locations were chosen according to whether or not they were accessible and whether or not the outcrops hosted populations of plant trace fossils. Representative samples were collected from the Pleistocene Owl's Hole Formation and Grotto Beach Formation, and the North Point Member of the Holocene Rice Bay Formation. No data were collected from the Hanna Bay Member of the Rice Bay Formation simply because no vegemorph root traces were found during reconnaissance.

Locations 7 (The Thumb) and 12 (Owl's Hole) are mapped as the Pleistocene Owl's Hole Formation. As stated earlier, there have been numerous attempts at dividing the Owl's Hole Formation into separate members or formations. The stratigraphic column (Figure 1) used for this study shows an Upper and Lower Owl's Hole Formation based on Panuska and coworkers' (1998) Sandy Point Pits Magnetotype; the more complete stratgraphic column of Kindler et al. (2010) depends on AAR data to assist eolian classification. There are few reliable ways to differentiate the Owl's Hole Formation in real time and no conclusive field indicators besides fortuitous areas where three or more separate paleosols can be seen, as at the previously mentioned Glass Window on Eleuthera. Data collected from the two Owl's Hole locations may provide further insight to separating at least areas of transgressive-phase versus regressive-phase deposits within that unit.

Locations 1 and 2 on the map are Rocky Point and Barker's Point. These two areas are both mapped as undifferentiated Pleistocene Grotto Beach Formation (Carew and Mylroie, 1995; 1997). Location 10 is the type section for the French Bay Member of the Upper Pleistocene Grotto Beach Formation. This is a transgressive-phase eolianite dune suite. Plant trace populations are visually less dense than that of most known Cockburn Town Member eolianites. Locations 4, 5, 6, 8, 9 and 11 are mapped as Cockburn Town Member of the Grotto Beach Formation. These outcrops represent regressive-phase eolianite dune suites. The eolianite dunes overlie fossil reef and underlie a terra rossa paleosol in many places, indicating that they are indeed part of the Cockburn Town Member.

Location 3 represents the type section of the North Point Member of the Rice Bay Formation. The North Point Member is differentiated from the overlying Hanna Bay Member in that its foreset beds dip below modern sea level. Both units are recognizable in the field as Holocene in age as they lack a terra rossa paleosol, indicating too little time to collect the aerosol dust from the Sahara that contains the iron oxides that give those paleosols their red color (Foos, 1987). The ^{14}C data confirm the age of the North Point Member rocks to be mid-Holocene in age (Carew and Mylroie, 1995a; 1997). The North Point Member is obviously a transgressive-phase eolianite sequence due to the fact that there has not yet been a regression during the Holocene, and that the stillstand did not occur until ~3 ka, two thousand years after the North Point Member was deposited at ~5 ka (Carew and Mylroie, 1995a; 1997).

Data collection

Each of the 12 locations was investigated prior to any measurements or data collection. Sites for data collection were determined at each location based on the presence or absence of plant trace fossils, the level of preservation or lack thereof, and accessibility. Crab Cay and French Bay were the most extensively measured outcrops with 10 measurements each of 3-dimensional (3-D) trace populations. As the French Bay Member has been mapped as MIS 5e transgressive-phase, and Crab Cay of the Cockburn Town Member as MIS 5e regressive phase (Carew and Mylroie, 1995a, 1997), the expanded collection regime offered a good comparison suite of last interglacial sample data. Data taken were the compass orientation of the quadrat, strike and dip of local eolian bedding, and thorough descriptions of the local bedding features, fossil characteristics, and other geologic features at each site. Also measured at each location were the aforementioned bedding parallel trace fossils that seemed to be similar regardless of depositional history (Figure 3B). These measurements were treated as a separate data set for later analysis, which is not reported here.

North Point and Sandy Point were the least measured with 4 sites. North Point had fewer measurements due to the lack of plant trace populations (not unexpected given its transgressive nature and its young age). There were also fewer measurements at Sandy Point because it is a very small area of outcrop. Most of the other locations consisted of approximately 5 to 6 sample sites each.

The goal was to establish a simple, field-based methodology that would allow assessment of the vegemorph abundance while field operations were on-going, and from that assessment, determine if the eolianite unit was transgressive or regressive phase as defined by Carew and Mylroie (1995a; 1997). A variety of measurements were considered. Vegemorph diameter and vegemorph length were investigated, but determined to be in part controlled by later diagenesis and preservational bias, and so were not utilized. The number and spacing of vegemorphs was interpreted to be a measure of vegemorph abundance, and a technique to do such a data collection regime was designed

Data collection was conducted at each site using a 50 cm x 50 cm quadrat and a tape measure

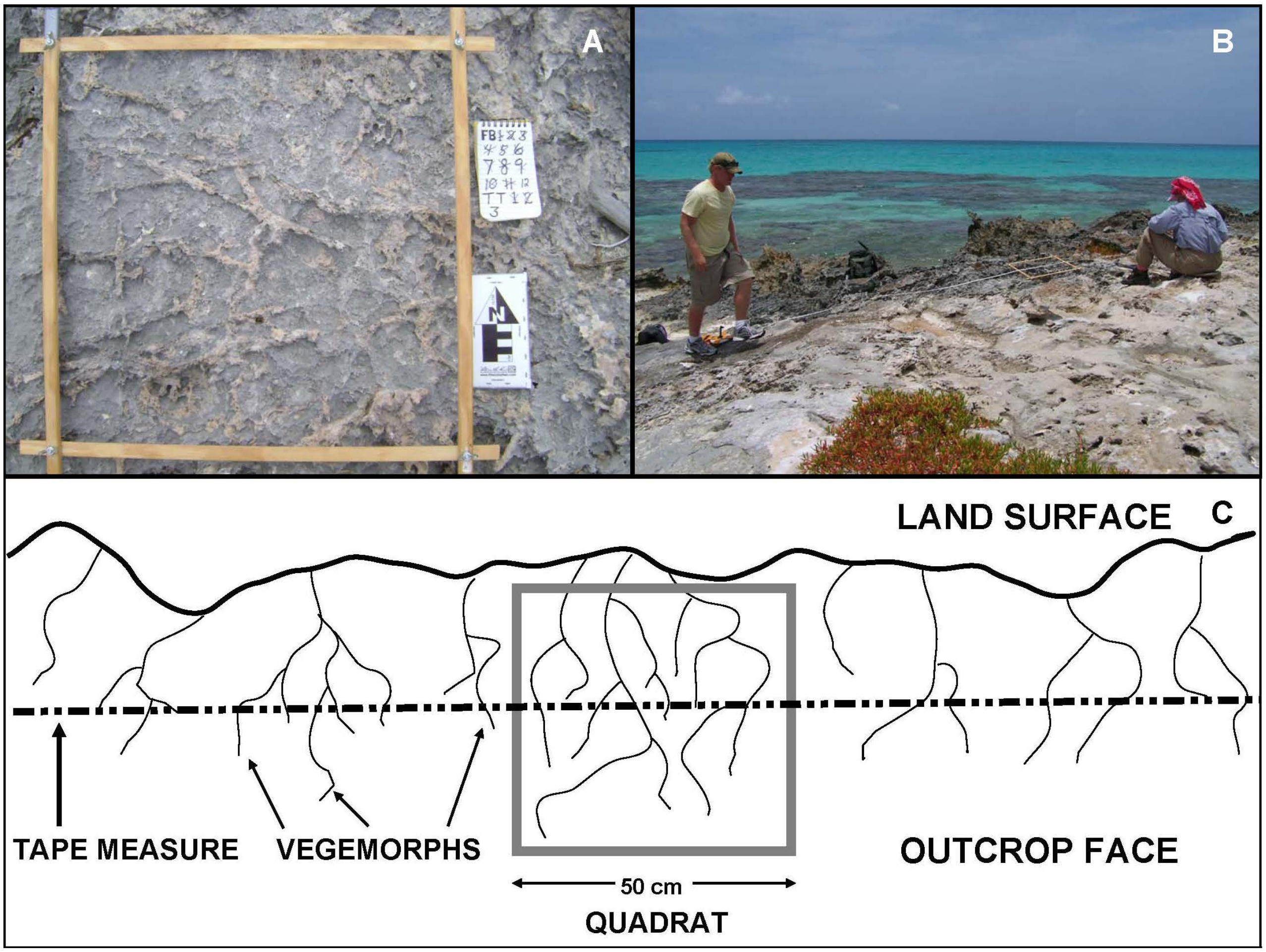

Figure 5: Vegemorph data collection. A) 50 cm x 50 cm quadrat placed over vegemorphs at their locally most visually dense concentration. Notebook was used to show site identity, scale bar is 6 cm long on its long axis. B) View showing a tape measure stretched out along the outcrop, centered on the quadrat to determine how vegemorph spacing changes with distance from the area of highest vegemorph concentration. C) Cartoon to show how the quadrat was placed at the densest vegemorph location, and how the tape measure was extended through the quadrat center to 20 m out on each side, or the edge of the outcrop, which ever came first. Each vegemorph intersection was recorded as a distance from the quadrat center.

(Figure 5). The quadrat was placed at each site where traces were visually most abundant or densest. This was typically at the top of the outcrop, as the vegemorph traces resemble a fibrous root system that is most dense toward the soil surface (in this case, a red-colored terra rossa paleosol or a white protosol). A picture was taken of the quadrat at each site with the location name, site number, and scale in the photograph (Figure 5A). A tape measure was then used to mark each occurrence of a plant trace fossil (Figure 5B), beginning in the center of the quadrat and continuing through the quadrat to the edge of the outcrop, or 20 m, which ever came first. The tape measure was consistently oriented so that it ran through the middle of the quadrat and along the section provided by the outcrop. Each occurrence of a vegemorph was recorded as a distance from the quadrat center moving along the tape measure (Figure 5C), using the center of the vegemorph as the measurement point.

The tape entrance and exit points on the quadrat were also recorded for later statistical use. This technique created both a total number of intersections of the tape with the vegemorphs, and the spacing, or interval, between them. This interval value could be averaged for the width of the outcrop, important as many outcrops had a width less than the 20 m measurement distance from each side of the quadrat.

Statistical analyses

Field data were entered into spreadsheets in two separate ways. The interval or spacing between each successive vegemorph trace was entered along with the distance from center for each vegemorph site at each location. The intervals for each site at each location were then averaged. The data were also entered into two other, separate spreadsheets as number of counts per 10 cm and number of counts per 25 cm. These data simply represent the number of observances within a fixed distance from start to finish.

In order to test the hypothesis that the populations of plant traces measured in transgressive-phase and regressive-phase deposits are in fact different, one-way analysis of variance (ANOVA) of the interval spacing data was conducted. The assumptions for all ANOVA tests are that observations are independent both within and between samples, variance is homogeneous in all samples, data are normally distributed, and observations are assigned to groups using one or more factors.

First, the Kolnogorov-Smirnov Test for goodness of fit for continuous data was used to test whether the data sets from each location in the study area were normally distributed. Next, the homogeneity of variance among all samples was determined using Levene's test for equal variance. The homogeneity of variance among the samples determined which post-hoc analyses would be used to compare the means from the different locations. In cases where variance was determined to be homogeneous, the Bonferroni Test was used. In cases where variance was not homogeneous, the Tamhane's T2 test was used. The Tamhane's T2 test is a more conservative ANOVA test that is appropriate when variances are unequal or when variances and group sizes are unequal.

After the assumptions for performing a comparison of means using ANOVA were met, several hypotheses were tested:

1. Populations from regressive eolianites are the same.
2. Populations from transgressive eolianites are the same.
3. Populations from transgressive and regressive eolianites are different.

The data were also used to attempt to answer other questions:

1. Is there a difference among populations from Pleistocene and Holocene deposits?
2. Can the data be used to determine where Rocky Point and Barker's Point fit within the Grotto Beach Formation or Owl's Hole Formation?
3. Can the data be used to differentiate the Owl's Hole Formation into separate, transgressive and regressive phases?

The ANOVA tests were performed for both the overall interval spacing length averages among locations as well as the averages that were obtained from measurements solely within the quadrat. This was done in part to see whether the populations were the same or different when measured at their most dense areas. The results of these tests were also used to help set a specific distance to which one should measure in order to get a representative sample that can accurately distinguish dune suites based on the population of plant trace fossils.

Interval spacing was then plotted against distance from the starting point of measurement for each site at each location. Linear Regression was performed for each location and trendlines were added to each plot showing the formula (y=mx+b), R^2-values, and p-values. This was done to try and show any disparity among the trendlines between the transgressive-phase locations and regressive-phase locations. In the field, it was observed and noted that regressive-phase populations such as at Crab Cay and The Gulf tended to maintain uniformity in interval spacing of successive fossils even when measured far from the starting point. Populations observed in transgressive-phase deposits such as at French Bay seemed to become much more spread out the farther the measurements strayed from the starting point. The difference in the curves also aided in the determination of a proper distance of measurement needed to get a representative sample.

Graphs plotting distance versus the total number of counts were created for the 10 cm count data. These graphs were planned to reveal a trend among transgressive-phase and regressive-phase plant trace populations. In transgressive-phase eolianites, where plant traces are sparse, the total count of observations should not go up much as distance is increased. In regressive-phase eolianites, where populations are dense and extensive, the total count of observations should trend toward a more dramatic increase as distance increases.

The quadrat photographs from each site were used to apply the Droser and Bottjer (1986) Ichnofabric Index to determine which indices fit for each site. The results were then analyzed to determine which index or range of indices fit best for each location. The final step in this process was to assign indices to both transgressive-phase and regressive-phase dune suites as a whole. That work was never completed.

RESULTS

The extent of plant trace fossils, or vegemorphs, in The Bahamas has been documented observationally on San Salvador and other Bahamian Islands: New Providence Island (Carew et al., 1996; Mylroie et al., 2012), South Andros Island (Carew et al., 1998), Eleuthera Island (Panuska et al., 2002; Kindler et al., 2010), Long Island (Curran et al., 2004), Cat Island (Mylroie et al., 2006) and Rum Cay (Mylroie et al., 2008). The model has also been used successfully on Abaco Island (Walker et al., 2008). Qualitatively, it seems that vegemorphs are more abundant in regressive-phase eolianite dune suites than in transgressive-phase eolian dune suites (Carew and Mylroie 1995; 1997). However, in some locations there are quantities that are not of this observational norm and confusion can occur. The results of this study should not only prove that there is a difference between the populations observed within transgressive and regressive eolianites, but also establish a method of determining this difference in the field. Because the MSc thesis was never finished, not all the data applications mentioned in the methods section were completed. Presented below is what can be confirmed from the work.

Statistical analyses

Interval spacing

Interval spacing data were derived from the original measurements in the field that noted each occurrence along a measuring tape at a given site. Each site yielded total measurements, and measurements taken within the 50 cm quadrat. The intervals were averaged for each site at each location for both the total average and the 50-cm-quadrat average interval spacing. The averages from each site were then averaged for a total average from each location. Figure 6 shows the total averages and the 50-cm-quadrat averages for each location.

Figure 6 shows that many of the known regressive-phase eolianite locations such as Crab Cay and The Gulf have average intervals that persist throughout the entire length of measure. That is, the 50-cm-quadrat interval average is approximately the same as the total length average. Some of the total lengths measured are up to 40 m. On the other hand, transgressive-phase deposits such as North Point and French Bay have average intervals that are much less at the 50-cm-quadrat length than the total length interval average. Figure 6 shows this result as a percentage. This approach is important because it determines that one must measure the full length of a population in order to be able to clearly distinguish between transgressive-phase and regressive-phase plant trace fossil populations. For instance, if only a 50-cm-quadrat length is measured for a transgressive-phase population, an accurate representation of the data

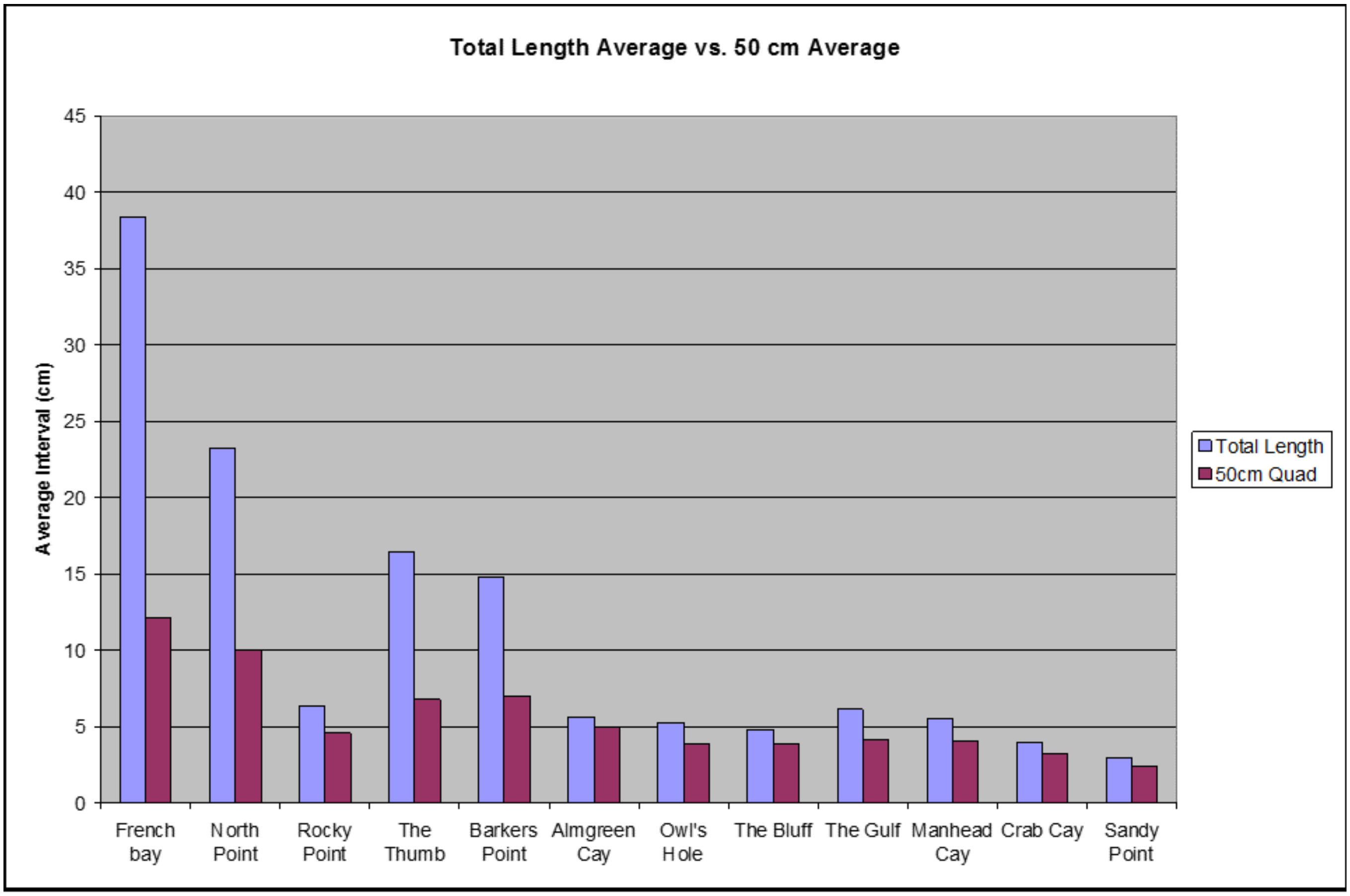

Figure 6. Bar graph plot of total length average and 50-cm-qudrat length average for all 12 sites. The vertical axis is percentage, to normalize different total lengths of measurement within each site. Known transgressive-phase eolianites, French Bay and North Point, show a large disparity between the two length averages, indicating vegemorph abundance decreases away from the center of highest concentration. The Bluff, The Gulf, Manhead Cay, Crab Cay and Sandy Point, all known regressive-phase eolianites, show equivalency between the two length averages, indicating a constant vegemorph density across the transect. Barkers Point and Rocky Point, unclassified at the time of the study, seem to fall into the transgressive-phase and regressive-phase categories, respectively.

would not be retrieved and the dune suite may not be correctly classified as a transgressive-phase versus a regressive-phase deposit.

One-way ANOVA tests were then performed for both the total average intervals and the 50-cm-quadrat average intervals. As previously stated, the conditions for the use of an ANOVA test are that the data are normally distributed and homogeneous in variance. To test whether or not the data was normally distributed, the Kolmogorov-Smirnov Test (K-S test) was used. The K-S test gives 2 tailed p-values that indicate whether or not the data are normally distributed. The null hypothesis was that the distribution of data is not significantly (p value < 0.05) different from normal. The results show that the null hypothesis that the data are not significantly different from normal can be accepted for each location.

In order to meet the condition of homogeneity in variance, the Levene test for variance was used. The null hypothesis is that the population variances are not significantly different and will be rejected if the p value is less than 0.05. The results show that for both the total interval average and the

50-cm-quadrat interval average data the variances are in fact heterogeneous as p-values are less than 0.05 and the null hypothesis that the population variances are equal can be rejected.

The two conditions for ANOVA were tested for. The condition that the data are normally distributed checked out. However, the variance between populations was proven to be heterogeneous. Because the variance between populations was heterogeneous a more conservative ANOVA test known as the Tamhane's T2 test was used. This test is often used when populations are either heterogeneous with respect to variance or when population group sizes (number of sites in this case) are unequal. The null hypothesis was that the means from all of the locations are the same. This would only be rejected for p values less than 0.05 at the 95% confidence interval. This analysis was used to compare both the means among locations from the total interval counts and the 50-cm-quadrat interval counts. The comparison of the means obtained from averaging the interval spacing from observation to observation has shown that there is significant difference among some of the populations. The most important difference that the results show is that the transgressive-phase eolianite location of French Bay is in fact significantly different than all other locations except for North Point which is also a transgressive-phase deposit. However, the results of the test are quite conservative because the variance among populations was different and the conservative Tamhane's T2 test had to be used.

Next, the interval data from each station at each location were plotted against distance from the measurement starting point. The data from all stations at each location were then combined and scatter plots were created for each location to show any trends in variability in interval spacing as distance increases (Figures 7). A trendline representing the average interval spacing for each location was also added to each chart to show how far individual measurements strayed from this average. Because populations of plant traces are more dense in regressive-phase deposits than in transgressive-phase deposits, scatter plots from locations measured in regressive-phase eolianites should not stray as far from the average interval as locations from transgressive-phase eolianites. Figure 7 shows data from transgressive-phase deposits at North Point and from regressive-phase deposits at Almgreen Cay. Figure 8 shows data from undifferentiated Pleistocene deposits at Barkers Point and Rocky Point, indicating that they are transgressive-phase and regressive-phase, respectively. The data are less compelling than for Figure 7, and reflect the reason for their initial classification as undifferentiated by Carew and Mylroie (1995a; 1997). Simple visual assessment of these outcrops was insufficient at the time of the original field work, but measurements demonstrate an actual difference that can be compared to known examples, as displayed by Figure 7.

The interval versus distance scatter plots show that the interval spacing between successive plant traces varies with distance as measurements are taken further from the starting point. It seems that in regressive-phase eolianites, the change in interval spacing with distance is less pronounced than in transgressive-phase eolianites (Figure 7). In this case, the starting point is at, or close to, the top of the population as viewed in outcrop. This was done because one would expect a root population to thin out deeper underground. In most cases, observances were very dense up-section and less dense down-section and sometimes draped by a terra rossa paleosol.

10 cm counts

The 10-cm-count data are simply the amount of plant traces that were observed every 10 cm until the end of the measurement. These counts were then averaged for each station at each location and then the total average for each location was calculated in order to perform an ANOVA test to compare the means among the locations. The 10 cm counts were used as another measure for determining any significant difference among populations of plant traces between the different locations. The Figure 9 shows the total average counts from each location.

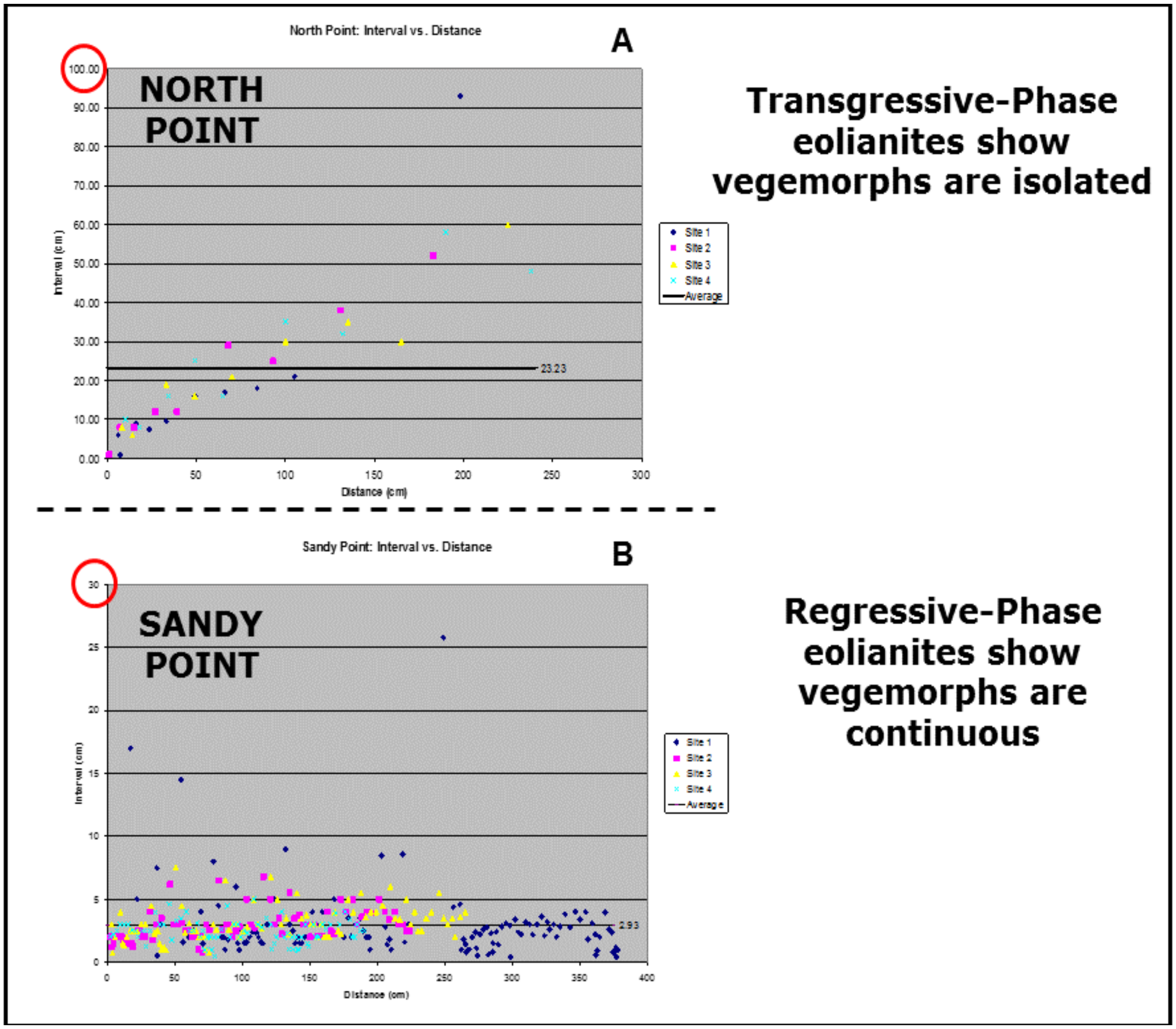

Figure 7: Plot of interval distance (vertical axis) between individual vegemorphs versus distance from the quadrat (horizontal axis). A) Plot for North Point, showing a continuing increase in separation interval or spacing of vegemorphs as distance from the quadrat increases, a key identifier of transgressive-phase eolianites. Average separation distance is 23.23 cm (horizontal black line). B) Plot for Sandy Point, showing compact and low separation interval or spacing of vegemorphs as distance from the quadrat increases, a key identifier of regressive-phase eolianites. Average separation distance is 2.93 cm (horizontal black line). Red circles show that the vertical scale on each plot is different (100 cm for A and 30 cm for B, respectively).

Again, for the ANOVA to be conducted the data must be normally distributed and variances between the data sets must be homogeneous. The Kolmogorov-Smirnov (K-S) test for goodness of fit for continuous data was again used to verify a normal distribution. The K-S test gives 2 tailed p-values that indicate whether or not the data is normally distributed. The null hypothesis was that the distribution of data is not significantly (p value < 0.05) different from normal. That is, if p-values are less than 0.05, the null hypothesis is rejected and the data are not normally distributed. The results show that the null hypothesis that the data are not significantly different from normal can be accepted for each location. The Levene Test for equality among variances was then used again to test for homogeneity. The null hypothesis was that the populations variances are not significantly different ($p < 0.05$). Resulting p-values that are less than 0.05 indicated that the null hypothesis is rejected and the data do not share homogeneous variances.

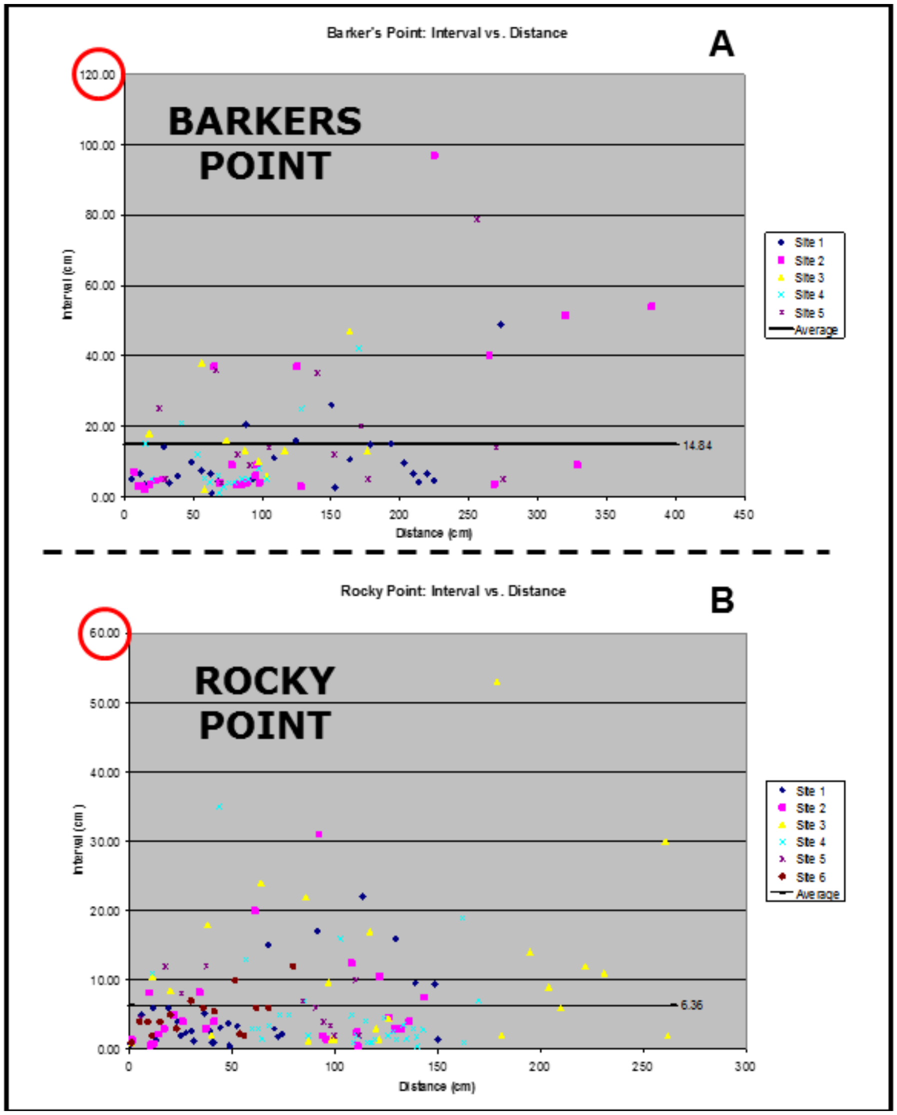

Figure 8: Plot of interval between individual vegemorphs versus distance from the quadrat; axes as in Figure 7. A) Plot for Barkers Point, showing an apparent continuing increase in separation interval or spacing of vegemorphs as distance from the quadrat increases. Average separation distance is 14.84 cm (horizontal black line). B) Plot for Rocky Point showing a smaller increase in separation interval or spacing of vegemorphs as distance from the quadrat increases. Average separation distance is 6.36 cm (horizontal black line). Red circles show that the vertical scale on each plot is different (120 cm for A and 60 cm for B, respectively). The data suggest that Barkers Point is transgressive-phase, and that Rocky Point is regressive-phase, but the data are less compelling than that shown in Figure 7, and reflects why these outcrops were left undifferentiated during the Carew and Mylroie (1995;1997) field work.

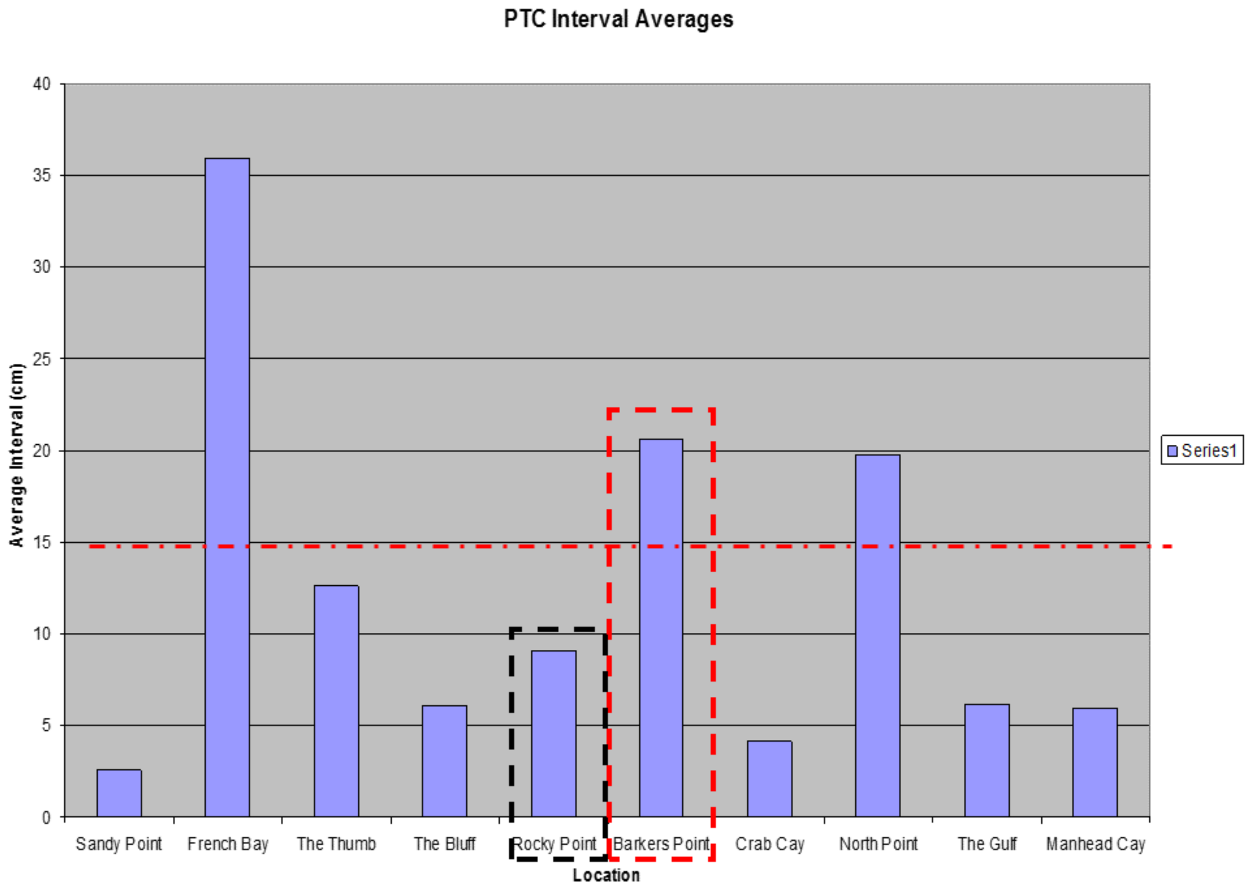

Figure 9: Bar graph of 10 of the 12 locations (Owl's Hole not studied, Almgren Cay not shown due to similarity with other regressive-phase sites, see Figure 6). Picking a 15-cm-average spacing interval for vegemorphs (dashed-dotted horizontal line), the eolian outcrops fall into two classifications: above 15 cm, trangressive phase; below 15 cm, regressive phase. Dashed boxes indicate undifferentiated eolianites from Barkers Point and Rocky Point, classified for the first time into transgressive phase and regressive phase, respectively. The Thumb, based on other criteria (Mylroie and Carew 2014) has been classified as regressive phase; however, it is close to the 15 cm cutoff (for example, the cutoff could be set at 12 cm and The Thumb would be included but not any of the regressive phase examples).

Just as was the case with the interval spacing data, the 10 cm data are normally distributed but are not homogeneous with respect to variance. Thus, the more conservative Tamhanes T2 ANOVA test must be used to compare the means from the data set. The null hypothesis was that the means from all of the locations are the same. This would only be rejected for p-values less than 0.05 at the 95% confidence interval. This analysis was used to compare both the means among locations from the total interval counts and the 50-cm-quadrat interval counts. The 10 cm ANOVA test results show more significant difference among the locations than the interval spacing results showed. Most importantly it shows that the known regressive deposit locations of Crab Cay, Almgreen Cay, and Sandy Point are all significantly different from the two known transgressive deposit locations of North Point and French Bay (Figure 9).

DISCUSSION

The data show that measurements of vegemorph abundance and spacing in Bahamian eolianite outcrops can be used as a quantitative tool to differentiate transgressive-phase eolianites from regressive-phase eolianites. Outcrops previously mapped by Carew and Mylroie (1995a; 1997) as transgressive or regressive phase using a variety of criteria (Table 1) were shown to be identifiable using solely vegemorph data. These results have bearing on a question in Bahamian stratigraphy involving an interpretation that some of the deposits mapped by Carew and Mylroie (1995a; 1997) as regressive phase eolianites of the Cockburn Town Member of the Grotto Beach Formation. Based on AAR results, Hearty and Kindler (1993) mapped the units at Crab Cay, Almgren Cay, and The Bluff as MIS 5a, approximately 85 ka in age. The issue is fully discussed in Chapter 3 of Vacher and Quinn (1997), with presentations by workers on both sides of the issue. Regardless of the actual stratigraphic position, the vegemorph data indicate that these units are clearly different from transgressive-phase units, be they either Pleistocene in age (French Bay Member of the Grotto Beach Formation) or Holocene in age (North Point Member of the Rice Bay Formation). As noted earlier, the outcrop at The Gulf also falls in the regressive-phase position. That outcrop shows the eolianites have been deposited on top of a MIS 5e reef of the Cockburn Town Member (Mylroie and Carew, 2014). Between the two units is a calcarenite protosol, indicative of a short time of subaerial exposure (<2 ka), as opposed to the terra rossa paleosol that forms from long exposure (>10 ka). The vegemorph data indicates that The Gulf is regressive phase; given that it overlies a MIS 5e fossil reef without a long-term time of subaerial exposure before being buried by the eolianite eliminates MIS 5a as a stratigraphic option. By extension, Crab Cay, Almgren Cay, and The Bluff are also MIS 5e regressive-phase deposits; i.e. Cockburn Town Member of the Grotto Beach Formation. There remains the chance that Crab Cay, Almgren Cay, and The Bluff are MIS 5a regressive phase, but if so, no MIS 5a transgressive-phase eolianites have yet been identified.

The vegemorph data also allow two undifferentiated outcrops to be classified. Barkers Point fits the criteria for transgressive-phase eolianites, and Rocky Point fits the criteria for regressive-phase eolianites. Both of these outcrops are important, as they sit on the northwest side of San Salvador (Figure 4). This part of San Salvador displays a pattern of wind from the northwest in the interior dune structure (Figure 4), whereas the dunes on the east and central part of San Salvador show wind direction from the east (trade winds or easterlies). The northwest wind pattern associated with the Barkers Point and Rocky Point outcrops is thought to be the result of winter storms that come off the North American continent (Carew and Mylroie, 1995a; 1997). It is important that these two sites show the transgressive-phase and regressive-phase couplet of eolianite generation seen elsewhere on the island, independent of wind direction. On the east coast, the outcrop at The Thumb displays the highest vegemorph spacing interval of any regressive-phase eolianite. It is the only Owl's Hole unit in the data base (Owl's Hole itself was not used as the limited space within that pit cave did not allow for a long enough outcrop width for proper analysis), so it is not known if this spacing value is diagnostic of the Owl's Hole regressive-phase eolianites.

The data of Figure 9 suggest that a vegemorph spacing interval average of 15 cm separates transgressive-phase eolianites (>15 cm) from regressive-phase eolianites (<15 cm). If this relationship is truly valid, it means that workers in the field, after a few minutes of taking measurements and creating an average, can properly classify eolianites in terms of formation on the transgression or the regression. These results are preliminary, being restricted to the study of a few outcrops on a single island. San Salvador was an excellent choice for such a preliminary study, as the large amount of geologic data collected there over the years by many workers allowed a better characterization of the eolianites prior to the study. These factors give the authors' confidence that the tool is valid and useable. Given that outcrops similar to those found on San Salvador are common over the entire Bahamian archipelago, it may prove a useful tool for bracketing transgressive-phase and regressive-phase eolianite depositional events during the interglacial cycles of the Quaternary.

CONCLUSIONS

A study of vegemorph abundance and spacing in Quaternary eolianites of The Bahamas allows differentiation of trangressive-phase eolianites from regressive-phase eolianites while in the field. In particular, an average vegemorph spacing distance of 15 cm separates transgressive-phase eolianites (>15 cm) from regressive-phase eolianites (<15 cm). Two outcrops of previously unknown classification, Barkers Point and Rocky Point on San Salvador Island, are now shown to be transgressive phase and regressive phase, respectively. Their location on a portion of the island displaying influence by northwesterly winds demonstrates that the transgressive-phase to regressive-phase couplet pattern holds true independent of wind direction. Using vegemorphs may assist in determining when eolianites on other Bahamian islands formed during each interglacial sea-level highstand. The work may also be applicable to other Quaternary eolianite locations, such as Bermuda in the North Atlantic, or Rottnest and Kangeroo Islands off the Australian coast.

ACKNOWLEDGEMENTS

The authors thank the Gerace Research Centre for logistical and technical assistance, and for the research permit, G-102, under which the work was done. Permission to visit private lands on San Salvador is greatly appreciated. The authors also thank the many geologists who have worked on San Salvador to provide the geological background that made this work possible. Thanks go in particular to Jim Carew and Al Curran.

REFERENCES CITED

Carew, J.L., and Mylroie, J.E. 1995a. A stratigraphic and depositional model for the Bahama Islands. Pp. 5-31. In H.A. Curran and B. White (Eds.). *Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda.* Geological Society of America Special Paper 300.

Carew, J.L., and Mylroie, J.E. 1995b. Quaternary tectonic Stability of the Bahamian Archipelago: Evidence from fossil coral reefs and flank margin caves. *Quaternary Science Reviews* 14: 144-153.

Carew, J.L., Curran, H.A., Mylroie, J.E., Sealey, N.E., and White, B. 1996. *Field Guide to Sites of Geological Interest, Western New Providence Island, Bahamas*. Bahamian Field Station, San Salvador Island, Bahamas, 36 p.

Carew, J.L. and Mylroie, J.E. 1997. Geology of the Bahamas. Pp. 91-139. In H.L. Vacher and T.M. Quinn (Eds.). *Geology and Hydrogeology of Carbonate Islands.* Elsevier Science Publishers.

Curran, H.A. and White, B. 1987. Trace fossils in carbonate upper beach rocks and eolianites: Recognition of the backshore to dune transition. Pp. 242-254. In H.A. Curran and B. White (Eds.). *Proceedings of the 3rd Symposium on the Geology of the Bahamas.* CCFL Bahamian Field Station, Ft Lauderdale, FL.

Curran, H.A., Mylroie, J.E., Gamble, D.W., Wilson, M.A., Davis, R.L., Sealey, N.E., and Voegeli, V.J. 2004. *Geology of Long Island Bahamas: A Field Trip Guide.* Gerace Research Centre, San Salvador Island, The Bahamas, 24 p.

Droser, M.L. and Bottjer, D.J. 1986. A semiquantitative field classification of ichnofabric. J*ournal of Sedimentary Petrology* 56: 558-569

Foos, A. 1987. Paleoclimatic interpretation of paleosols on San Salvador Island, Bahamas. Pp. 67-72.

In H.A. Curran and B. White (Eds.). *Proceedings of the 3rd Symposium on the Geology of the Bahamas.* CCFL Bahamian Field Station, Ft Lauderdale, FL.

Hearty, P.J. and Kindler, P. 1993. New perspectives on Bahamian geology: San Salvador Island, Bahamas. *Journal of Coastal Research* 9: 577-594.

Kindler, P., Mylroie J.E., Curran , H.A., Carew, J.L., Gamble, D.W., Rothfus, T.A., Savarese, M., and Sealey, N.E. 2010. *Geology of Central Eleuthera, Bahamas: A Field Trip Guide.* Gerace Research Centre, San Salvador Bahamas, 74 p.

Mylroie, J.E., Carew, J.L., Curran, H.A., Freile, D., Sealey, N.E., and Voegeli, V.J. 2006. *Geology of Cat Island, Bahamas: A Field Trip Guide.* Gerace Research Centre, San Salvador Island, The Bahamas, 43 p.

Mylroie, J.E., Carew, J.L., Curran, H.A., Martin, J.B., Rothfus, T.A., Sealey, N.E., and Siewers, F.D. 2008. *Geology of Rum Cay, Bahamas: A Field Trip Guide.* Gerace Research Centre, San Salvador Island, The Bahamas, 59 p.

Mylroie J.E., Carew, J.L., Curran , H.A., Godefroid, F.M., Kindler, P., and Sealey, N.E. 2012. *Geology of New Providence Island, Bahamas: A Field Trip Guide.* Gerace Research Centre, San Salvador, The Bahamas, 57 p.

Mylroie J.E. and Carew J.C. 2014. *Field Guide to the Geology and Karst Geomorphology of San Salvador Island.* Gerace Research Centre, San Salvador Island, 90 p.

Mylroie, J.E. and Mylroie, J.R. 2017. The role of karst denudation on accurate assessment of glacioeustasy and tectonic uplift on carbonate coasts, In M. Parise, F. Gabrovsek, G. Kaufmann, and N. Ravbar. (Eds). *Advances in Karst Research: Theory, Fieldwork, and Applications*, Geological Society, London, Special Publication 466, https://doi.org/10.1144/SP466.2

Panuska, B.C., Mylroie, J.E., and Carew, J.L. 1999. Paleomagnetic evidence for three Pleistocene paleosols on San Salvador Island. Pp. 93-100. In H.A. Curran and J.E. Mylroie (Eds.). *Proceedings of the Ninth Symposium on the Geology of the Bahamas and Other Carbonate Regions,* Bahamian Field Station, San Salvador Island, Bahamas.

Panuska, B.C., Boardman, M.R., Carew, J.L., Mylroie, J.E., Sealey, N.E., and Voegeli, V. 2002. Eleuthera Island Field Trip Guide, *Eleven Symposium on the Geology of the Bahamas and Other Carbonate Regions.* Gerace Research Center, San Salvador Island, The Bahamas, 20 p.

Vacher, H.L, and Quinn, T., 1997, *Geology and Hydrogeology of Carbonate Islands,* Elsevier Science Publishers.

Walker, L.N., Mylroie, J.E., Walker, A.D., and Mylroie, J.R. 2008. The Caves of Abaco Island, Bahamas: Keys to Geologic Timelines. *Journal of Cave and Karst Studies* 70: 108-119.