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FORAMINIFERA IN BEACH DEPOSITS OF SAN SALVADOR ISLAND, THE BAHAMAS

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ABSTRACT

Beach sands were sampled for microfossil analysis along the isolated Bahamian carbonate platform of San Salvador Island in an effort to assess and explain spatial variances in foraminiferal content. This preliminary survey work, conducted at the suborder taxonomic level, was performed to aid future paleoenvironmental research efforts by addressing general distribution trends in relation to geographic variables. Shoreline deposits of San Salvador predominantly contain calcareous tests of shallow-water benthic foraminifera of the Miliolina and Rotaliina suborders. Spatial changes in suborder ratio are discussed in context of coastal geologic framework and beach-sediment texture. Sediment texture and microfossil content should reflect hydrodynamic and sediment-sourcing regimes. The Miliolina suborder dominates the island-wide beach assemblage, comprising over 75% of picked individuals. However, suborder ratios vary considerably between the 13 embayed beaches studied. Different habitat characteristics (e.g. makeup of live populations) likely contribute to these variances and should be addressed. Coastal hydrodynamics and post-mortem test alteration are also likely to influence beach-assemblage compositions. While the dynamic and coarse-grained beach environment at Sandy Point, for example, contains highly-altered specimens of *Archaias angulatus* in abundance, a large and relatively abrasion-resistant miliolid, finer-grained sands from more sheltered beach environments are more species-diverse and contain more fragile Rotaliina specimens. This general trend is captured in island-wide PCA analysis, which broadly distinguishes beaches from windward and leeward sides of the island, respectively. Coastal hydrodynamics and foraminiferal dispersal patterns require additional constraint, offering opportunity for continued work.

INTRODUCTION

The Bahamian island of San Salvador sits atop an isolated carbonate platform that faces the open Atlantic (Figure 1). Its isolation, rapid transition to deep water (with 4 km of ocean depth found just 10 km from shore), irregular carbonate bedrock framework (Titus, 1982, 1984), and high susceptibility to hurricane impacts (Caviedes, 1991; Klotzbach, 2011) have made San Salvador a popular site for late Holocene climate studies (Niemi, 2008; Park et al., 2009). Microfossils (e.g. ostracods and foraminifera) found in many of the island's coastal sedimentary archives (e.g. lagoons and ponds) have proven useful indicators of past storm (overwash) activity and been widely used to aid paleoenvironmental and climatic reconstructions (Bowman and Teeter, 1982; Sanger and Teeter, 1982; Teeter et al., 1987; Sipahioglu, 2008; Dalman, 2009; Park, 2012; Michelson and Park Boush, 2016). This paper documents an effort to inventory foraminifera within beach deposits of San Salvador, the proximal source for overwash; the investigation was prompted by work on storm deposits and hydrodynamics (Mattheus and Fowler, 2015; Mattheus and Yovichin, 2017). This island-wide study was undertaken to elucidate potential spatial trends that could relate to coastal setting, offshore habitat characteristics (e.g. reef occurrence), and/or wave and current exposure.

Foraminifera, a type of marine protist, construct tests of cemented calcium carbonate or agglutinated grains. Live benthic specimens, which exist as substrate-attached, encrusting, and/or mobile varieties, are documented across San Salvador's shelf environment. They are common within seagrass beds and reefs, but are found attached to other hard substrates as well (Lewis, 2004; Buchan and Lewis, 2008; Morgan and Lewis, 2012; Darroch et al., 2016; Martin and Lewis, 2016). Sensitivity to a number of environmental variables, including nutrient availability, salinity, temperature, and water energy, make benthic foraminifera useful paleoecologic indicators (Murray, 1991; Morgan and Lewis, 2012). Upon death, their tests disperse due to wave and current activity and are incorporated into sediments often removed from the original habitat. While live and death assemblages have been documented across several of San Salvador's seagrass, reef, and nearshore communities (Lewis, 2004; Buchan and Lewis, 2009; Morgan and Lewis, 2012; Darroch et al., 2016), little is known about test accumulation along the beach

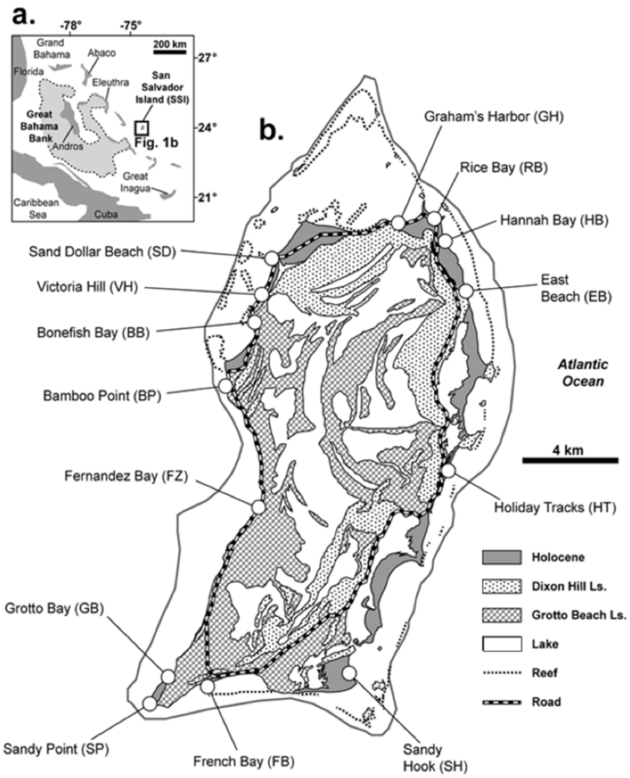


Figure 1. Geologic map of San Salvador Island and surrounding shelf (solid gray outline) showing the locations of sampled beaches and abbreviations used throughout the text for referencing. This geologic framework is based on work by Titus (1987); while updates to the Pleistocene carbonate bedrock units have since occurred, they are of little relevance to this study as the map delineates extent of Holocene sand cover equally well. Reef distribution shown here is adapted from maps by Robinson and Davis (1999); this is an incomplete picture of reef distribution as many popular patch reefs such as Snapshot Reef and Telephone Pole Reef, which are situated within Fernandez Bay (FZ) are not shown at this scale. Table 1, which lists site characteristics, is based on this map. Patch reefs and seagrass beds are common throughout the shelf system; it is beyond the scope of this paper to address the live habitats and our analysis focuses solely on island-wide trends in the ratio of miliolids to rotaliids, offering insights into potential influences thereupon (rather than establishing distinct sourcing pathways).

shorelines. Characterizing death assemblages here could offer insight into transport pathways (i.e. dispersal patterns) from the offshore live communities, provided population dynamics of the source area are known. Furthermore, as beaches supply sand for storm overwash, constraint of assemblage patterns here could offer information to help characterize paleostorm events from coastal pond and lagoon deposits. Areas of recurrent marine incursion are plentiful along San Salvador's coastal perimeter and the emplacement of beach-derived sands has been the subject of several investigations (Park, 2012; Mattheus and Fowler, 2014). As factors such as storm trajectory and strength influence coastal hydrodynamics (i.e. surge levels and current patterns; Parnell et al., 2004; Mattheus and Yovichin, 2018), constraint of live and fossil assemblages across the shelf and shoreline systems offers a potential blueprint for studying paleostorm characteristics from coastal deposits.

As our study focus was geared at evaluating micropaleontological data in context of coastal setting (e.g. shoreline orientation) and beach-nearshore energy (i.e. degree of wave and current exposure), discussion benefited from prior work addressing differences between live and death assemblages and the influences of test-degradation processes. Glenn-Sullivan and Evans (2001) infer that habitat preferences control live foraminiferal assemblages (in offshore habitats) while sediment (i.e. death) assemblages are highly influenced by wave energy. Sediments are therefore generally enriched with respect to larger, more robust tests as small, delicate species are more heavily impacted by predation, dissolution, and abrasion. Time and distance from source should therefore significantly alter assemblage compositions. This type of biased preservation is strongly suggested by studies of differential test abrasion and dissolution of reef-dwelling foraminifera (Peebles and Lewis, 1988, 1989; Kotler et al., 1991, 1992). How these insights, derived in part by physical experiments in laboratory settings, apply to the San Salvador coastal system requires constraint. A summary of background information on test resiliency follows, providing context for this investigation.

BACKGROUND

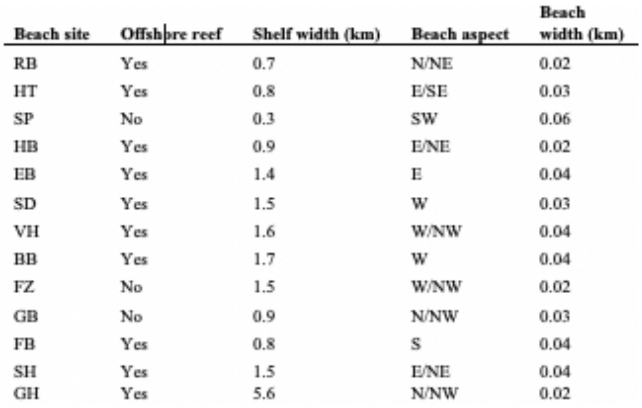
Taphonomic studies of benthic foraminifera in The Bahamas have provided insight into species distributions across shallow carbonate shelves (Bowman, 1982; Bowman and Teeter, 1982; Peebles and Lewis, 1988, 1991). Prior work has also addressed zonation patterns across several of San Salvador's offshore areas, focusing mainly on factors such as water depth and substrate type (Buchan, 2006; Buchan and Lewis, 2009; Morgan and Lewis, 2010; Martin and Lewis, 2016). In general, the Miliolina suborder (of which *Archaias angulatus* is dominant) appears to dominate the back-reef lagoons while the Rotaliina (e.g. *Amphistegina*) are more common in the fore-reef slope environment (Martin, 1988; Lewis, 2004). Post-mortem test preservation is impeded by several factors, including bacterial degradation, predation, dissolution, and physical abrasion (Peebles et al. 1989; Kotler et al., 1991). Test size, structure, and desirability to microboring organisms (e.g. gastropods) impact rates of dissolution and abrasion, which can result in pronounced differences between live and death assemblages, even if little transport is involved. Peebles et al. (1988), who investigated preservation potentials in reef and lagoon settings, demonstrated that differences in test microstructure can relate to the degree of infestation (by borers). The Rotaliina are generally not as heavily bored as the Miliolina, which has implications for test deterioration. Weakened tests can break apart more easily and dissolution can more effectively attack those that are heavily bored due to increased surface area. It must be noted that Peebles et al. (1989) infer opportunistic rather than selective predation. Gastropods tend to feed on the dominant taxa; counter-intuitively, miliolines (e.g. *Archaias*) were found to be more abrasion-resistant on San Salvador, despite heavier infestation by microboring organisms and being more dissolution-prone than rotaliines (given higher Mg content). This observation stands in contrast to other studies that downplay the role of preferential abrasion on assemblage compositions at the suborder level. It is subsequently suggested that abrasion alone is an unimportant agent of test destruction in natural carbonate settings, even high-energy ones (Kotler et al., 1992). In studying the effects of abrasion on tests of common Caribbean foraminifera of Discovery Bay (Jamaica), Kotler et al. (1991) noticed that abrasion was not sufficient to destroy foraminifera in low-energy settings and played only a minor role in altering foraminiferal assemblages in high-energy settings. Dissolution is arguably a more effective agent of test destruction, particularly in low-energy settings; however, the effects of abrasion should become more noticeable as transport distance and/or beach energy increases.

It is clear from prior work that many complex processes are involved in modifying foraminiferal death assemblages in shelf settings, including predation, dispersal (by currents), abrasion, and dissolution. Tests found in beach deposits should thus serve as a point of comparison to offshore assemblages and may help address post-mortem alteration histories and transport pathways and/or distances. The following section describes the sampling locations along the San Salvador coastal perimeter.

FIELD SITES

San Salvador covers an area of around 160 km^2. The N-S trending island is close to 21 km in length and up to 8 km wide (Figure1). It is characterized by an irregular carbonate bedrock topography, sculpted by episodic inundation and exposure throughout the Quaternary (Titus, 1982, 1984, 1987; Carew et al., 1984; Boardman et al., 1988; Carew and Mylroie, 1995). The highly-embayed and topographically-varied shoreline, which totals around 60 km in length, has been shaped by the interaction of coastal hydrodynamic processes (i.e. waves) with the bedrock terrain (aeolianites, beach rock, and reef deposits). Unconsolidated Holocene sand deposits are sparse on San Salvador, comprising a thin, discontinuous veneer atop consolidated Pleistocene sediments. The thickest and most extensive sandy lithosome occurs at Sandy Hook (SH), situated on the windward E/SE part of the island (Figure 1).

Thirteen embayed beaches from all sides of the island were sampled for this study. They are distinguished by beach/shelf morphology, offshore reef and seagrass occurrence, and sediment fabric, which serves as a proxy for wave energy. A 1972 Bahamian Lands and Surveys Department map and its digital derivatives (Robinson and Davis, 1992) plot the distribution of major offshore reefs and offer insight into beach and shelf widths. Average beach widths range from around 0.02 km for Rice Bay (RB) to around 0.06 km at Sandy Point (SP, Figure 1 and Table 1). Shelf widths vary from approximately 0.3 km at SP to around 1.7 km at Bonefish Bay (BB). The spatial distribution of patch reefs and shelf-edge reefs is highly heterogeneous (Figure 1; Table 1). The compartmentalization of the island perimeter into separate coastal cells (i.e. embayments) sets the stage for a comparison of beach-sand textures and foraminiferal content to shelf morphometric variables. The geologic framework of San Salvador and prior texture studies of beach sands (Lee et al., 1986; Clark et al., 1989; Gardner, 1993) suggest minimal sediment exchange between coastal cells; however, the shelf hydrodynamics have yet to be concretely established. The following section details the field-sampling, data processing, and statistical procedures employed to gain a better understanding of what beach-sand fabric and foraminiferal content might reveal about sediment sourcing and/or coastal hydrodynamics.



Beach site	Offshore reef	Shelf width (km)	Beach aspect	Beach width (km)
RB	Yes	0.7	N/NE	0.02
HT	Yes	0.8	E/SE	0.03
SP	No	0.3	SW	0.06
HB	Yes	0.9	E/NE	0.02
EB	Yes	1.4	E	0.04
SD	Yes	1.5	W	0.03
VH	Yes	1.6	W/NW	0.04
BB	Yes	1.7	W	0.04
FZ	No	1.5	W/NW	0.02
GB	No	0.9	N/NW	0.03
FB	Yes	0.8	S	0.04
SH	Yes	1.5	E/NE	0.04
GH	Yes	5.6	N/NW	0.02

Table 1. Study area characteristics by study site, including beach and offshore shelf variables. Shelf and beach morphometrics were derived from GoogleEarth imagery while offshore reef occurrence was assessed from maps by Robinson and Davis (1999), which captured only major (e.g. shelf-edge) reef lines.

METHODS

Previously-published texture data for San Salvador beaches were not incorporated into this analysis. Grain-size and microfossil assessments were performed on the same sediment samples to ensure meaningful comparisons. Sediment grabs were retrieved in March of 2014 from foreshore, backshore, and dune systems (total n=36; Figure 1; Table 1). The sampling was performed in adherence to a schematic targeting major sedimentary beach sub-environments (Figure 2). The foreshore was recognized as the portion of the beach influenced by daily tidal inundation under non-storm conditions. It sloped seaward, lacked aeolian structures (e.g. wind ripples), and was devoid of leaf litter and/or other organic detritus. Wrack lines (i.e. storm debris) often separated this environment from the backshore, which is less frequently inundated by the sea (i.e. only during storm events) and visibly reworked by aeolian processes. The dune environment was situated landward and often separated from the backshore by an erosional scarp (Figure 2). Three surface scoops of ~100 g were homogenized per sample. Processing and analysis commenced at the Gerace Research Centre (GRC). After drying in an oven overnight (at 100° C), samples were run through a sample splitter to generate unbiased subsamples for microfossil ID and sediment-texture studies. Grain-size analysis was performed at the GRC using the standard sieve method, whereby relative weight constituencies of gravel and major Wentworth sand classes were established. Samples for microfossil analysis were transported to Youngstown State University's Clastic Sedimentology lab and Lake Superior State University facilities for analysis. Samples were repeatedly split until a manageable size for identifying foraminifera was derived (around 50 g). Foraminifera were extracted under binocular microscopes using a fine, wetted brush and glued to micro-slides for identification and cataloguing. The goal of the analysis was n=50 per sample; however, most samples yielded fewer specimens. Foraminifera were identified using guides and plates provided by literature sources (Peebles and Lewis, 1988, 1989, 1991; Kotler et al., 1992; Javaux and Scott, 2003; Lewis, 2004) and online databases (e.g. World Foraminifera Database). Statistical analyses were performed at the sub-order taxonomic level, even though many specimens could be identified to the genus level (or beyond). Key foraminiferal taxa in the shallow waters surrounding San Salvador are the miliolines, rotaliines, and textulariines. The taphonomic states (pristine to heavily altered) were described for the abundant and large miliolid *Archaias angulatus.* This approach was similar to that used by Buchan and Lewis (2009) and Morgan and Lewis (2010), who ranked samples from pristine to highly altered. In our study, the assessment of test alteration used the following classes: A rating of ‘A’ was applied if <33% of specimens picked from a sample displayed visible signs of modification (e.g. pitting and/or fractured edges); a rating of ‘B’ was assigned when 33-66% of foraminifera were visibly altered and a rating of ‘C’ was assigned when >66% of foraminifera were distinctly modified. This analysis was treated as a qualitative indicator of overall degree of alteration.

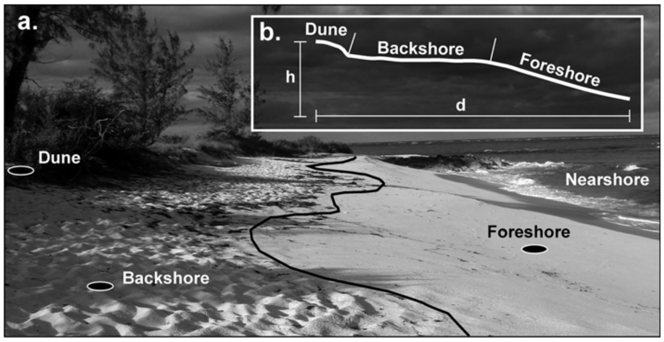


Figure 2. Field photograph of a beach on San Salvador Island showing respective sedimentary sub-environments sampled for analysis (a) and where they plot along a conceptual topographic profile across the beach (b). Dune, backshore, and foreshore environments are distinctly separated by pronounced breaks in slope, surface texture (e.g. swash-smoothed versus wind-rippled), and mean grain size.

STATISTICAL PROCEDURES

Relative Miliolina and Rotaliina abundances and weight percentages of different sediment size fractions were subjected to Principal Components

Analysis (PCA; SPSS version 20) for each spatial position (shoreface, backshore, and dune) at each of the thirteen beaches. The Textulariina (only two specimens total) and the silt/clay sediment fraction (occurring in only three dunes and at <0.5%) were not included due to their trivial contributions to the data set. The first two PCA axes (Eigen values of 3.40 and 1.69, and percent variance explained of 42.5 and 21.1, respectively) are presented as an ordination. A third PCA axis was marginally statistically useful (Eigen value of 1.11 and explaining 14.0% of variance), but was not included in the ordination for the sake of brevity and clarity. Also, this third PCA reflects predominantly the gravel fraction, which never constituted more than 3.2% of sediments in any sample, thus offering little meaningful explanatory value over the first two PCA axes that were graphed.

Environment	**Suborder**	**RB**	**HT**	**SP**	**HB**	**EB**	**SD**	**VH**	**BB**	**FZ**	**GB**	**FB**	**SH**	**GH**
Shoreface	Miliolina	17	23	25	32	31	34	36	27	9	32	41	20	46
Shoreface	Rotaliina	20	18	0	10	14	7	4	16	3	14	2	11	3
Shoreface	Textulariina	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	**37**	**41**	**25**	**42**	**45**	**41**	**40**	**43**	**12**	**46**	**43**	**31**	**49**
Backshore	Miliolina	28	36	22	24	25	40	38	2	27	4	44	22	42
Backshore	Rotaliina	19	10	1	20	20	2	8	5	12	3	2	13	3
Backshore	Textulariina	0	0	1	0	0	0	0	0	0	0	0	0	0
	Total	**47**	**46**	**24**	**44**	**45**	**42**	**46**	**7**	**39**	**7**	**46**	**35**	**45**
Dune	Miliolina	24	32	22	39	26	33	46	38	34	28	36	31	37
Dune	Rotaliina	18	5	0	8	17	8	4	9	7	17	2	4	5
Dune	Textulariina	0	0	0	0	1	0	0	0	0	0	0	0	0
	Total	**42**	**37**	**22**	**47**	**44**	**41**	**50**	**47**	**41**	**45**	**38**	**35**	**42**

Table 2. Results of foraminiferal counts, grouped by suborder and organized by beach sub-environments for all study-area locations.

RESULTS

Microscopy

The Miliolina dominate the general beach assemblage, accounting for around 78% of all individuals picked in this study (Table 2). The dominant suborder species is *Archaias angulatus*, easily recognized by its relatively large ammonoid-like test form (Figure 3). Rotaliina is the second-most common suborder (approximating 22% overall). The most common rotaliid specimen was *Homotrema rubrum*. Only two specimens belonging to the Textulariina suborder were identified (Table 2). Given a near total absence of Textulariina in beach deposits, assemblage compositions are expressed as variances of relative Miliolina and Rotaliina abundances, which show distinct spatial trends (Figure 4). The highly exposed, energetic, and coarse-grained shoreline at SP, which represents an end-member beach in terms of grain size (Figure 5), is dominated almost exclusively by Miliolina. Nearby Fernandez Bay (FZ) is also characterized by very low Rotaliina percentages (25%, 37%, and 17% of the total specimen population from foreshore, backshore, and dune environments, correspondingly; Table 2). Foreshore samples from east-facing beaches, the island's windward side, contain higher Rotaliina percentages than elsewhere, particularly SW-facing ones (Figure 4). Pristine foraminifera, occasionally found in foreshore and backshore samples, were rarely encountered in dune deposits and *Archaias angulatus* specimens sampled from dune deposits were observed to be more highly degraded (marked by pronounced pitting and broken chambers) than those from backshore and foreshore environments. Additionally, foraminifera picked from east-facing beaches (e.g. EB, HB, and RB; Figure 1) were noticeably less altered, in general, than those from beaches on the island's west side (Table 3).

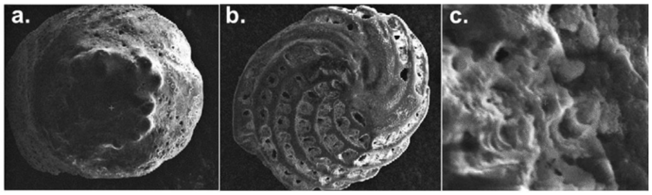


Figure 3. Scanning electron images taken with a JEOL JSM-6100 SEM (between 50 and 75 X magnification), showing Discorbis rosea, also known as Rotorbinella rosea (a) and Archaias angulatus (b), commonly encountered species of the Rotaliina and Miliolina suborders, respectively. An additional close-up image (>100 X magnification) provides a textural glimpse of the effects of post-mortem test alteration (c). Scales are approximations (given uncertainties relating to antiquated equipment and processing software); images serve merely to offer visual aid for textures and should not indicate size relationships between specimens.

Sediment texture

Results of grain-size analysis capture variances in sediment texture from beach to beach and between beach subenvironments. These stem from varying amounts of reef debris (i.e., bioclasts), peloids, and aggregate grains and reflect different coastal hydrodynamic and sediment-sourcing regimes. Foreshore samples relate more directly to ambient hydrodynamic conditions while backshore and dune samples characterize past conditions (e.g. storm lags) and modification by aeolian processes (e.g. sorting; Figure 2). The foreshore environment is coarsest along the SW and NW portions of San Salvador (Figure 5). The SP site contains the coarsest shoreface, backshore, and dune sediments, comprised of around 77%, 71%, and 83% coarse sand, respectively (Table 4). The NW beaches (VH, SD, and GH) are also dominated by coarse-grained sand. A fine-grained sand modal class, on the other hand, characterizes beaches along the NE portion of the island. Fine-grained sand percentages in foreshore deposits at HB and EB, for example, exceed 50%, while backshore and dune deposits here contain slightly less fine-grained sand, with medium-grained sand representing the dominant size class (Figure 5; Table 4). An absence of coarse-grained sand or very low percentages thereof (<10%) stand in noticeable contrast to the beaches in the SW (SP and GB) and NW (VH, SD, and GH) of San Salvador (Table 4).

PCA results

Sediment types and foraminiferal suborders segregated distinctly in PCA ordination space, indicating the potential quantitative association between them. Sand fractions were clearly distinguished along the PCA 1 axis, which explains 42.5% of data variance, with coarser sands to the left of the y axis (Figure 6). Likewise, the two dominant foraminiferal suborders diverged, with Miliolina to the left and Rotaliina to the right of the y axis. In contrast, there were no clear gradients *along* the y axis, which explains a further 21.1% of data variance. However, examination of the ordination plot in Figure 6 suggests some degree of "arch" or "horseshoe" effect, despite the general resistance of PCA to this when using environmental data such as sediment grain-size distributions. The reader should note how the gradient in sand fractions from very coarse to very fine follows not a straight line in ordination space, but a curved trajectory from the upper left quadrant to the upper right, hence precluding a clear interpretation of the PCA 2 axis. Shoreface, backshore, and dune samples at some beaches clustered closely in ordination space (e.g. at SP, SH, FB), whereas most did not (at HT, BB, VH, EB). Divergence among the different spatial position samples at individual beaches was typically greater along the PCA 2 axis than along the more definitively interpretable PCA

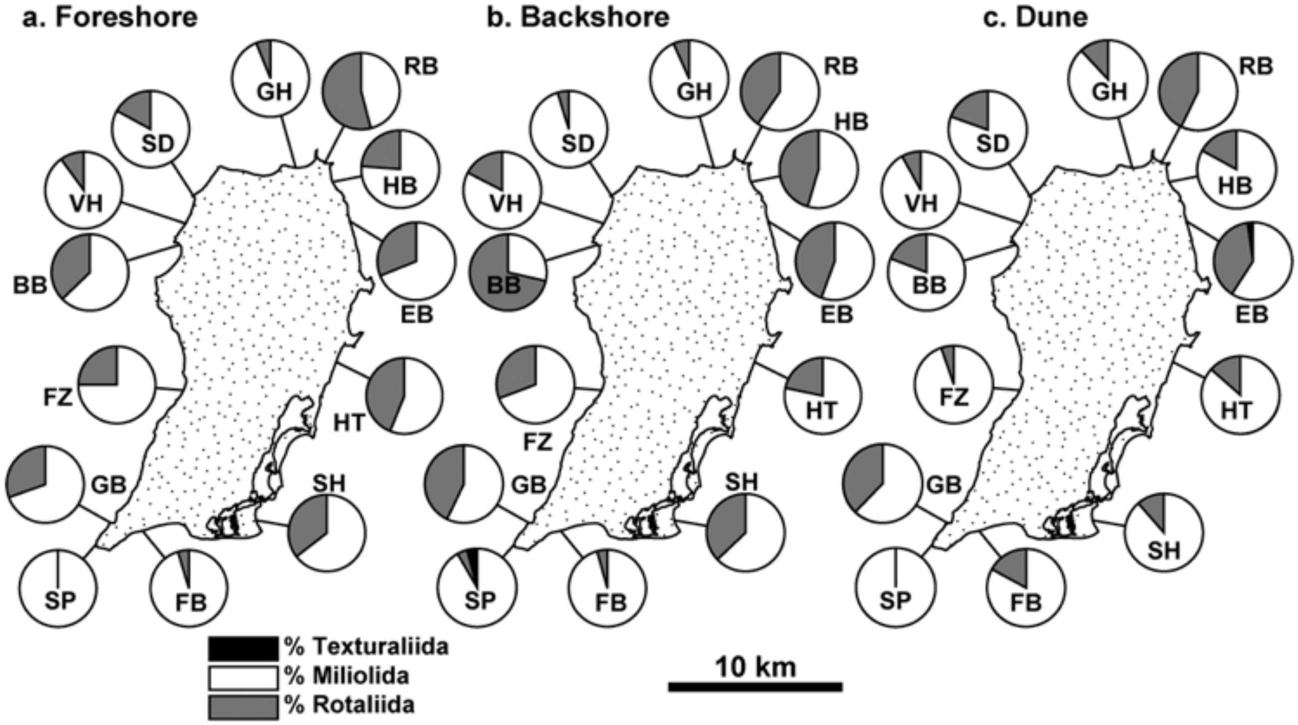


Figure 4. Distribution plots showing relative abundances of the three studied suborders of foraminifera in foreshore (a), backshore (b), and dune (c) deposits across San Salvador Island.

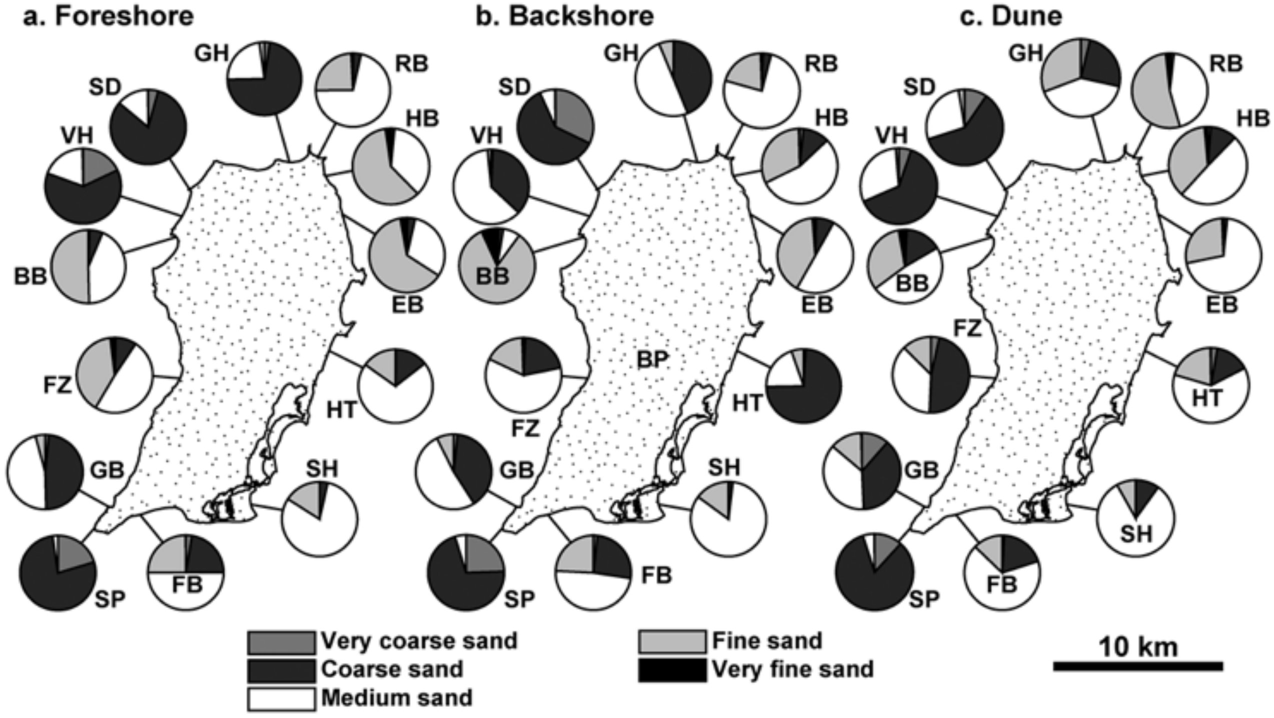


Figure 5. Distribution plots showing relative abundances of sand fractions in foreshore (a), backshore (b), and dune (c) deposits across San Salvador Island.

East-facing beaches	**Foreshore**	**Backshore**	**Dune**	**Other beaches**	**Foreshore**	**Backshore**	**Dune**
RB	A	A	A	SP	C	B	B
HT	A	C	C	SD	C	C	C
HB	C	A	C	VH	B	C	C
EB	B	B	C	BB	B	A	B
SH	B	B	B	GB	C	A	B
FZ	A	B	B	GH	C	C	B
				FB	C	C	C

Table 3. Results of an assessment of post-mortem test alteration performed on sampled foraminifera using the following classes: A (<33% of specimens show clear signs of modification such as pitting, fractured edges, etc.), B (33-66% of foraminifera are visibly altered), and C (>66% of foraminifera are distinctly altered). This analysis is not species-specific and was performed on all specimens collected from respective sediment samples. The results are to be used as a qualitative measure of overall degree of degradation.

Environment	**Suborder**	**RB**	**HT**	**SP**	**HB**	**EB**	**SD**	**VH**	**BB**	**FZ**	**GB**	**FB**	**SH**	**GH**
Shoreface	Miliolina	46	56	100	76	69	83	90	63	75	70	95	65	94
Backshore	Miliolina	60	78	92	55	56	95	83	29	69	57	96	63	93
Dune	Miliolina	57	86	100	83	59	80	92	81	83	62	95	89	88
Environment	**Grain size**													
Shoreface	Diameter at 50 %	227	527	924	501	217	877	845	241	197	798	568	500	681
Backshore	Diameter at 50 %	438	478	1,011	432	448	964	615	167	524	608	531	485	585
Dune	Diameter at 50 %	261	515	969	273	241	786	816	-	-	634	311	537	250
	Reef Association	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes
	Beach aspect	N/NE	E/SE	SW	E/NE	E	W	W/NW	W	W/NW	N/NW	S	E/NE	N/NW
	Shelf width (km)	0.02	0.03	0.06	0.02	0.04	0.03	0.04	0.04	0.02	0.03	0.04	0.04	0.02

Table 4. Synthesis of patterns in the distribution of foraminiferal suborders, mean sediment size, and environmental aspects of studied beach sites

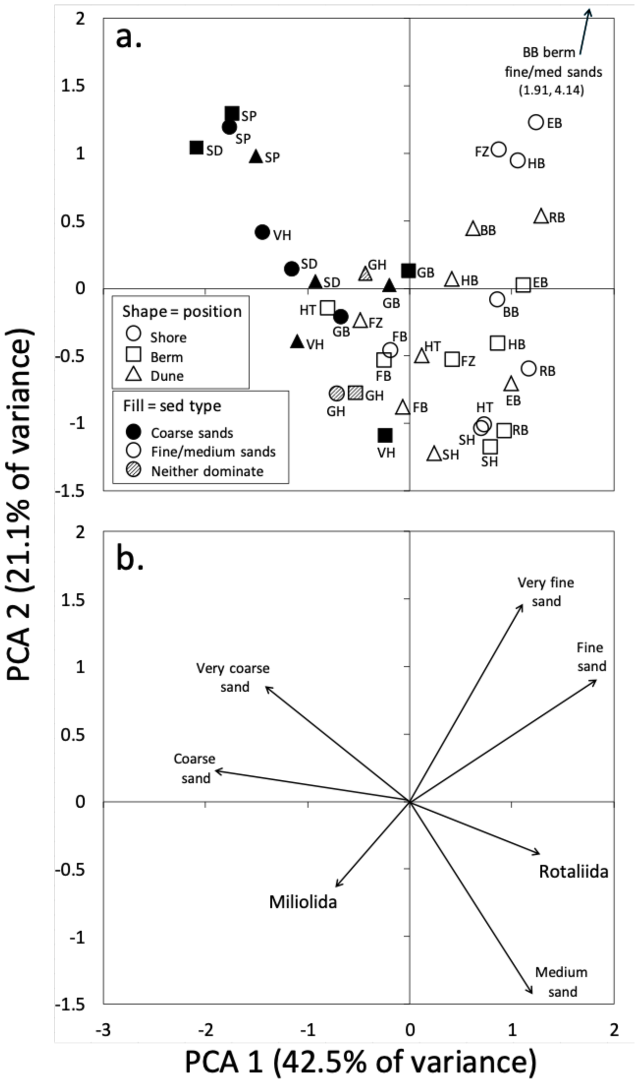


Figure 6. Principle Components Analysis (PCA) ordination of foraminifera orders and sediment grain sizes at San Salvador beaches, identified in panel (a) by site (abbreviations as used in other Figures and Tables), beach position (marker shapes), and dominant sediment fraction (marker fill). Vector arrows in panel (b) denote loadings (i.e. coefficients) for variables in the analysis. These loadings, which can range from -1 to +1, are multiplied by two in order to enhance readability on this plot.

1. There did not appear to be any island-wide pattern in ordination space differentiating among shore, backshore, and dune samples overall (Figure 6).

DISCUSSION

A broad survey of San Salvador beach sands offers data on foraminiferal suborder ratios, spatial variances therein, and associated sediment textures. This preliminary assessment provides insights to help guide future research endeavors to better constrain distribution dynamics, which should relate to foraminiferal habitat preference (and thus geologic framework), dispersal patterns (i.e. coastal hydrodynamics), and differential test resiliency. Prior studies that compare live and death assemblages across offshore habitats (e.g. seagrass and reef environments) have related compositional variances to differential test deterioration (Peebles and Lewis, 1988, 1989; Kotler et al., 1991, 1992). Some species undergo more rapid deterioration following death given poor resiliency to chemical and physical breakdown. The result of this is that live and death assemblages may differ significantly, even within the primary habitat. Increased travel distance should amplify such variances. Studies addressing assemblage dynamics offer some discussion points for contextualizing foraminiferal content in beach sands of San Salvador. Prior work in seagrass sites at Cut Cay, situated in the NE portion of the island (Buchan and Lewis 2006, 2009; Morgan and Lewis, 2012), and reef habitats along the western coast (Lewis, 2004), resolved offshore-trending assemblage gradients relating to environmental factors such as water depth and substrate type. At Cut Cay, where 54 species of foraminifera were described, very few specimens of the Miliolina suborder were found in seagrass beds, which were dominated by the Rotaliina (Morgan and Lewis, 2012). The latter, typified by smaller and more fragile tests, showed a strong substrate preference; while larger miliolines such as *Archaias angulatus* were not as common on the seagrass vegetation (as the rotaliines), they accumulated in sediments more easily due to their relative resistance to abrasion (Martin, 1986). The miliolines are the dominant constituent in our beach samples and *Archaias angulatus* was the most abundant species found, a stark contrast to offshore observations. Greater transport distance (or increased time since death) is more likely to alter tests (by abrasion and dissolution), which leads to a relative enrichment of beach deposits in more robust species.

Variances in preservation potential have previously been entertained as possible mechanisms for generating diverse foraminiferal assemblages in sedimentary records (Peebles and Lewis, 1989; Kotler et al., 1992). Factors such as test size, composition (high versus low-Mg calcite), and architecture (e.g. coiled agglutinated) represent intrinsic variables influencing these dynamics.

Suggestively, trends in dominant suborder ratios in San Salvador beach sands reveal a spatial correlation with mean grain size, which reflects the energy levels of respective depositional settings (Figures 4 and 5). This is resolved from an island-wide PCA analysis associating coarser-grained deposits (which largely dominate the island's westward-facing shores) with Miliolina assemblage-dominance. The SP site, in particular, is characterized by the coarsest beach sediments on San Salvador (Figure 5) and exclusively contains miliolines (Figure 4). Almost all foraminifera sampled from this beach are heavily altered *Archaias angulatus*, known for its large size and abrasion-resistant test comprised of high-Mg calcite (Martin, 1988; McIntyre-Wressnig, 2011). While its dominance likely relates, in part, to its size (i.e. depositional dynamics as a function of particle diameter), resiliency characteristics may contribute to its relative enrichment. SP, which is located in close proximity to the SW platform edge (Figure 1), is not only an exceptionally dynamic beach (in terms of wave and current exposure; Loizeaux et al., 1993; Beavers et al., 1995; Voegeli et al., 2006), it is also more distal to reef and seagrass habitats, where foraminiferal abundances and diversity are high. Greater transport distances and longer/more intense abrasion histories, as evidenced by the high degree of test alteration (Figure 3), likely factor into the lack of foraminiferal diversity at SP.

Past work has downplayed the role of abrasion as an important agent of test destruction (Kotler et al., 1991, 1992); however, much of the research focus was on lower-E shelf settings, where dissolution and infestation (by microborers) take on major roles in the process of test degradation. Littoral and beach dynamics, as influenced by wave and current activity, should influence assemblage compositions by promoting abrasion and the loss of less robust species with time. Separation of foraminifera by size is another likely process factoring into changes in death-assemblage composition in shoreline sediments, given the range of different textures observed (Figure 5). The geologic and ecologic complexities of San Salvador, which include high along-strike variances in shelf morphology, offshore reef and seagrass bed occurrence (Table 1; Figure 1), offer many opportunities to study the dynamics of sediment (and foraminiferal) sourcing and routing. Although more information from the offshore realm is needed to address this (e.g. hydrodynamic and ecologic data), our assessment of beach sands offers some preliminary insights. The qualitative observation that foraminiferal tests recovered from dune sands were generally more highly abraded than those from respective foreshore samples reflects both distance traveled (across/along the interface of terrestrial and aquatic environments) and age. Grains here are also subjected to heavier dissolution given increased freshwater influence (i.e. rainfall). It should be mentioned that the loss of fine surface textures by pitting, a clear result of dissolution, is more likely to obscure the recognition of some types of foraminifera, particularly smaller ones. Some 'fresh' foraminifera can be transported landward quickly by surge waters (i.e. without undergoing a long history of abrasion in the nearshore/beach environment). With exception of such outliers, which may offer useful information on storm occurrence, weathering and assemblage composition gradients likely exist from offshore habitat to beach. These should generally relate to time of alteration by physical and chemical processes. Grains in the subaerial realm have generally traveled far and are highly degraded. A more detailed assessment foraminifera at the species level in each of the subenvironments along this spatial gradient (and their test conditions) would likely offer additional insights.

The role of *Homotrema rubrum* (a rotaliine) as a transport indicator is particularly important to consider in future work, given its distinct appearance (red color) and documented abundance in outer reef settings (MacKenzie et al., 1965; Pilarczyk and Reinhardt, 2012; Pilarczyk et al., 2014).

Tichenor and Lewis (2018) have documented its abundance in nearshore areas of San Salvador. Improving our understanding of sediment sourcing and linkages between offshore habitats and foraminiferal distributions across beach environments would require detailed documentation of what is living in the vicinity of each particular beach and assessing hydrodynamics (e.g. tidal currents). The role of storms is an additional point to address as varying storm paths and wave characteristics may have varying impacts on dispersal patterns, which could be elucidated from foraminiferal taphonomy of the subaerial realm (e.g. storm washover deposits).

CONCLUSIONS

Beach sands from the small isolated carbonate platform of San Salvador Island, Bahamas, offer a glimpse into spatial variances in the ratio of dominant foraminiferal suborders. This survey of the island's beaches offers a jumping-off point for studying foraminiferal dispersal patterns from offshore habitats (e.g. seagrass beds and reefs). Different preservation potentials of tests, related largely to composition, size, and architecture, cause assemblages to change with increasing dispersal distance and time spent undergoing reworking in nearshore and shoreline sediments. High-E shoreline sites on the island are depleted with respect to smaller and weaker tests and are dominated by highly abraded *Archaias angulatus,* a large and relatively robust species of the Miliolina suborder. Distance traveled and the continuous reworking within high-E beach environments appear to influence foraminiferal death assemblages, whereby smaller, less resilient tests (which are less impacted by boring) are more quickly destroyed and larger, robust ones enriched in sediments over time. Physical and chemical alteration processes within nearshore and shoreline environments may trump biological effects on test degradation, which are probably more pronounced in lower energy settings (or closer to the source region). The roles of biologic effects on test degradation are complex as factors involving predator habitat preferences and other ecologic variables are difficult to pinpoint and are beyond the scope of this initial assessment. Observed spatial trends in foraminiferal suborder ratio probably also relate to habitat type as certain foraminifera prefer certain settings (e.g. *Homotrema rubrum* abundance in outer reefs). A PCA analysis comparing relative contributions of the Miliolina (with respect the overall assemblage) to mean grain size of corresponding beach deposits (viewed as a proxy for energy of respective coastal cells) distinguishes east- from west-facing (i.e. windward from leeward) beaches. This should relate to a combination of different habitat preferences, abrasion histories, and test resilience. Continued study of how death assemblages vary across offshore and nearshore environments of San Salvador may provide useful information for studying foraminifera in coastal hurricane deposits (e.g. paleostorm trajectory). Particular emphasis on evaluating potential transport indicator species (e.g. *Homotrema rubrum*) would be particularly helpful in this regard.

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