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**(Cover photo: San Salvador coastline by Erin Rothfus)**

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**ABSTRACT.** Numerous small seeps occur along the southern slope of Trial Hill Ridge in the Pigeon Cay area to the east of Alligator Point, Cat Island, Bahamas. This ridge parallels the Exuma Sound shoreline to the south and is the area's most prominent topographic feature. Thin soil cover and dense vegetation presently cap the ridge, which is made of carbonate eolianite of the Holocene Rice Bay Formation, with both members of the formation represented. Hanna Bay Member beds, consisting of beach backshore and dune deposits, overlie eolianites of the North Point Member, which are well exposed along the ridge's southern flanks as prominent foreset beds of uniform southward dip.

The seeps form triangular aprons below discharge points aligned east to west about 18-20 m inland and upslope from the shore and defining a field about 400 m long immediately south of the highest parts of Trial Hill. Aprons represent shallow erosional incisions into the North Point eolianites and contain two types of carbonate precipitates: 1) dense, brown laminated crusts, made of elongated calcite crystals; and 2) porous microbial bushes, stained dark brown to black, and containing micritic to finely crystalline equant calcite. Results of petrographic and stable isotope analyses indicate that these laminated crusts are an example of travertine that precipitated in areas of active meteoric water flow. They are surrounded and underlined by tufa-like microbialite that formed in moist areas between flow events. Seeps were inactive during our field observations, but likely have periodic, relatively low discharge related to rainfall conditions.

Such seeps are rare in Holocene strata of the Bahamas because their formation requires a unique combination of stratigraphy and topography. Trial Hill provides a localized area where meteoric water recharges through the porous Hanna Bay eolianite and is perched and deflected down-dip along bedding planes of underlying, slightly better lithified North Point eolianites before it surfaces at the points where Hanna Bay rocks laterally pinch out. Water interaction with soil and vegetation in the recharge area is likely responsible for the corrosive nature of seepage and dark color of associated precipitates. Communities of microbes also provide sites of localized carbonate precipitation and organic staining within the seep aprons.

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## INTRODUCTION AND STUDY AREA

The high porosity and permeability of carbonate rocks in the Bahamas result in rapid infiltration of meteoric water and in the absence or scarcity of permanent surface streams (Carew and Mylroie, 1994). Any existing surface flows on carbonate islands, including spring discharges, are characterized by small, shallow and ephemeral drainage channels that do not provide significant storage of freshwater (Ferry et al., 1997). In the Bahamas, springs are more likely to occur in the laterally extensive and thick Pleistocene carbonate rocks, which dominate the surface of most islands, rather than in the Holocene carbonates that are generally restricted to island margins (Carew and Mylroie, 1997). Although a contrast in hydraulic conductivity between younger Holocene carbonate sandy deposits and the underlying Pleistocene limestone could provide situations for spring formation at contacts between these deposits, springs are still very rare on Bahamian islands.

Small-scale springs or seeps have been observed within the Pleistocene deposits in the Sandy Point Caves area on San Salvador Island (Mylroie, personal communication, 2012). To date, there have been no specific previous documentations of springs and their carbonate precipitates from Holocene deposits in the Bahamas.

This work describes one such example from Cat Island. Due to their small size, ephemeral nature, and low discharge related to immediate antecedent rainfall conditions, we refer to these springs as seeps, although they have characteristics comparable to springs at larger scales (Jones and Renaut, 2010). The seeps are present in Holocene carbonate eolian strata exposed along the southern slope of Trial Hill Ridge in the Pigeon Cay area to the east of Alligator Point (Figure 1). This ridge parallels the Exuma Sound shoreline to the south and a tidal inlet to the north. Trial Hill is the most prominent topographic feature of the area; it is about 1 km long, less than 100 m wide, and almost 19 m tall. The seeps are located 18-20 meters inland and laterally upslope from the shore, defining a field about 400 m long immediately south of the highest parts of Trial Hill (Figure 1).

The main objectives of this study were to document the distribution and morphology of the seeps, and to analyze the associated carbonate precipitates. These objectives were accomplished through field and petrographic observations and stable isotope analyses. Although generally rare, localized in distribution, and small in scale, the occurrence and characteristic features of Bahamian subaerial springs and their carbonate precipitates can provide important new information about fresh-water discharge as controlled by local stratigraphy and geomorphology. In addition, the shallow drainage channels of these springs are unique small-scale geomorphologic features that represent complex environmental systems characterized by the formation of calcareous deposits under the influence of variable biotic and abiotic processes.

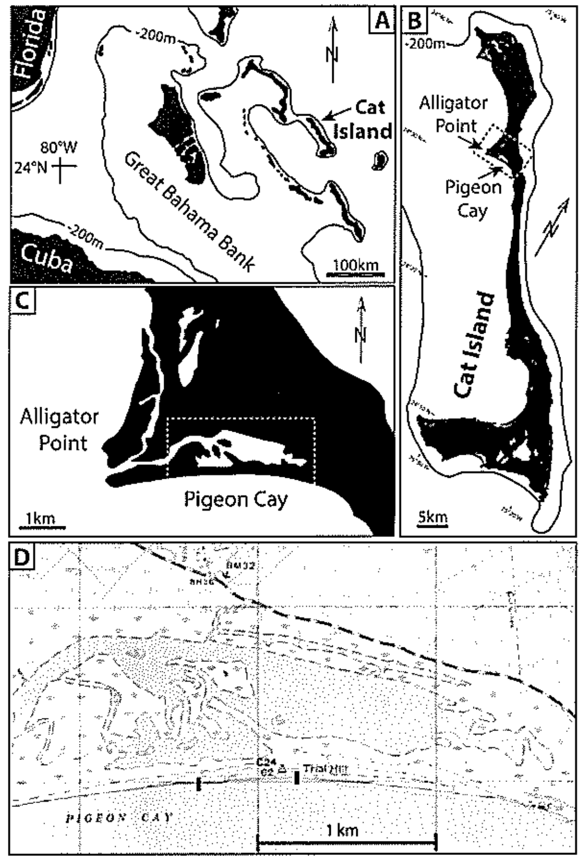


*Figure 1. Maps of the study area. A) Location of Cat Island along the eastern margin of the Great Bahama Bank (modified after Kindler and Hearty, 1995). B) Location of Alligator Point and Pigeon Cay on the western (leeward) side of Cat Island (dashed area is enlarged in C). C) The study site (dashed area enlarged in D) is located in the Pigeon Cay area to the east of Alligator Point. D) Location of the Trial Hill ridge between the Exuma Sound shoreline to the south and a tidal inlet to the north. The seeps are located 18-20 meters inland and laterally upslope from the shore, defining a field about 400 m long immediately south of the highest parts of Trial Hill (between the two black hash marks on the topographic map).*

Documentation of such modern examples is critical for understanding the formation and preservation of ancient calcareous spring deposits, which are only rarely found and recognized in the geological record (e.g., Perry, 1994; Evans, 1999; Melezhik and Fallick, 2001; Renaut et al., 2002;

Jones and Renaut, 2010). Moreover, this study of Cat Island seeps yields unique new insights into the geology of the island, which has not been previously examined in great detail. As such this research builds onto the pioneering work by Lind (1969) who was the first to describe Cat Island coastal landforms, Mylroie et al. (2006) who presented an overview of the geology of the island in their field trip guidebook, and Glumac et al. (2011) whose previous work focused on other unique features of Holocene eolianites from the Alligator Point area on Cat Island.

## DISTRIBUTION AND MORPHOLOGY OF SEEPS AND ASSOCIATED CARBONATE PRECIPITATES

The southern slope of Trial Hill Ridge is characterized by an array of small seeps (Figure 2A), which were inactive during our field observations in January 2009. A thin soil cover and dense vegetation now cap this ridge made of carbonate eolianite of the Holocene Hanna Bay Member, Rice Bay Formation. Underlying eolianite of the North Point Member of the same

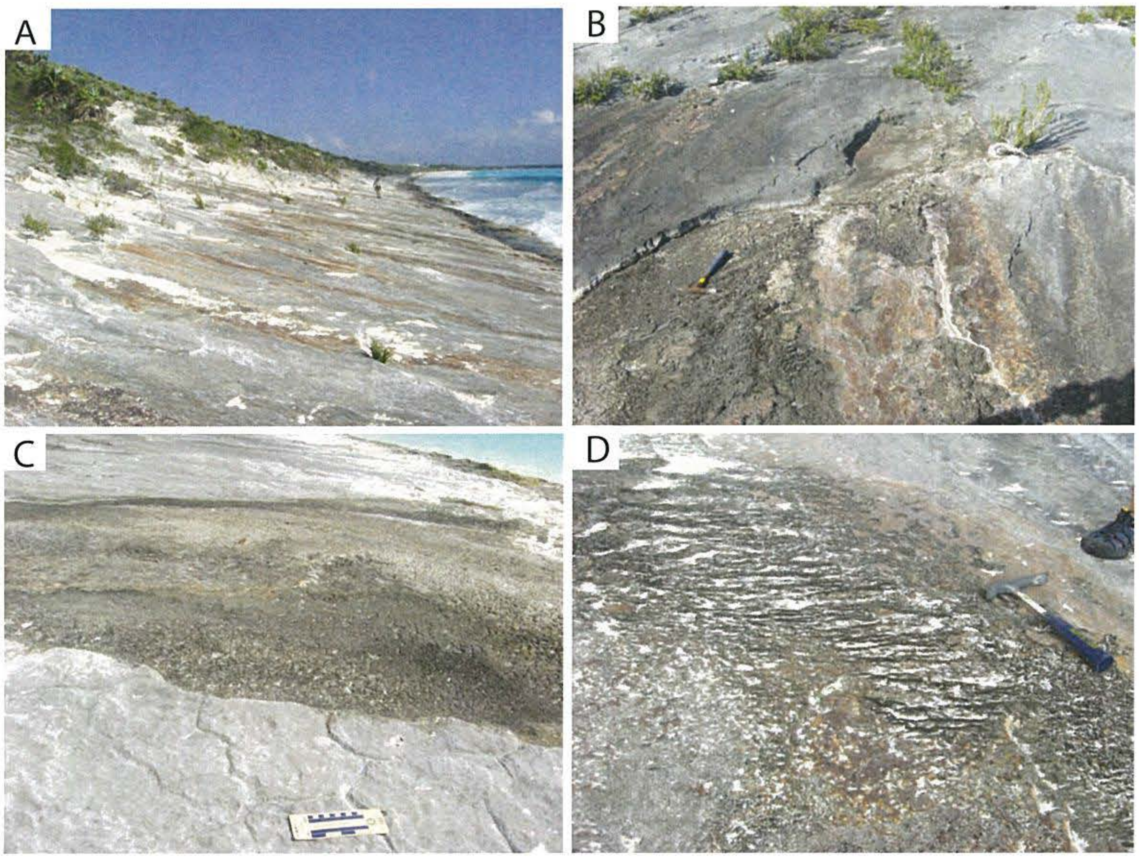


*Figure 2. Field photographs illustrating the distribution and morphology of seeps. A) An array of small seeps along the southern slope of Trial Hill (note person for scale). A thin soil cover and dense vegetation cap this Holocene ridge made of carbonate eolianite of the Hanna Bay Member, Rice Bay Formation. Underlying eolianite of the North Point Member, same formation, is well exposed as prominent foreset beds of uniform 10-15° dip to the south. Seeps emerge at the contact between these two member deposits (note hammer for scale = 26 cm long). B) Seeps form small triangular aprons below discharge points. C) Aprons are shallow (up to 10 cm deep) erosional incisions into the North Point eolian ooid grainstone characterized by the common occurrence of polygonal sandcracks. D) Brown to black, organically stained carbonate precipitates, which are in places arranged in cascading patterns, occur within the aprons.*

formation is well exposed along the ridge's southern flanks as prominent foreset beds of uniform 10-15° dip to the south (Figure 2A).

The seeps form small triangular aprons below discharge points (Figure 2B). These aprons are shallow (up to 10 cm deep) erosional incisions into the North Point eolian ooid grainstone characterized by common polygonal sandcracks (Figure 2C; Glumac et al., 2011). Within the aprons are brown to black, organically stained carbonate precipitates, which are in places arranged in cascading patterns (Figure 2D). There are two distinct types of carbonate precipitates associated with the seeps: finely laminated brown crusts with dense, hard and smooth upper surfaces, and surrounding irregular patches or "bushes" of dark brown to black, porous microbialite (Figure 3).

The laminated crusts are up to 1.5 cm thick and composed of large, elongated calcite crystals with radiating bladed to fibrous morphology (Figure 4). Individual crystals extend upward through numerous fine laminae. These coarse-crystalline laminated crusts coat the exposed surfaces of the relatively well-lithified North Point eolian ooid grainstone. Ooids at the contact with the crust are sharply truncated and the degree of grainstone micritization increases towards the contact (Figure 4). Sets of laminae and/or individual laminae are also erosionally truncated and overlain by more laminae and/or surrounded by the porous, black irregular patches of microbialite. These patches are composed of porous micrite to finely crystalline equant calcite (Figures 4A-H). The micritic material can also be present at the contact between ooid grainstone below and laminated crust above (Figures 4E-F). The upper surface of ooid grainstone deposits below the micritic crust is intensely micritized by microboring (Figures 4E-F). Individual ooids, weathered from the eolian grainstone bedrock are commonly found incorporated within the micritic patches (Figures 4G-H).

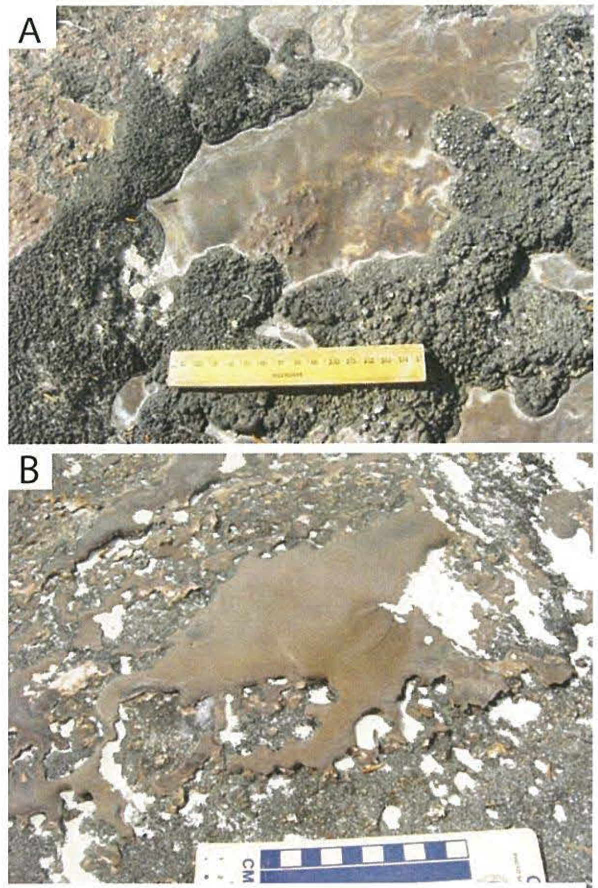


*Figure 3. Field photographs showing the two distinct types of carbonate precipitates associated with the seeps. A) Brown crusts with dense, hard and smooth surfaces (center of photographs) surrounded by irregular patches of dark brown to black, porous material. B) A separate, similar example.*

## STABLE ISOTOPE ANALYSIS

### *Methods*

Samples for stable isotope analysis consisted of a small amount of carbonate powder collected from polished slabs and thin section billets using a microdrill mounted on a binocular microscope. All samples were heated at 400°C for 1 hr to remove volatile organic components, then reacted with 100% anhydrous phosphoric acid ($H_3PO_4$) for 10 min, and analyzed using an on-line automated carbonate preparation system (Kiell III) linked to a Finnigan-MAT DeltaXL+ ratio mass

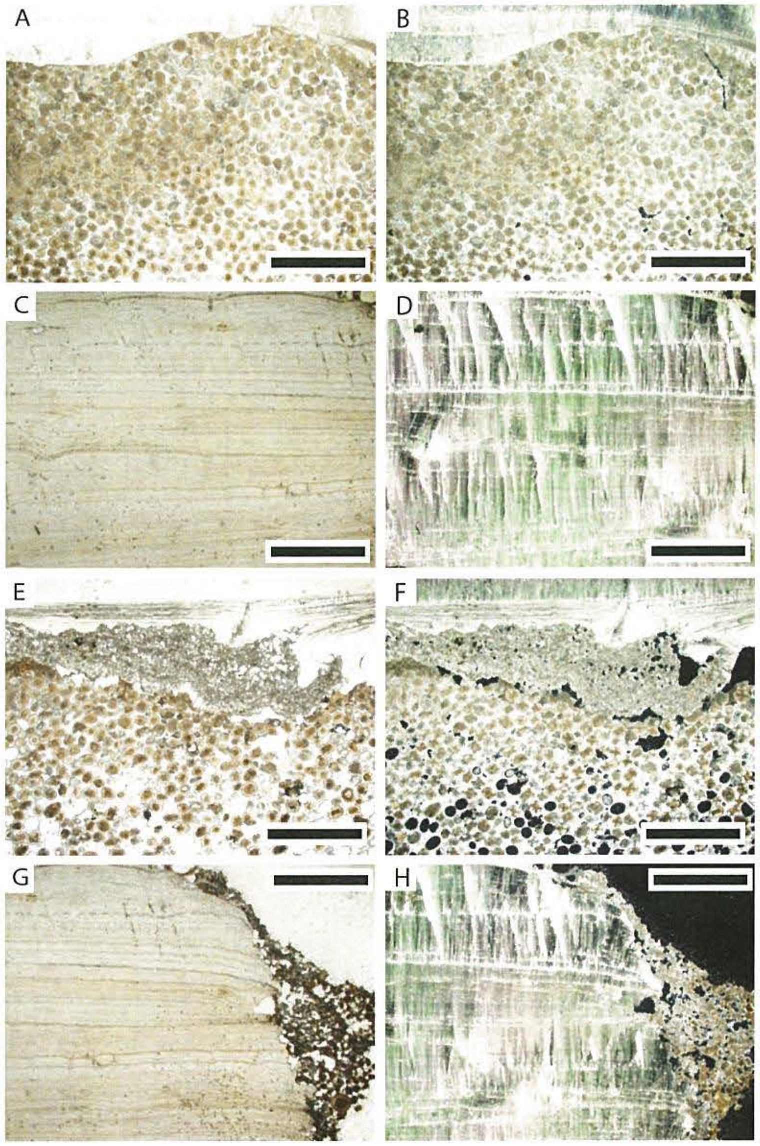


*Figure 4. Paired thin-section photomicrographs: plain-polarized light (left) and cross-polarized light (right); scale bar = 2 mm. A and B) Contact between sharply truncated, relatively well-lithified North Point Member eolian ooid grainstone below and laminated seep precipitate above. Note truncation of ooids at the contact and increase in the degree of micritization of grainstone towards the contact. C and D) Characteristic finely laminated pattern of the hard, dense seep crusts. The laminae are composed of large elongated calcite crystals with radiating bladed to fibrous morphology. Individual crystals extend upward through numerous fine laminae. E and F) Micritic material present at the contact between ooid grainstone below and laminated crust above is interpreted as microbialite composed of porous micrite to finely crystalline equant calcite. The top surface of ooid grainstone is intensely micritized by microboring. G and H) Porous micritic microbialite commonly surrounds and overlies the dense laminated crusts composed of elongated calcite crystals. Individual ooids, weathered from the eolian grainstone bedrock are commonly found incorporated within microbialite.*

spectrometer. Standard isobaric and phosphoric acid fractionation corrections were applied to all measurements. Internal analytical precision, monitored through daily analysis of carbonate standards, was better than or equal to 0.1 ‰ for both carbon and oxygen isotope values. Stable isotope results (Figure 5) are expressed as $\delta^{13}C$ and $\delta^{18}O$ values in ‰ relative to the Vienna PeeDee Belemnite standard (VPDB).

Stable isotope analyses were carried out on eight samples of whole-rock eolianite deposits, twenty samples of coarse-crystalline laminated crusts, and two samples of bushy micritic microbial deposits. Although abundant, it was difficult to collect enough mineral powder of homogenous micrite from the porous microbialite without the danger of contaminating samples with the surrounding or incorporated non-micritic components such as ooids (Figures 4E-H). Multiple samples of different individual laminae were collected from the same sample of laminated crusts composed of coarse, elongated crystals. Mineralogical composition of samples was checked by using X-ray diffraction. Eolianite was composed of aragonitic ooids and the surrounding calcitic cement, and both laminated crusts and bushy micritic microbialite were entirely composed of calcite.

*Results*

Carbon isotope values ($\delta^{13}C$) of the eight analyzed eolianite samples range from 2.4 to 4.5 ‰, and average 3.4 ‰, while their oxygen isotope values ($\delta^{18}O$) range from -2.2 to -0.3 ‰, and average -1.5 ‰ (Figure 5). The twenty samples of laminated crusts have their $\delta^{13}C$ values ranging from -6.1 to -2.6 ‰ (average -4.6 ‰), and $\delta^{18}O$ values from -7.6 to -4.5 ‰, with an average value of -6.1 ‰. The $\delta^{13}C$ and $\delta^{18}O$ values of the two samples of micritic bushy microbialite were +0.5 and -3.7 ‰, and -2.8 and -1.8 ‰, respectively (Figure 5). The three different components analyzed define three distinct compositional fields, which do not exhibit any overlaps on the $\delta^{13}C$ vs. $\delta^{18}O$ crossplot (Figure 5). The whole-rock eolianites have the most positive $\delta^{13}C$ and $\delta^{18}O$ values in the suite of samples analyzed, and the samples of laminated crusts exhibit the most negative values (Figure 5). The isotopic composition of the two bushy microbialite samples is intermediate between those of eolianites and laminated crusts (Figure 5).

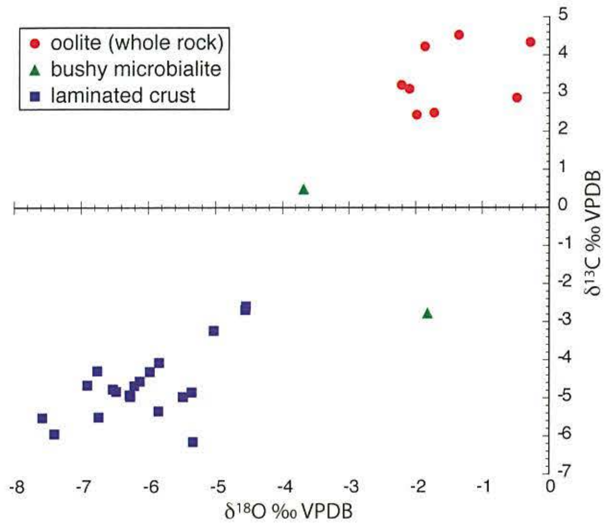


*Figure 5. Stable isotope composition and comparison between the host North Point eolian ooid grainstone (whole rock) and the two types of carbonate precipitates found within the seeps: bushy microbialites and laminated crusts.*

*Interpretations*

The relatively positive stable isotope values recorded for eolianite (whole rock) samples are consistent with the composition of oolitic marine carbonate sediment moderately altered by meteoric fluids during subaerial exposure and lithified by meteoric calcite cement (e.g., Lohmann, 1988; James and Choquette, 1990). These values contrast with the relatively negative isotope values of laminated crusts and reflect precipitation of calcite from actively flowing seep waters representing meteoric fluids that interacted with soil and terrestrial vegetation in the recharge area (Figure 6). The intermediate composition of bushy microbialites is consistent with their formation in moist areas between active seep flow events. Their isotopic composition is affected by evaporation and microbially mediated processes of calcite precipitation.

DISCUSSION

Springs are complex depositional and biological systems characterized by a variety of scales and morphologies, which are a function of the unique combination of an area's hydrology and geomorphology. Modern-day springs are found on every continent, with some producing thick and laterally extensive calcareous deposits whose texture reflects complex interplay between various physical, chemical, and biological processes (Jones and Renaut, 2010). Although rare and small, the presence of springs and associated calcareous deposits in the Bahamas can reveal important information about a range of biotic (i.e., microbial processes) and abiotic (e.g., geomorphology and stratigraphy) factors that control their formation and distribution.

Most cold-water springs and their precipitates in regions underlain by carbonates are of meteogene origin, meaning they form from groundwater charged with meteoric fluids, as opposed to thermogene springs that derive from deep thermal processes (Pentecost, 2005). Meteogene deposits generally form below springs issuing from perched water tables (Pentecost, 2005). The majority of land area of most Bahamian islands is close to sea level and the vadose zone is very thin. Only locally can the vadose zone reach substantial thickness, most commonly beneath eolian dune ridges. Although some of the Bahamian islands, such as Eleuthera, Cat Island and the Exumas have an almost continuous coastal fringe of Holocene deposits (Lind, 1969; Mylroie et al., 2006; Savarese and Curran, this volume), most of these partially lithified Holocene eolian sand deposits have a high infiltration capacity and there is no associated surface runoff (Whitaker and Smart, 1997).

On Cat Island, Trial Hill provides a localized area where water recharges through the porous Hanna Bay eolianite and surfaces when perched and deflected down-dip along bedding planes of underlying, somewhat better lithified North Point eolianite of the Holocene Rice Bay Formation (Figure 6). The result is the formation of numerous seeps on the southern slope of Trial Hill aligned parallel to the shore and extending for about 400 m (Figure 2A). The seeps are exclusively found on the slopes immediately beneath the highest parts of Trial Hill Ridge (Figure 1D). This topographic feature represents the only local area with sufficient recharge through relatively thick vadose zone where porous deposits overlie better lithified limestone and pinch out laterally to create conditions necessary for the formation of a perched water table and subaerial seeps (Figure 6). Since such seeps are

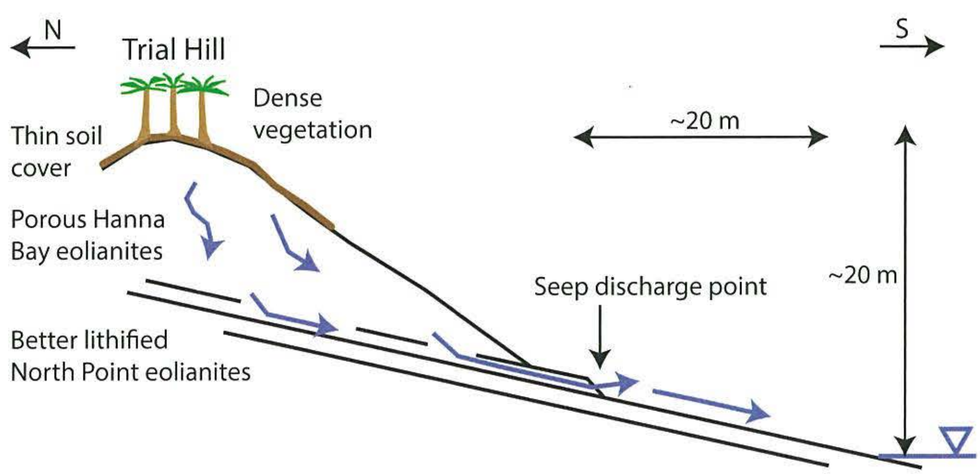


*Figure 6. Schematic representation of water flow and seep formation along a north-south transect through Holocene eolianites of the Trial Hill area on Cat Island, Bahamas.*

rare on the surface of Holocene deposits in the Bahamas, this Cat Island example nicely illustrates how the formation and distribution of seeps require a unique combination of stratigraphy and topography (i.e., the 'right' amount and location of Hanna Bay eolianites on top of North Point eolianites). Furthermore, the occurrence of such seeps on Holocene strata in other areas of the Bahamas may prove to be useful in locating and mapping contacts between these eolian deposits that formed within a single sea-level high stand and whose contact is not always easily recognized in the field due to the lack of a *terra rossa* paleosol.

According to vent location and geomorphological setting, the Cat Island seeps can be classified as a perched spring system with calcareous deposits forming proximal to the vent in a slope-system depositional regime (*sensu* Jones and Renaut, 2010). Perched water tables commonly result in springs breaking out on slopes and leading to rapid deposition, and springs on steep slopes tend to produce cascade deposits (Pentecost, 2005), similar to those present on Cat Island (Figure 2). The small ephemeral seeps from Cat Island are also comparable to the category of subaerial calcareous springs confined to small, local discharge aprons below spring vents. As such, the Cat Island seeps (Figure 2) are a good examples of small-scale springs following Jones and Renaut (2010), who illustrated examples from Iceland that consist of triangular-shaped discharge aprons of limited extent with cm-scale rimstone dam-pool systems. These small springs are very similar in morphology and processes to the famous large-scale examples from Pamukkale, Turkey (Ekmekci et al., 1995), but with notable differences expected due to variations in climate, freshwater precipitation regime, substrate, and other parameters.

Petrographic observations and comparisons with other documented examples of spring calcareous deposits support the interpretations derived from our field and stable isotope analyses. Micritic and sparitic fabrics of the Cat Island seep precipitates are examples of the following facies of calcareous spring systems (Pentecost, 2005; Jones and Renaut, 2010): the bushy patches of micritic carbonate are interpreted as microbialite tufa and the laminated crusts represent crystalline travertine (Figure 3). Clumps, shrubs and bushes of micrite are very common in calcareous spring deposits and are likely microbial in origin representing colonies of bacteria and cyanobacteria (Chafetz and Folk, 1984; Guo and Riding, 1994; Pentecost, 2005; among others). Microbes are abundant in many spring systems and can play important roles in the formation of calcareous deposits. Microbial bushes are most frequently associated with cool meteogene springs and appear to form preferentially in "quiescent shallow pools" (Pentecost, 2005, p. 28). This is consistent with the results of our stable isotope analyses (Figure 5), which suggest formation of bushy microbialites in moist areas, subjected to evaporation, in between active flow events. Microbes facilitate carbonate precipitation through their metabolic processes or by providing substrates for carbonate crystal nucleation and/or by trapping and binding carbonate grains on their surfaces (Chafetz and Folk, 1984; Das and Mohanti, 1997; Pedley and Rogerson, 2010; among numerous others). These processes commonly result in highly porous tufa deposits that represent a mixture of authigenically precipitated micrite combined with mechanically disintegrated components (Pentecost, 2005), which is comparable in texture and composition to the Cat Island bushy microbialites (Figures 3 & 4E-H).

The associated less porous crystalline travertine, on the other hand, formed by high rates of calcite precipitation from fast flowing waters (Guo and Riding, 1998; Pentecost, 2005; Jones and Renaut, 2010). This process commonly produces hard and resistant crusts (Chafetz and Folk, 1984) whose shape and distribution conforms to the underlying topography and ranges from horizontal to vertical and overhanging (Jones and Renaut, 2010). Such crusts are composed of columnar calcite crystals with their long or c-axes perpendicular to the growth surface (Jones and Renaut, 2010). The same fabric of radial, elongated or fibrous spar also forms crusts that are produced by running water along river courses in arid regions (Pentecost, 2005). Just like the Cat Island examples (Figure 3), these crusts may be smooth and sheet-like, and merge with cascade or minidam deposits (Figure 2, and Pentecost, 2005). Similar dense, laminated crusts composed entirely of columnar calcite crystals up to 1 cm long associated with microbial bushes were reported from Arbuckle Mountains of Oklahoma by Love and Chafetz (1988). Guo and Riding (1994) also noted the association of dense crystalline crusts, which form by active flows on slopes, and shrub fabrics related to restricted water flows in pool settings of Quaternary travertine deposits from Italy. Laminated crusts are also analogous to the flowstone speleothems in caves, but the crust surfaces tend to be more irregular due to plant growth and entrapment of detritus (Pentecost, 2005; Pedley and Rogerson, 2010).

Elongated crystals form by rapid precipitation from waters that are supersaturated with regard to calcite due to rapid $CO_2$ degassing, but seasonal changes in spring discharge and degassing rate can cause elongated crystals to temporarily stop growing. This is reflected in the formation of lamination or growth lines, which is the most obvious feature of travertines (Jones et al., 2005; Pentecost, 2005). Crystalline travertines from Cat Island have numerous laminae that represent cessation and reinitiation of precipitation (Figure 4). Flowing surface water can also diagenetically alter pre-existing spring precipitates (Tucker and Wright, 1990; Pentecost, 2005; Jones and Renaut, 2010). The most obvious diagenetic alteration is surface dissolution and erosional truncation of older laminae, which is commonly observed in our Cat Island examples and occurs when travertines become exposed to waters undersaturated with respect to calcite, such as direct rainfall and soil-percolation waters (Pentecost, 2005). The soil zone with terrestrial vegetation that now caps Trial Hill is likely the most important contributor of carbonic acid that causes limestone dissolution and produces the characteristic corrosion features, including shallow erosional incisions into the North Point eolianites (Figures 2B & C) and erosional contacts between travertine laminae. These features suggest undersaturation, erosion, and dissolution prior to reestablishment of calcite precipitation due to subsequent $CO_2$ enrichment of seep water. The dark color of seep precipitates also likely reflects water interaction with soil and vegetation of the recharge area, as well as the presence of communities of microbes that provide sites of localized carbonate precipitation and organic staining within the seeps.

Any future research at Trial Hill should attempt to determine the timing of seep initiation in the area in order to discriminate between possible recent anthropogenic (e.g., modifications in vegetative and soil cover) vs. past natural influences. Nonetheless, the documented ephemeral characteristics and frequent switches from areas of active precipitation to sites of exposure and erosion within these Cat Island seeps indicate their very dynamic nature, which is mainly controlled by pronounced seasonal changes in the amount and distribution of rainfall. The Bahamas Archipelago has a tropical marine climate, with mostly dry winters characterized by occasional rains associated with cold fronts, and by wet summers with persistent trade winds and convective rainfall (Whitaker and Smart, 1997; Sealy, 2006). In addition, the Bahamas are within the North Atlantic hurricane belt with the hurricane season officially lasting from June 1 until November 30 (Sealy, 2006). The Alligator Point area on Cat Island receives about 1000 mm of rainfall annually and has about 80 to 100 rainy days per year, with the rainy season lasting for about 6 months from approximately mid-May to mid-October (Sealy, 2006). Thus it is not surprising that the seeps were inactive during the dry season in January when our observations were made.

## CONCLUSIONS

1) Subaerial springs are not commonly found within Holocene deposits of the Bahamas. The formation of springs requires a unique combination of stratigraphy and topography.

2) Trial Hill Ridge in the Pigeon Cay area to the east of Alligator Point on Cat Island provides a localized setting where water recharges through the porous Hanna Bay Member eolianite of the Holocene Rice Bay Formation, and is deflected down-dip when it reaches bedding planes of underlying, slightly better cemented North Point Member eolianite of the same formation. The water surfaces at the points where the Hanna Bay rocks laterally pinch out. This produces numerous small springs or seeps aligned parallel to the Exuma Sound shoreline and restricted to the slopes immediately south of the highest parts of the hill. Location and distribution of seeps delineate the contact between Hanna Bay and North Point eolianites in this area. Seeps were inactive during the dry season in January when observations were made, but likely have relatively low discharge related to immediate antecedent rainfall conditions.

3) There are two types of carbonate deposits associated with the seeps. The dense laminated carbonate crusts are an example of crystalline travertine that forms in areas of active water flow, surrounded by porous bushy microbialites that represent carbonate tufa-like material forming in moist areas between flow events. These interpretations were supported by the results of comparative field, petrographic, and stable isotope analyses.

4) The corrosive nature of seepage and dark color of associated carbonate precipitates is related to water interaction with soil and vegetation of the Trial Hill recharge area, and the biological contribution of $CO_2$ to the system is reflected in the stable isotope data. Microbial communities provide sites of localized carbonate precipitation and organic staining within the seeps.

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