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Fredrick D. Siewers and Jonathan B. Martin

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DISTRIBUTION OF FRESH WATER ON RUM CAY AND IMPLICATIONS FOR GENERATION OF SECONDARY POROSITY

Jonathan B. Martin and Jason Gulley
Department of Geological Sciences
University of Florida
PO Box 112120
241 Williamson Hall
Gainesville, Florida 32611-2120

ABSTRACT

The size of freshwater lenses and the amount of secondary porosity on carbonate platforms are thought to correlate positively with island width and mean annual precipitation and inversely with secondary dissolution porosity and hydraulic conductivity. Rum Cay and San Salvador Island have markedly different distributions of freshwater and secondary porosity although they are similar in size, are located about 30 km apart, and thus share a similar climate, including roughly equivalent mean annual precipitation and negative annual average water balances. The negative water balance causes water to be saline in lakes that form in swales between Pleistocene dune ridges on San Salvador Island. The lakes cover around a third of the land surface and separate individual freshwater lenses contained within the dune ridges. Rum Cay has flat topography, with few dune ridges, intervening swales, or lakes. Preliminary data presented here suggest a continuous freshwater lens exists on the island. Flank margin caves formed at the distal margins of freshwater lenses in dune ridges on San Salvador during the marine isotope stage 5e high stand. Most of Rum Cay would have been flooded at this time, and thus the distal margins of fresh water lenses, and conditions necessary to form flank margin caves, would have been confined to the edges of the island. Island topography appears to exert a strong control over the modern distribution of fresh water on these islands and on development of secondary porosity.

INTRODUCTION

The availability of potable water resources and the spatial distribution of secondary porosity on carbonate platforms, including the Bahamian Archipelago, are critically related to the thickness and areal extent of freshwater lenses. Freshwater lenses occur as layers of fresh water overlying saltwater (Sealey, 2006). The contrasting densities of the two types of water, along with permeability of aquifers, control the thickness of fresh water lenses according to the Ghyben-Herzberg principle (Budd and Vacher, 1991). The boundary between fresh and salt water is a zone of mixed brackish water that has variable thicknesses depending on tidal mixing (Oberdorfer et al., 1990) and distribution of effective porosity (Lu et al., 2009; Stoessell, 1995). Lens thickness is thus generally positively correlated with recharge and negatively correlated with hydraulic conductivity, which increases as dissolution creates secondary porosity, thinning the fresh water lenses (Vacher, 1988).

Dissolution of carbonate minerals in freshwater lenses is primarily restricted to the top of the water table and where brackish water forms from mixing of the fresh and salt water. No dissolution occurs below this zone because the saline groundwater is supersaturated with respect to calcite. Brackish water is undersaturated relative to calcite because mixing of fresh water and seawater results in linear variations in the reactant concentrations (e.g., Ca^{2+} and CO_3^{2-}), but saturation state is related to Ca^{2+} concentration by a power law (Drever, 1997; Stumm and Morgan, 1996). Dissolution is also enhanced at the top of the lens where diffusion of CO_2 from oxidation of organic carbon in the soil zone creates carbonic acid at the top of the water table (e.g., Giles and Marshall, 1986; Whitaker and Smart, 2007a; Whitaker and Smart, 2007b). Dissolution creates cavernous secondary porosity at the top of the water table, locally known as banana holes, and flank margin caves at the distal end of the fresh water lens (Harris et al., 1995; Mylroie and Carew, 1995) where undersaturated water from the top and bottom of the lens coalesce and specific discharge is greatest allowing flushing of reaction products from the lens (Moore, 2009; Mylroie and Carew, 1995).

Flow rates in freshwater lenses depend on climate, which controls recharge and the magnitude of evapotranspiration, and island width, which affects the size of the freshwater catchment and thus recharge (Vacher, 1988). Island width may be an inappropriate proxy for lens width in some Bahamian islands. Some of these islands, for example San Salvador Island, contain several small discrete lenses within topographic highs resulting from preservation of Pleistocene eolian dunes separated by lakes that formed in the swales between the dunes (Davis and Johnson, 1989). Nonetheless, islands with large amounts of recharge and thick freshwater lenses experience greater net dissolution and resulting increase in hydraulic conductivity. This link between recharge and dissolution is demonstrated by a systematic decline in both mean annual precipitation and hydraulic conductivity as one progresses south along the archipelago (Lucia, 1995; Whitaker and Smart, 1997a; Whitaker and Smart, 1997b).

Understanding the controls on lens position, thickness, and areal extent is thus fundamental to understanding the distribution of freshwater and development of secondary porosity on carbonate islands. In this paper we present preliminary water chemistry data collected from Rum Cay, Bahamas and compare it with previously reported water chemistry data from San Salvador Island, Bahamas (Davis and Johnson, 1989). Our preliminary data suggest that fresh water lenses of the two islands have distinctly different sizes and chemical characteristics. We discuss the potential causes of the differences in the distribution of fresh water on the islands, and speculate on the implications for secondary porosity generation considering differences in their fresh water lenses.

GEOLOGY AND HYDROGEOLOGY OF SAN SALVADOR ISLAND AND RUM CAY

Islands with similar landmass areas should have similar hydrogeological systems if their climate, aquifer properties, and the size of fresh water lenses are similar. The two islands discussed in this paper, San Salvador Island and Rum Cay, are similar in size and located on individual platforms. The islands are at approximately the same latitude, are separated by only ~30 km, and share an identical climate. Both islands experience evapotranspiration rates of between 1375 and 1500 mm per year but have average annual precipitation of about 750 to 1000 mm and thus an average annual negative water budget (Sealey, 2006). These similarities between the two islands suggest they could have similar hydrogeology and hydrogeochemistry.

San Salvador

San Salvador Island covers an area of about 170 km^2 on a relatively small platform, which extends only a few hundred meters offshore from its present coastline (Fig. 1). The geology of San Salvador Island is well known, serving as the type locality for Bahamian stratigraphy (Carew and Mylroie, 1997). The central portion of the island is composed of variably cemented Pleistocene dune ridges, which provide topographic relief. Dunes in the central and southern portion of the island have a north-south orientation as a result of being built by the northeast trade winds, while east-west trending dunes in the northwestern portion of the island have been built by frontal storms crossing the islands from the north. The dunes are characterized by common dissolution features, including abundant banana holes and flank margin caves (Carew and Mylroie, 1994).

Although the geology and stratigraphy of San Salvador Island are well known, only a few published studies have focused on water resources, sources of water, and controls on the chemical composition of the water (Davis and Johnson, 1989; Martin and Moore, 2008). The dune ridges are separated by numerous lakes in the interior of the island and these lakes comprise nearly one-third of the island's total area. Many of the lakes have periodic variations in water level that mimic ocean tidal frequency, but many of the lake tides are out of phase with the ocean tides and have smaller amplitudes. The tidal variations indicate the lakes are connected to the ocean and lake

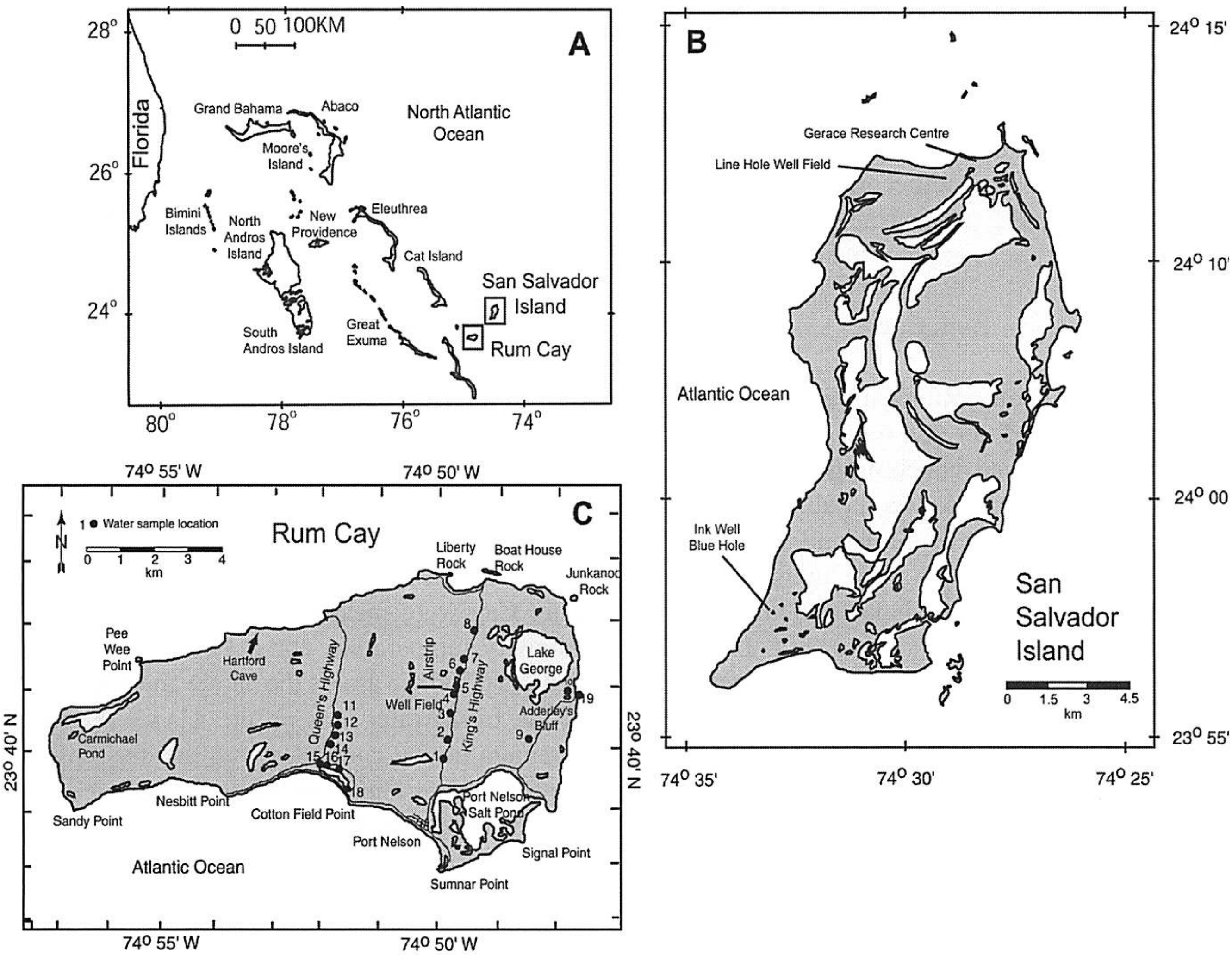

Figure 1. Maps of sampling locations. A. Northern Bahamas Archipelago showing the proximity of San Salvador Island and Rum Cay, B. San Salvador Island. The gray areas reflect land and the white areas are saline to hypersaline lakes. C. Rum Cay. Lake George is saline, but all other sampled sites are fresh to brackish. Port Nelson Salt Pond is connected to the ocean through a narrow inlet and is mostly normal marine salinity.

drains are common with those lakes with good conduit connections have near seawater salinity (Davis and Johnson, 1989). The lakes commonly contain water that is near or exceeds seawater salinity.

A conceptual model for hydrogeology of San Salvador Island, as well as the causes of hypersaline conditions in the lakes, was proposed by Davis and Johnson (1989). The model suggests multiple sources of water fill the lakes, including rainwater, seawater flowing through conduits connecting the lakes to the open ocean at the edge of the island, and water seeping from fresh water lenses below the eolianite dune ridges that separate the lakes. The negative water budget, coupled with the large surface areas of the inland lakes, causes the lakes to become hypersaline, by up-coning of underlying marine water, particularly during the dry season (Mylroie et al., 1995).

Rum Cay

Until recently, Rum Cay was inaccessible by commercial airlines and thus only two papers have been published concerning its geology or hydrogeology. Mitchell (1987) published the first report on the geology of the island, in which he subdivided the island into five units, including a low-elevation tidal creek facies that occupies most of the interior of the island (Fig. 1C). The highest point on Rum Cay is the northeastern corner of the island, rising to about 37 m above sea-level (Mylroie et al., 2008). The elevation of the island decreases to the west and the highest point on the western end of the island is 12 m at Black Rock. The tidal creek facies described by Mitchell (1987) is low lying with a flatter topography than the dune and swale topogaphy found on San Salvador.

Mitchell (1987) remained the only published work concerning Rum Cay until a geology field trip guide was published as part of the 14th Symposium on the Geology of Bahamas and Other Carbonate Regions (Mylroie et al., 2008). During the reconnaissance for that field trip, the geology of Rum Cay was placed in the framework of the San Salvador stratigraphy (e.g., Carew and Mylroie, 1995). Surface water is more limited on Rum Cay relative to San Salvador and includes Lake George, developed in the swales between dunes in the northeastern portion of the island and Carmichael Pond, the largest lake on the island, which is located on the western and topographically lower side of the island (Fig. 1). The middle of the island lies within the tidal facies mapped by Mitchell (1987) and was found during the reconnaissance for the field trip to contain numerous karst windows that intersect the water table. During the trip, limited physical and chemical parameters of the water were measured at selected sites. These data are reported in Mylroie et al. (2008) and reproduced here along with a comparison of water composition between San Salvador Island and Rum Cay, discussions of what may control the chemical composition on the two islands, and speculation of how the differing water chemistry may influence dissolution of the islands.

PRELIMINARY RESULTS: RUM CAY HYDROGEOCHEMISTRY

Eighteen bodies of surface water around Rum Cay were measured for their salinity, conductivity, temperature, and pH between 16 and 19 February 2008 to assess the nature and distribution of the fresh water lens on the island. This measurement period coincides with the dry season in the Bahamas. The sampled pools included small karst features, moderate-sized shallow lakes, and a new marina that had recently been dredged to the west of Cotton Field Point (Fig. 1). In addition to the inland pools, seawater on the eastern side of the island near Adderley's Bluff was measured for salinity, conductivity and temperature. All measurements were made using an Orion model 130 portable conductivity/salinity meter and an Orion model 250A pH meter. The latitude and longitude of each pool were recorded using a handheld

Table 1. Salinity, Conductivity, Temperature, and pH of water of select surface water pools on Rum Cay, Bahamas

Road	Location	Site*	Latitude	Longitude	Date	Time	Salinity	Conductivity (µS/cm)	T (°C)	pH
King's Highway	Tanker Site	1	23° 39.765'N	74° 49.978'W	16-Feb-08	8:00	0.1	655	25.0	8.4
	Ophiomorpha Pit	2	23° 40.218'N	74° 49.797'W	16-Feb-08	9:00	0.0	62	23.5	8.4
	North of well field	3	23° 40.626'N	74° 49.747'W	16-Feb-08	9:10	0.0	45	23.9	8.3
	Salt Pond	4	23° 40.928'N	74° 49.687'W	16-Feb-08	9:40	3.8	6260	25.2	8.3
	Unnamed pool 1	5	23° 41.094'N	74° 49.660'W	16-Feb-08	9:50	0.0	67	23.2	9.1
	Unnamed pool 2	6	23° 41.265'N	74° 49.553'W	16-Feb-08	10:00	0.0	95	22.1	8.3
	Twin sisters	7	23° 41.454'N	74° 49.524'W	16-Feb-08	10:05	0.0	291	23.7	8.9
	Mermaid pond	8	23° 41.863'N	74° 49.355'W	16-Feb-08	10:20	0.3	988	25.1	8.2
East coast road	Adley's pond	9			16-Feb-08	15:30	4.8	7540	30.9	8.6
	South of L. George	10			16-Feb-08	16:50	27.4	38000	31.3	8.3
Queen's Highway	Pool 1	11	23° 40.513'N	74° 52.555'W	19-Feb-08	11:10	19.8	31731	28.1	8.6
	Pool 2	12	23° 40.445'N	74° 52.060'W	19-Feb-08	11:20	0.2	403	24.3	8.0
	Pool 3	13	23° 40.391'N	74° 52.060'W	19-Feb-08	11:25	0.2	332	30.4	8.9
	Pool 4	14	23° 40.152'N	74° 52.077'W	19-Feb-08	11:35	5.7	11116	28.9	7.9
New Marina	Mangrove, west end	15	23° 39.627'N	74° 51.783'W	19-Feb-08	11:50	3.7	8298	27.8	9.0
	W. Channel	16	23° 39.615'N	74° 51.738'W	19-Feb-08	12:00	2.6	6701	25.0	9.3
	Main pool (surface)	17	23° 39.508'N	74° 51.571'W	19-Feb-08	12:05	2.1	5903	26.1	8.9
	Channel to ocean	18	23° 39.288'N	74° 51.611'W	19-Feb-08	12:20	11.5	20354	27.5	N/A
Ocean water	East side of island	19			16-Feb-08	17:50	39.7	53100	26.3	

* Site numbers keyed to location map

GPS. No samples were collected during the trip and thus the chemical composition of the water is unknown. Results of the measurements are reported in Table 1.

All of the pools that were measured had salinities less than seawater value despite measurements being conducted during the dry season when salinities of lakes on San Salvador are typically at their highest values (Davis and Johnson, 1989). Salinity values ranged from 0 to 27.4 practical salinity units (psu), with an average salinity of all the pools of 6.4 psu with a standard deviation of 11.0 psu. Other than a small pond south of Lake George (location 10, salinity = 27.4 psu) and the northern most pool on the Queen's highway (location 11, salinity = 19.8 psu), no pool had a salinity greater than 5.7 psu. Disregarding the two samples with elevated salinity, the water had an average value of 1.6 psu and a standard deviation of 2.0 psu (Table 1).

The low salinity of surface water on Rum Cay differs greatly from hypersaline surface water on San Salvador Island (Davis and Johnson, 1989; Martin and Moore, 2008). Davis and Johnson (1989) report Cl^- concentrations of surface water across the island that range from about 31 g/L to as much as 139 g/L, but do not report salinity or specific conductivity values for the water. To compare the Cl^- concentrations reported in Davis and Johnson (1989) with our salinity data from Rum Cay, Cl^- concentrations have been converted to salinity assuming the Cl^- is derived from seawater, that it behaves conservatively (i.e., not changed through water-rock interactions), and that it is has been concentrated through evaporation. If the seawater had an original Cl- concentration and salinity identical to unaltered seawater of 19.8 g/L and 35 psu, respectively, the average salinity is around 77 psu for surface water on San Salvador as reported by Davis and Johnson (1989), or about an order of magnitude more salty than the average value on Rum Cay.

Although not all sites where surface water is exposed have been sampled on Rum Cay, particularly in the western portion of the island (Fig. 1), the presence of mostly low salinity water suggests that the freshwater lens extends across the entire island. With this extent, the fresh water lens would be larger than most of the individual lenses that occur on San Salvador Island, although overall permeability of the islands is similar. Additional evidence for a larger fresh water lens on Rum Cay than San Salvador Island is shown by low salinity in the new marina that has been dredged on the southern side of the island. Salinity of water at the top of the pool ranges between 2.1 and 3.7 psu, with a general decrease in salinity with distance from the coast. A channel dredged to connect the marine with the ocean was silted in at the time these measurements were made but had a salinity of 11.5 psu in pools of water on the marina side of the channel. No vertical salinity gradient occurs in the upper 1.5 m of the pool, which is the limit for the cable length on the conductivity probe (Table 2). There is a slight, 0.2° C decrease in temperature over the upper 1.5 m of the water column, indicating the pool has stable density stratification. The relatively low and constant salinity throughout the marina suggests that although the fresh water lens has been breached during its construction, there has been little intrusion of seawater into the pool, at least in the upper 1.5 m of the water column. We have no information if a halocline is present in the harbor and if so at what depth.

CONCEPTUAL MODEL FOR HYDROGEOLOGICAL EVOLUTION OF SAN SALVADOR AND RUM CAY

The link between P_{CO_2}, fresh and salt water mixing, and solubility of carbonate minerals suggests that differences in the distribution of fresh water on Rum Cay and San Salvador Island should control the distribution of macropores such as banana holes and flank margin caves. The extensive exploration of San Salvador Island (for example numerous papers within this volume as well as the

Table 2. Conductivity and Temperature gradient in main pool of new marina

Depth (m)	Salinity (psu)	Conductivity (µS/cm)	Temperature (°C)
0	3.4	5903	26.1
0.5	3.4	5903	26.0
1.0	3.4	5903	26.0
1.5	3.4	5903	25.9

previous 13 symposium volumes) clearly shows flank margin caves along many dune ridges and banana holes and pit caves developed on the tops of the ridges. Although exploration is considerably more limited on Rum Cay than San Salvador Island, the locations of known flank margin caves are largely confined to the perimeter of Rum Cay as would be expected given the location of the distal edge of the fresh water lens at past sea-level highstands. Additional work needs to be done, particularly to understand the saturation state of the fresh water on Rum Cay with respect to carbonate minerals as controlled by its P_{CO2} and extent of mixing between fresh and salt water.

Hydrogeological settings would have differed between San Salvador Island and Rum Cay as sea level changed during the Quaternary and the differences in hydrogeology could have contributed to differences in the distribution of cavernous porosity between these islands. During the Marine Isotope Stage (MIS) 5e highstand, sea level was an estimated 5 to 7 m higher than present and San Salvador's dune and swale topography resulted in the island being divided into many smaller islands, each with their own individual freshwater lens. Flank margin caves formed at the distal margins of these freshwater lenses because of the combination of dissolution (either through elevated P_{CO2} or the mixing of fresh and saltwater) and high specific discharges in this region. Banana holes formed at the top of the water table, and are smaller than flank margin caves because they are located further from discrete inputs of CO_2 from the vadose zone and because the flow paths are shortest at the top of the water table. The generally low elevation on Rum Cay allowed most of the island to be flooded during the MIS 5e high stand, thus forming the tidal creek facies described by Mitchell (1987). Flank margin caves should be restricted to higher elevations found along coast of the island.

When sea level was lower than today, both islands would have been completely exposed forming continuous freshwater lenses across the width of the islands. Freshwater lenses during sea level lowstands have been assumed to be incapable of generating significant secondary porosity (Melim, 1996). Dissolution and actively-forming caves are reported from the top of the freshwater lens in Guam where the vadose zone is 180 m thick (Whitaker et al., 2006). Although this vadose zone is about 60 m thicker than expected in the Bahamas during the last sea level low stand, Guam may not serve as a perfect analogy to the Bahamian islands during the last sealevel low stand since it is tectonically uplifted and has a volcanic basement to trap the freshwater lens, rather than having it float on seawater as in the Bahamas.

Continuous freshwater lenses would have remained on San Salvador Island and Rum Cay until Holocene sea level rise reached the elevation of the swales on San Salvador Island, thus creating a series of lakes there. Although the topography is flatter on Rum Cay than San Salvador, its overall elevation is higher, and thus a fresh water lens would remain across the entire island. This scenario suggests the interplay between island size, topography, and climate impacts the position of the freshwater lens, groundwater quality, and karstification. One key factor linking topography with the salinity of water on both islands is the area of the exposed surface water. San Salvador has large lakes with extensive evaporation, while Rum Cay has surface water exposed only in small holes.

CONCLUSIONS

Climate is unlikely to cause the differences in salinity of the surface water found on Rum Cay and San Salvador Island because they are located only about 30 km apart. Instead, differences in salinity result from differences in their topography, with the small number of eolianite dune ridges and swales limiting the number of large lakes on Rum Cay compared to San Salvador Island. Consequently, Rum Cay experiences less evaporation and concentration of salts than San Salvador Island and thus lacks hypersaline conditions of the surface water. The small number of dunes and lakes on Rum Cay limits evaporation and allows a large fresh water lens to form. Because there is less topographic relief across Rum Cay, fewer large dissolution voids (e.g., flank margin caves) have formed at past sea level high stands compared to those on San Salvador Island. Difference in average salinity of surface water on these two islands is topographically controlled and this topography appears to also influence dissolution.

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