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MIXED GENERA SHALLOW WATER RHODOLITHS FROM ROATÁN, HONDURAS

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ABSTRACT. Rhodoliths are concentric nodules of calcareous red algae. The features, formation and distribution of very shallow water (<2m) rhodoliths have only recently been explored (Basso et al., 2009). The rhodoliths of Little French Cay Island, Roatán, Honduras occur in less than 1m of water in grass beds adjacent to a tidal channel leading to Crawfish Rock. These rhodoliths are found in a relatively small area part of which is surrounded by an artificial pen. The rhodolith size and density were measured both inside (3.08 +/- 0.60 cm diameter and 122 rhodoliths/m^2) and outside (3.66 +/- 1.01cm diameter and 21 rhodoliths/m^2) the pen. The rhodoliths are ellipsoidal to spheroidal in shape and are composed of mixed genera algae (tentatively identified as *Neogoniolithon* and *Hydrolithon* along with other genera). Potentially, the presence of very shallow water rhodoliths is more prevalent than previously thought in the Caribbean. In general, rhodoliths tend to be transported off the shelf by the high hurricane frequency as posited by Ballantine and others (2000). Roatán has been impacted by 35 hurricanes in the last 160 years; the last major one being Hurricane Mitch in 1998. The small size of these rhodoliths in these shallow waters would indicate that they are transported off-bank and potentially large deposits of rhodolith pavements exist on the slope as has been observed in the rock record (i.e., Oligocene of Georgia by Manker and Carter, 1987).

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INTRODUCTION

Honduras covers approximately 112,000 km^2 of land bordering the Caribbean Sea on the widest part of the isthmus of Central America (Figure 1). Its tropical climate is influenced by seasonal easterly trade winds, which cause a rainy season for approximately eight months and a dry season from November to February. The Bay Islands group (Figure 1) consists of three major islands (Utila, Roatán and Guanaja) on the edge of the 75 km wide continental shelf located in the western Caribbean (Figure 1). These islands are the center of Honduras' reef-related tourism and the nation's fishing industry (Fenner, 1993; Harborne et al., 2002).

To date, the carbonate environments of Roatán have not been fully investigated and published studies have focused on sedimentation rates (e.g., Mehrtens et al., 2001) and sediment composition and transport (Mehrtens et al., 2001; DeVore et al., 2012). In our 2011 study, the sands within the lagoon and slope of CoCo View Resort (Little French Cay Island) were analyzed along various transects. They consisted of *Halimeda*, mollusks, echinoderm, red-algal and coral fragments. The amount of carbonate sediments generated is substantial and *Halimeda* is an important contributor of the carbonate factory. In 2011, an active rhodolith zone was discovered in the grass beds of Little French Cay Island. The significance of an additional site with shallow water rhodolith formation is helpful towards furthering our understanding of the formation of deeper water rhodolith assemblages. Furthermore, the site described in this contribution provides a modern analogue useful for interpreting rhodolith pavements in ancient carbonate successions such

Figure 1. Map of Honduras showing the Bay Islands to the north. Roatán is the middle island. The study area is on the southern shore of the island marked by a star. (map from http://www.roatanisland.net/map.htm)

as the 30 meter thick Oligocene sequence bordering the Suwanee Straits of Georgia described by Manker and Carter (1987).

GEOGRAPHIC AND GEOLOGIC SETTING

Roatán, the largest of the Bay Islands, is a relatively long, thin island oriented in a nearly east-west direction. The general geological features of Roatán and adjacent submarine areas are described elsewhere (Banks and Richards, 1969; McBirney and Bass, 1969; Davidson, 1974; Halas and Jaap, 1982; UNEP, 1988). Roatán is a composite island with a core of metamorphic assemblages associated with active faults. The island's topography results in significant rainwater runoff and the reefs surrounding Roatán are periodically subjected to siltation during heavy rains associated with storm events (Halas and Jaap, 1982). Hurricane Mitch, one of the deadliest hurricanes in the Atlantic, greatly damaged the Central American north coast in 1998. It caused over 9,000 deaths, with Honduras receiving the greatest impact (Guiney and Lawrence, 1999).

The southern shore of Roatán has a terrace at 10-12 m depth that may correspond to the "Ten-Fathom Terrace" or to a shallow terrace commonly present on many Caribbean reefs. In Roatán, this terrace may represent a down dropped block (Mehrtens et al., 2001). In contrast, the north coast Roatán supports a discontinuous fringing reef broken up by channels and bights that were formed by erosion during glacial events. Reefs on both coasts have relatively narrow landward lagoons dominated by sea grasses. Additional information on biological and ecological zonation is provided in UNEP/IUCN (1988), Fenner (1993), and Kramer and others (2000).

The Bay and Swan Islands stretch in an arc between 29 and 56 km off the coast of Honduras (Figure 1) and are part of the Bonacca Ridge. The Bonacca Ridge forms an extension of the Sierra de Omoa Mountains on the edge of the Honduran shelf and, as a result, on the northern, ocean-facing side of the islands, the shallow water extends seaward only a short distance before the shelf-break. The Bonacca Ridge is a horst dissected by northeast–striking subsidiary faults, positioned just south and parallel to the Motagua/Swan Islands fault zone. To the south of the Bay Islands (Utila, Roatán, Barbareta, Guanaja and smaller islands), a normal fault separates the Bonacca Ridge from the Tela Basin (Pinet, 1975; Rogers, 2003; Rogers and Mann, 2007; Cox et al., 2008).

Bedrock on Roatán is pre-Cenozoic in age and is composed of suites interpreted as a low-grade greenschist and overlaying high-grade amphibolite facies (McBirney and Bass, 1969). The lithological similarity between Roatán and the Motagua Valley (Guatemalan mainland) has evoked workers to suggest that Roatán was a sliver of continental crust from the Chortis block (McBirney and Bass, 1969; Holcombe et al., 1990; Ave Lallemant and Cordon, 1999; Cox et al., 2008). The Flowers Bay Fault cuts across western portion of Roatán, and associated faults northeast faults intersect the island (Cox et al., 2008).

The elevation and position of fossil reefs and associated carbonate units have been used to document late Quaternary faulting events and four fabrics have been recognized. These consist of: dismicrite, coral boundstone, fossiliferous grainstone, and fossiliferous wackestone (Cox et al., 2008).

BACKROUND

Definition: What is a Rhodolith?

Rhodoliths are smooth or knobby nodules of free-living non-geniculate (i.e., lacking uncalcified joints) red algae (Rhodophyta, Corallinales). Within the order Corallinales, the families Corallinaceae or Peyssonneliaceae are the two families principally associated with rhodolith formation. Rhodoliths are mainly composed of Mg-calcite secreting red algae (Barnes et al., 1970; Toomey, 1975). However, aragonitic nodules of Peyssonnelids have also been described (Ballantine et al., 2000; Hillis and Jones, 2000).

Calcareous algal nodules have been described in the literature as oddities for over 225 years (e.g., Ellis and Solander, 1786). Today the literature on rhodoliths is extensive and over the last 40 years it has increased dramatically. Bosence (1983a) proposed a classification for rhodoliths and provided a literature review. Foster (2001) up-dated that review and mapped areas where rhodoliths have been found (Figure 2). Ballantine and others (2000) revisited the literature and documented the first occurrence of very shallow (<1m) water rhodoliths in the western Atlantic and Caribbean. These and other more recent studies (e.g., Gischler and Pisera, 1999; Freile and Fuks, 2001) further affirm the findings of Ballantine and others (2000) that rhodoliths beds are a feature frequently encountered in the shallow (<10m) western Atlantic and Caribbean, although very shallow occurrences are rare or have not been fully documented.

Historically, the shape, texture, morphology and growth patterns of rhodoliths have been used as paleoenvironmental indicators of both bathymetry and relative wave or tidal energy. However, this generalization may not be applicable in all situations. Reid and MacIntyre (1988) have argued that in the eastern Caribbean,

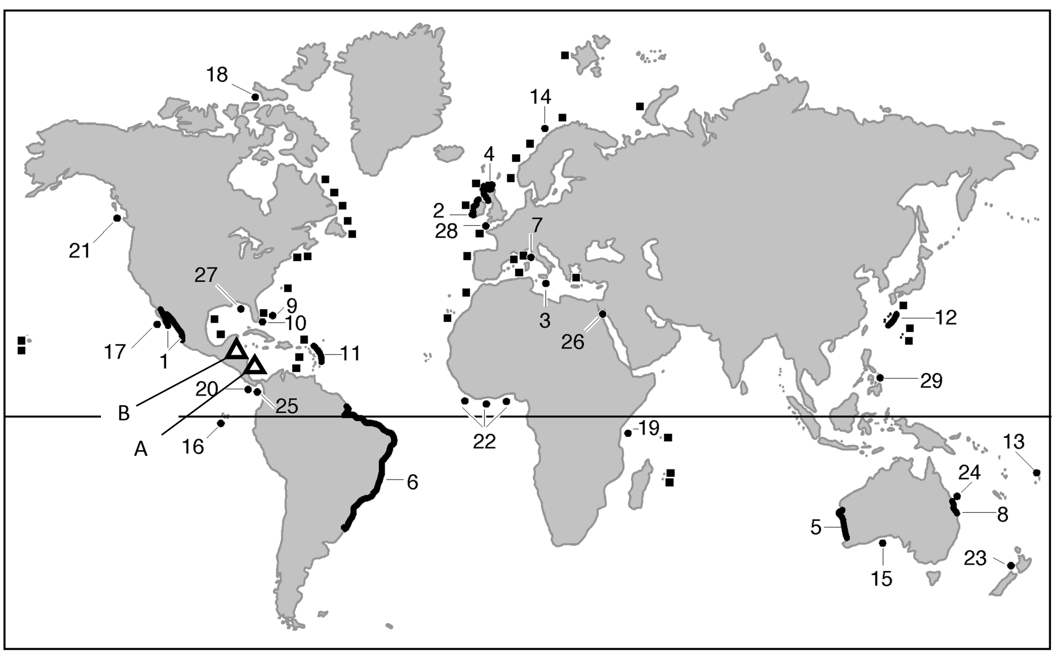

Figure 2. A map indicating the world distribution of living rhodolith beds. Squares are from map in Bosence (1983b). Circles indicate locations of individual beds, and dark bands indicate large, continuous beds or numerous individual beds from Foster (2001) map. Triangles indicate other studies in the Western Atlantic including the present one - (A) Freile and Fuks, 2001 (San Blas Islands, Panama) and (B). Current Study (Roatán). (Map modified from Foster, 2001)

paleoecological indicators such as nodule formation do not have a direct correlation with specific environmental conditions. There are still numerous questions to be addressed regarding the growth, morphology and consortia of red algae and other organisms involved with rhodolith formation and the conditions under which they form. Central to some of these questions is documenting and obtaining more information regarding the formation of rhodoliths in very shallow conditions.

Morphology and Composition of Rhodoliths

The bulk of the shallow water rhodoliths reported in the literature (e.g., Basso et al., 2009) are spheroidal to ellipsoidal in shape as are the ones in Roatán. Shapes of nucleated rhodoliths are strongly controlled by the original shape of the nucleus (Basso and Tomaselli, 1994; Ballantine et al., 2000). The frequent movement of rhodoliths will result in their final shape tending towards spherical (Basso et al., 2009). Tank experiments and field observations of fruticose rhodoliths, however, point to a close correlation between high protuberance degree and exposure to currents (Bosence, 1976; Basso and Tomaselli, 1994; Basso et al., 2000). The present study suggest that the tidal currents experienced in the grass-beds of the lagoon could be responsible for the degree of protuberances in the rhodoliths in the study area.

Basso et al. (2009) analyzed shallow water rhodoliths from many broader studies and classified them into five major structural groups: (A) low-density, non-nucleated, fruticose and monospecific rhodoliths (also unattached branches *sensu* Basso, 1998), composed of one or more genera primarily *Phymatolithon*, *Lithothamnion*, and *Lithophyllum* existing in middle to high latitudes; (B) high-density, nucleated rhodoliths (prâlines *sensu* Basso, 1998), dominated by *Hydrolithon* and associated with other mastophoroids (*Neogoniolithon* or *Spongites*) and *Lithophyllum* in the tropics; (C) unattached branches or fruticose rhodoliths of *Neogoniolithon* that are associated with sea-grass meadows; (D) mainly fruticose and monospecific rhodoliths comprised of one or more genera including *Mesophyllum*, *Lithothamnion*, *Hydrolithon*, *Neogoniolithon* which occur under tidal currents in Southern Hemisphere cool waters; and (E) *Sporolithon* prâlines, also from the cool waters of the Southern Hemisphere. In Roatán, although several different morphologies are present, rhodoliths with fruticose and prâlines forms are most commonly represented within assemblages (Figure 3A and B).

Many different species are responsible for rhodolith nodule formation including the

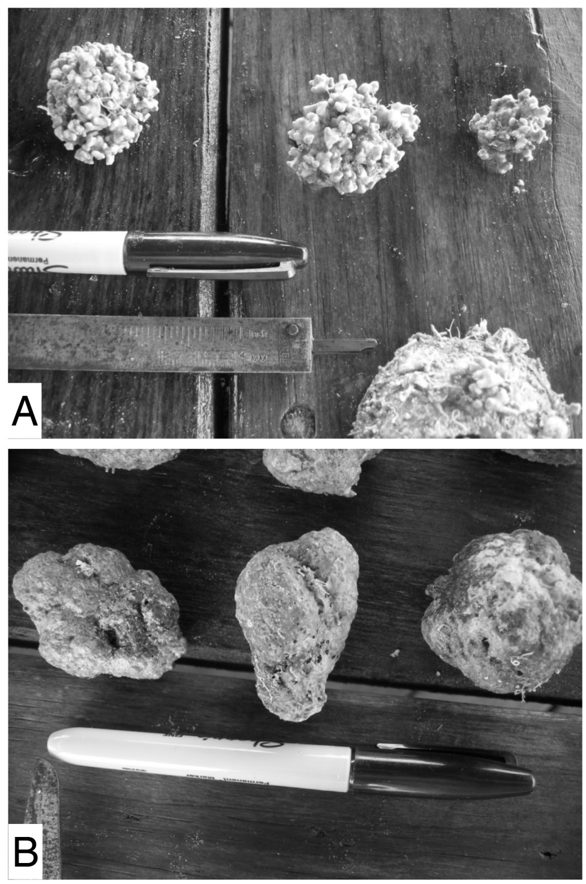

Figure 3. Examples of rhodolith morphologies present in the study area. They range from A) knobby to branching (prâlines to fruticose) to B) smooth and abraded prâlines and are primarily elliptical to spherical in shape. All samples were alive when collected.

following widespread tropical and temperate Coralline taxa (e.g., Prager and Ginsburg, 1989; Amado-Filho et al., 2012) - *Lithothamnium* (deep subtropical waters), *Lithophyllum* and *Neogoniolithon* (shallow tropical waters), *Archaeolithothamnium, Hydrolithon*, *Lithoporella*, and *Mesophyllum, Sporolithon* (deeper >40m tropical waters), as well as the shallow water Peyssonnelids - *Peysonnella* (e.g., Hills and Jones, 2000) and *Cruoriella* (Ballantine et al., 2000). We have tentatively identified the algae as *Neogoniolithon* in the fruticose nodules and *Hydrolithon* in the prâlines forms.

METHODS

The study site is located within the CoCo View resort marina. The shallow lagoon is flanked by a series of cabanas, a boardwalk, and a submerged mesh fence forming a small, protected area of seagrass beds shielding the dive boats and shore from wakes (Figure 4). The plastic fence has approximately 1.0 cm diameter mesh and acts as a sieve for any material transported into or out of the enclosed area. Since rhodoliths were found both within and outside the enclosed seagrass beds, the configuration permits testing whether the rhodoliths would be transported from very shallow water to deeper environments. If transport seaward occurs, one would expect the densities of rhodoliths within the enclosed area to be greater than those outside of the enclosure.

Four transects (Figure 4) were run within a seagrass bed enclosure at the west end of the CoCo View Resort. Two additional transects were run outside the enclosure. Each transect had several stations approximately 3-5 meters apart and at each station the rhodoliths present in four $0.25m^2$ quadrats were counted (Table 1 and 2). Transect 1 had 5 stations along the transect, transect 2 had 7 sample sites; transect 3 had 3 locations and transect 4 which ran perpendicular to transects 1, 2 and 3 had six stations and also four quadrats were sampled at each station. Outside the enclosure, two parallel transects one with 7 and the other 9 stations were counted; each station

Figure 4. Google Earth satellite view of study area at the CoCo View Resort. White arrow points to rhodolith area (A) seagrass beds (inside artificial pen); area (B) is outside the enclosure and near a sand blowout area, visible in the photograph. The lines mark transect lines inside and outside enclosure. Three 30-45 meter transects were run North-South inside the enclosure and one 45 meter transect was run East-West; while two 50 meter transects (NE-SW) were run outside the enclosure. The thick white line at the top is a scale line of 250 meters.

TRANS 1	A	B	C	D
Stat.1 (S)	19	10	7	12
Stat.2	6	5	1	5
Stat.3	1	0	4	0
Stat.4	0	2	0	0
Stat.5 (N)	1	0	1	0
TRANS 2	A	B	C	D
Stat.1(N)	0	0	0	0
Stat.2	0	1	0	0
Stat.3	0	1	4	5
Stat.4	2	3	4	1
Stat.5	17	9	2	5
Stat.6	0	0	0	0
Stat.7 (S)	0	0	0	0
TRANS 3	A	B	C	D
Stat.1 (S)	22	19	17	21
Stat.2	100%	100%	100%	75%
Stat.3 (N)	5	4	3	2
TRANS 4	A	B	C	D
Stat.1 (W)	80%	100%	100%	75%
Stat.2	50%	50%	12	13
Stat.3	20	7	3	16
Stat.4	0	0	0	0
Stat.5	0	2	0	0

Table 1. Densities cover data for rhodoliths from the grass-beds inside the enclosure. The measurements were taken at low tide at a depth of approximately 0.5meters. Transects 1, 2 and 3 run North-South, while Transect 4 runs East-West. A 0.25m^2 quadrat was used and 4 replicates were counted at each station (A-D). The number of stations varied from 3 to 7 on each transect. The transects varied from 30 to 45 meters long. The stations were 5 meters apart. Those stations that had 100% cover often had 2 layers of rhodoliths and over 200 specimens.

TRANS 1	A	B	C	D
Stat. 1 (SW)	2	7	1	1
Stat. 2	6	4	6	8
Stat. 3	2	0	0	0
Stat. 4	0	0	0	0
Stat. 5	0	0	0	0
Stat. 6	8	15	5	17
Stat. 7 (NE)	7	6	3	2
TRANS 2	A	B	C	D
Stat. 1(SW)	6	3	4	6
Stat. 2	2	2	1	1
Stat. 3	1	13	6	2
Stat. 4	0	0	1	4
Stat. 5	1	8	4	9
Stat. 6	12	25	8	22
Stat. 7	8	15	23	3
Stat. 8	2	7	8	3
Stat. 9(NE)	3	5	6	4

Table 2. Density cover data of rhodoliths from the grass-beds outside the enclosure. The measurements were taken at a depth of approximately 1.5meters. Transects 1 and 2 run Northeast-Southwest and are approximately 50 meters long. A 0.25m^2 quadrat was used and 4 replicates were counted at each station (A-D). The number of stations varied from 7 on T1 to 9 on T2. The stations were approximately 5 meters apart. The transects ended approximately 3 meters from the walkway that surrounds the enclosure.

also had four quadrats counted by 2 individuals using snorkel gear since water depth never exceeded 1.5 m (Figure 4). Additionally, 8 random quadrats from both inside and outside the

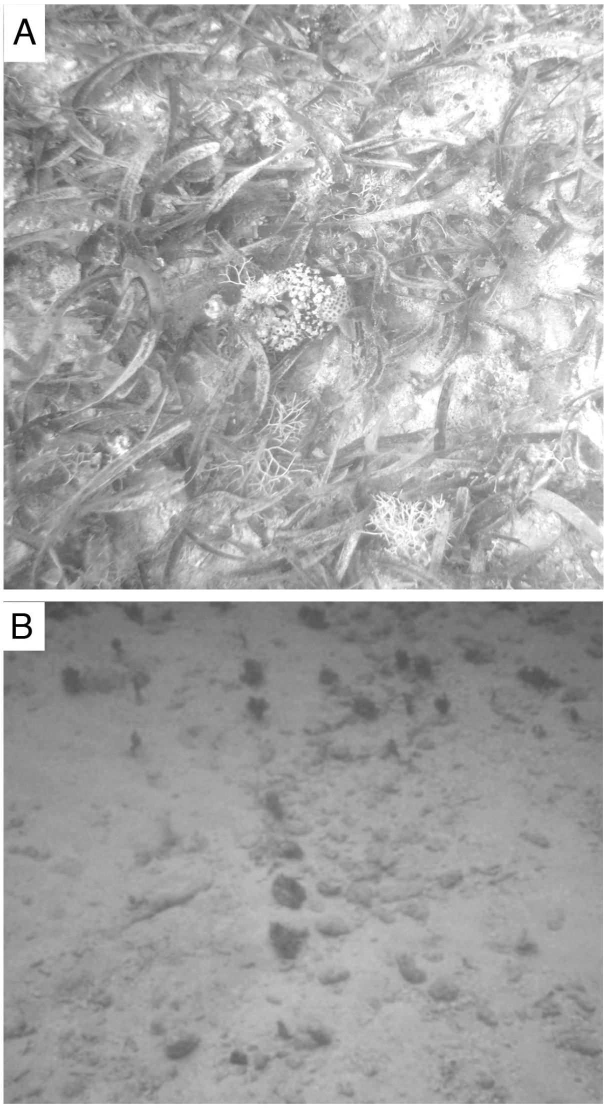

Figure 5. Underwater view of rhodolith beds from areas A and B (See Figure 4 for locations). Each rhodolith is approximately 3 to 4 centimeters in diameter. A) seagrass bed, inside the enclosure, center of photographs shows a fruticose rhodolith; B) sandy pavement area rhodoliths and Halimeda observed in this photograph corresponds to area B outside the enclosure.

enclosure were collected consisting of a total of 140 rhodoliths; these were measured and their shape and size where determined.

RESULTS AND DISCUSSION

The densities of rhodoliths are greatest towards the southwest by the enclosure's mesh

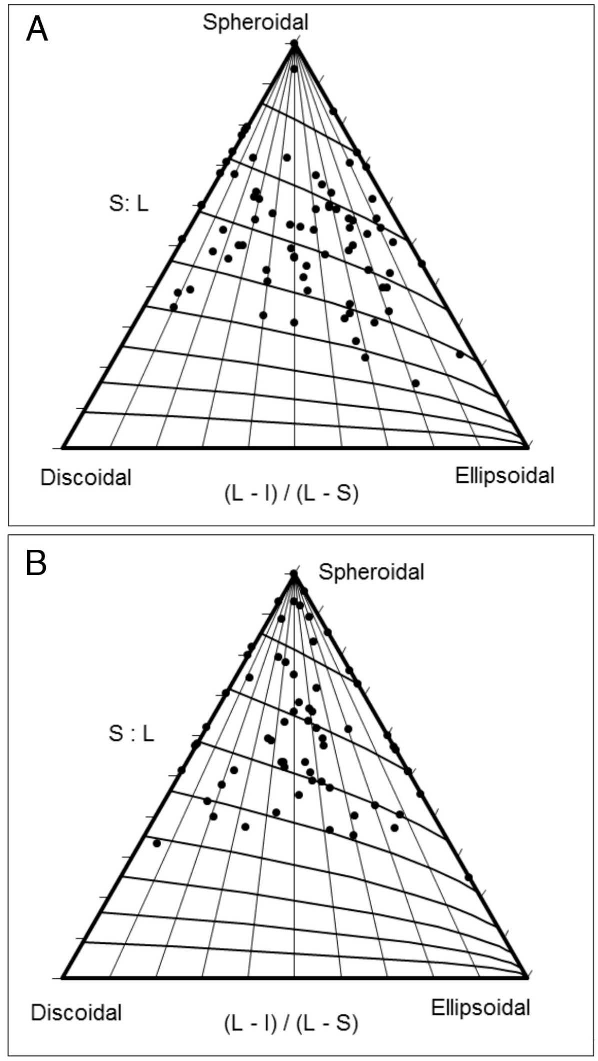

Figure 6. Shape classification of rhodoliths based on Sneed & Folk's (1958) descriptive shape classes. A) Within the enclosure. B) Outside the enclosure. Data were obtained using a program by Graham and Midgley 2000.

"wall" (Table1). The substrate in this area is pavement-like with 100% rhodolith cover in some areas. In the grass beds themselves, the rhodoliths are not as packed but they are present in moderately large numbers (Figure 5) on average 10-15 rhodoliths/m^2 (Table 1). The rhodoliths outside the enclosure are less densely packed (Table 2 and Figure 5) and more spherical than those inside (Figure 6). Overall the density of rhodoliths is 122/m^2 inside and 21/m^2 outside the enclosure. The difference in densities is so great that no statistical methods are needed to prove they are significant. The rhodoliths are all alive, their red coloring present upon turning them and have a mean diameter size of 3.08 +/- 0.60 cm inside the enclosure and 3.66 +/-1.01 cm outside and are spheroidal to ellipsoidal (Figure 6). The rhodoliths exhibit the characteristics of Basso et al. (2009) groups (B) high-density, nucleated rhodoliths pralines, and (C) unattached branches or fruticose rhodoliths (Figure 3).

The shape of rhodoliths is an indicator of overturning frequency (Bosence, 1983a, b). The change in rhodolith shape is also correlated to variations in hydraulic properties during growth (e.g., Braga and Martìn, 1988; Gischler and Pisera, 1999). Ellipsoidal and spheroidal forms are related to frequent turning in higher energy environments while discoidal and irregular growth-forms occur in less exposed areas where infrequent movement leads to flattened growth forms (Bosence, 1983a, b; Steller and Foster, 1995). A random set of quadrats were obtained for shape classification from both inside and outside the enclosure. The plots of clast axes, and percentages of Sneed and Folk (1958) shape classes were plotted using Graham and Midgeley (2000) excel program. These data for the inner and outside rhodolith beds are provided in Figure 6. Those subject to transport, located outside the enclosure, are predominantly spheroidal (30%) or spheroidal-to-ellipsoidal (25%). In contrast, the rhodolith bed inside the enclosure are not dominated by a single shape class of rhodoliths with the highest percentage of rhodoliths falling into the spheroidal-to-ellipsoidal class (17%) followed by 16% (both spheroidal and discoidal classes) and ellipsoidal (14%). The higher percentage of spheroidal forms, in the outer rhodolith bed is therefore not surprising and suggests that these rhodoliths are subject to more frequent turnover than those located within the enclosure. The presence of ellipsoidal and spheroidal forms in very shallow water environments is not unexpected since wind generated waves would provide a means of frequent turning. Rhodoliths were not observed in the deeper >2 m seaward sides of the sea grass beds.

The small size (3.08 +/- 0.60 cm diameter for the inner and 3.66 +/- 1.01cm diameter for the outer grass-bed rhodoliths) and the spheroidal to ellipsoidal shape of these rhodoliths could potentially indicate their rapid transport off-shore by storms, including both thunderstorms and hurricanes. The Bay Islands have been hit by a number of category 4 and 5 hurricanes as well as numerous other hurricanes and storms in the last 150 years (Figure 7). Hurricanes Mitch (Category 5) in 1998 and Iris in 2001 (Category 4) were the last major hurricanes to impact the area. Four storms (1920, 1926, 1942 and 1960) have directly impacted the study area (Figure 8). Ballantine and others (2000) have postulated that shallow water rhodoliths are readily transported offshore after strong storms. These workers also documented the existence of *Cruoriella* accretions around the transplanted rhodoliths. Based on rates published by Steller and Foster (1995) and Foster (2001), a 20-30 mm layer of growth, was estimated to indicate 12-24 years of *Cruoriella* accretion. The rhodoliths in Roatán are on average 30 mm in diameter. In order to address the likelihood of storm transport of these near shore rhodoliths, it is essential to locate and document channels with thick accumulations of rhodoliths (pavements) in deeper zones (>10m).

Outcrops of the Bridgeboro Formation (Early/Lower Oligocene *or* 33.9 to 28.4 Ma) in SW Georgia, USA, near Bainbridge, represent channel deposits (Suwannee Strait) and contain distinct rhodolith beds (Manker and Carter, 1987; Freile and Fuks, 2001). The Bridgeboro Formation is a rhodolithic limestone cemented with calcarenite along with whole echinoids and abundant calcareous nodules. In the Bridgeboro Formation the larger (>5cm) rhodoliths are present in the basal section where the density is 327/m^2 while the smaller rhodoliths (1-3 cm in diameter) are found in the upper unit where densities are 499/m^2 (Freile and Fuks, 2001). Echinoids and foraminifera are common constituents in this formation as well (Manker and Carter, 1987; Freile and Fuks, 2001). The lower-rhodolith bed of the Bridgeboro Quarry is characterized by a low diversity assemblage of taxa associated with rhodoliths while associated taxa are more diverse in the upper unit (Manker and Carter, 1987). At the Roatán site, the sea grass communities where the rhodoliths are forming are rich in nearshore, shallow water elements rare in the Bridgeboro rhodolith deposits (e.g., *Cerithium*, *Mancini*, and annelid tubes). Other organisms associated with mobile substrates and possessing the ability to move in association with a shifting substratum are absent in the Roatán material (e.g., *Chlamys*). The low densities, increased diversity of associated taxa provide a potential index for assessing the depth and mobility of rhodolith beds. In particular, the presence of *Manicini* attached to rhodoliths within the enclosure, suggests that these beds are not highly mobile and are subject to transport by infrequent storm events.

Interpreting ancient carbonate sequences containing rhodolith pavements could be aided by a better understanding of the relationship between rhodolith genesis in shallow water settings and subsequent transport to offshore environments. The occurrence of rhodolith pavements potentially serves as a marker for documenting storm events and changing climate regimes. The Eocene-Oligocene transition at 34 Ma constitutes one of the major episodes of climate change that occurred in the last 50 Ma (Ortiz and Kaminski, 2012). Between 35 and 15 Ma the Earth's temperature was approximately 3–4°C warmer than today and atmospheric carbon dioxide concentrations were twice as high (Cowie, 2012). Under such a climatic regime, hurricane strength and frequency could have been extreme as the climatic regime shifted towards a more seasonal one. The potential of using rhodolith packstones as a proxy for documenting intense storm events holds potential. However, additional studies of modern systems consisting of extremely shallow rhodoliths being transported into deep water are needed. In order to track this transport, it is necessary to find a setting where we definitively have shallow water rhodolith beds traceable to

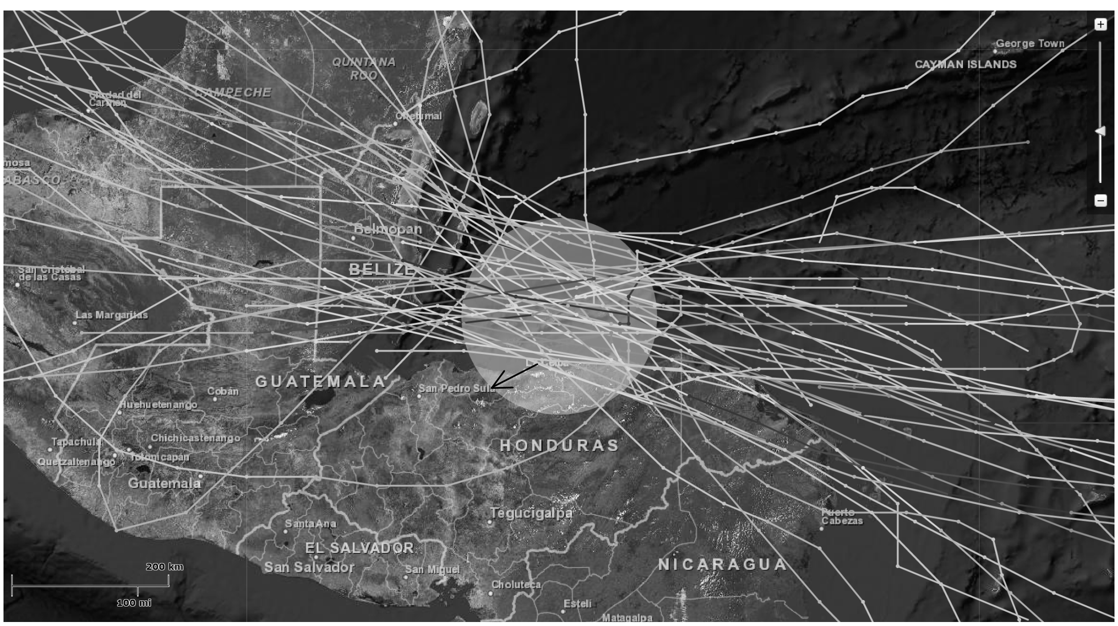

Figure 7. Hurricanes and tropical storms that have greatly impacted Central America between 1864 and 2013. Circle is centered over the location of Roatán and extends in a 65 nautical miles radius from the island (data from NOAA, http://coast.noaa.gov/hurricanes/?redirect=301ocm#).

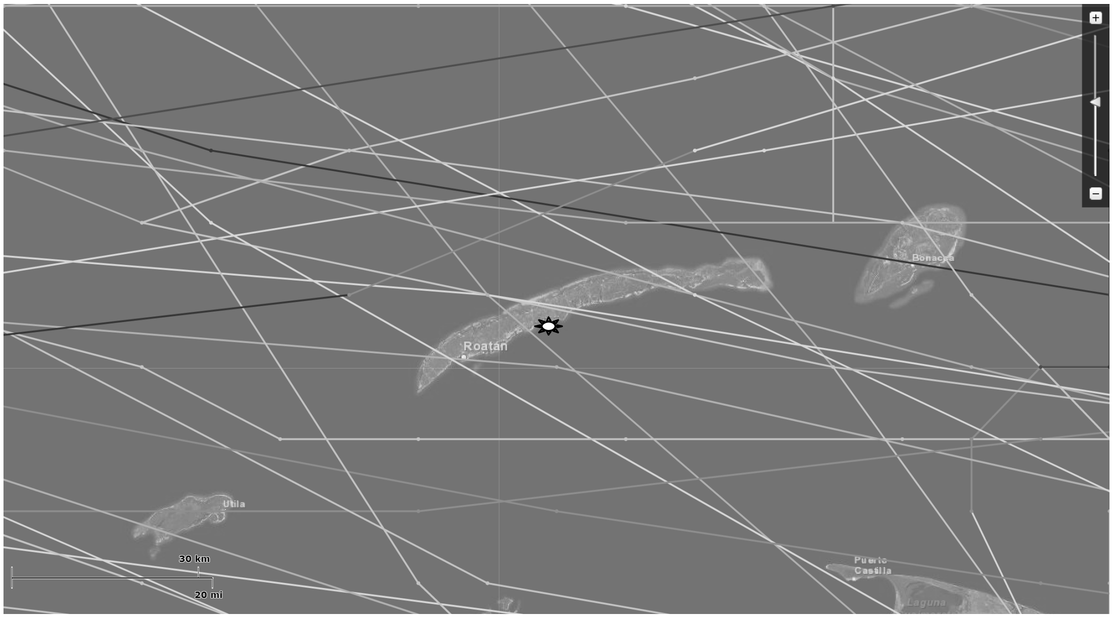

Figure 8. Hurricanes and tropical storms that have impacted Roatán directly between 1892 and 2011. Four storms (1920, 1926, 1942 and 1960) have directly impacted the study area which is marked by a star. The scale bar is 30 kilometers wide (data from NOAA, http://coast.noaa.gov/hurricanes/?redirect=301ocm#app=c64c&88cd-selectedIndex=0).

deeper water environments. In this regard, Roatán is ideal and we are currently documenting environments on the island where rhodoliths are transported to develop a model of origination and transport of rhodoliths on both shelves and slopes of bank walls.

CONCLUSIONS

1) Rhodolith formation in shallow water may be more prevalent than we previously believed. Since rhodolith pavements are not interpreted as being indicative of very shallow water regimes, we fail to examine very shallow water environments in regards to identifying actively growing rhodoliths.

2) Epifaunal growth on very shallow rhodoliths is altered during transport to deeper water environments. Modern rhodolith beds in deeper water environments therefore would exhibit some sort of anomalous growth pattern or shift in growth from very shallow water to deeper water conditions, which may be observed.

3) Storm events and their frequency potentially have a significant impact on preservation and occurrence of rhodolith pavements in carbonate sequences.

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