

## Occurrence and distribution of rhodolith beds on the Fernando de Noronha Archipelago of Brazil

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### ABSTRACT

Carbonate banks have been associated with a depth-window of 0 and 70 m in the major oceans of the world. Crustose coralline algae (CCA) are well recognized as the most important carbonate builders in the tropical Southwestern Atlantic continental shelf, forming structural reefs and extensive rhodolith beds. The Brazilian Fernando de Noronha Archipelago (FNA) is surrounded by poorly known insular shelf mesophotic reefs (>30 m depth). In this study, we used a remotely operated vehicle (ROV) and SCUBA diving to survey benthic features at 11 sites on the FNA. We found that rhodolith beds represent the main habitats of insular shelves of the archipelago from 10 to 100 m depth. Six coralline algae species were identified forming the rhodoliths. The mean abundance of rhodoliths ranged from  $294 \pm 26$  (mean  $\pm$  SE) to  $451 \pm 30$  ind m<sup>-2</sup>, while the mean diameter varied between  $3.4 \pm 0.3$  and  $5.9 \pm 0.4$  cm and live surface was always greater than 96%. In addition, we observed mounds built by the sand tilefish *Malacanthus plumieri* (Bloch, 1786) up to 40 m from the bed boundaries suggesting that *M. plumieri* populations play an important role in the dispersion of rhodoliths across the FNA shelf.

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### 1. Introduction

Due to its high ecological and touristic importance, the Fernando de Noronha Archipelago (FNA) has been included in a national marine park since 1988 with the goal of conserving Brazilian marine habitats. Marine systems and their habitats are being altered at a faster rate than initiatives aimed at the conservation and sustainable uses of these systems are being developed (Norse and Crowder, 2005).

Crustose coralline algae (CCA) are well recognized as the most important carbonate builders in the tropical Southwestern Atlantic Ocean, forming structural reefs and extensive rhodolith beds (Amado-Filho et al., 2007, in press; Riul et al., 2009; Pereira-Filho et al., 2012). Because of the habitat provided by rhodolith beds and the diversity of organisms associated with them, these rhodolith beds, like coral reefs, require special initiatives to develop appropriate strategies for their conservation (Amado-Filho et al., 2010).

Rhodoliths are also considered of great importance as calcium carbonate (CaCO<sub>3</sub>) sinks. The saturation state of CaCO<sub>3</sub> is largely determined by variations in the pH of seawater (Doney et al., 2009).

Ocean acidification reduces the structural integrity of carbonatic structures (Doney et al., 2009), and the pH values predicted for the end of the century according the Intergovernment Panel on Climatic Changes (IPCC) will have major implications for CaCO<sub>3</sub> dynamics (Feely et al., 2004). Great progress has been made in understanding CaCO<sub>3</sub> production by carbonatic reefs (Spalding and Kinsey, 1997; Kleypas, 1997; Amado-Filho et al., in press). On the other hand, the lack of data on the actual areas and on the depth distribution of the carbonate reefs in the world has hampered a more detailed appreciation of their importance for carbonate production and, therefore, their role in climatic effects (Vecsei, 2004). Rhodolith beds have been shown to provide habitat for some endemic species (Amado-Filho et al., 2007; Guimarães and Amado-Filho, 2009; Villas-Boas et al., 2009). Therefore, changes in carbonate dissolution represent losses of habitat and, consequently, losses of biodiversity.

Prager and Ginsburg (1989) described two main ways in which rhodolith dispersion occurs: (1) physical transport during surge events or hurricane-strength storms and (2) bio-induced repositioning due to benthic activities of the echinoderm *Meoma ventricosa* and the sand tilefish *Malacanthus plumieri*. Clark et al. (1998) showed that *M. plumieri* are found from the south of Brazil to North Carolina, USA. On the Brazilian coast, where there are no large areas covered by coral reefs (Figueiredo et al., 2008), the occurrence of *M. plumieri* overlaps with the range of rhodolith beds suggested by Foster (2001).

**Abbreviations:** CCA, crustose coralline algae; IPCC, Intergovernment Panel on Climatic Changes; FNA, Fernando de Noronha Archipelago.

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For coralline reefs dominated by corals, the most profound changes caused by anthropogenic impacts occur at depths shallower than 20 m, whereas reefs deeper than 30 m (mesophotic zone) have been observed to be free from the majority of these impacts (Bak et al., 2005; Lesser et al., 2009; Kahng et al., 2010). Therefore, reefs from the mesophotic zone may serve as important refugia for species that inhabit shallow reefs (Lesser et al., 2009). Vecsei (2003) pointed that the world's warm-water carbonate platforms are large-scale topographic features with systematic depth distribution. Based on this data he proposed a 0–70 m “depth window” for coralline reefs occurrence. However, the South Atlantic Ocean was not taken into account in the “depth window” hypothesis (Vecsei, 2003, 2004). Recently, Amado-Filho et al. (2007, in press), Riul et al. (2009), Bahia et al. (2010), and Pereira-Filho et al. (2012) have shown that extensive areas of the Southwestern Atlantic continental shelf and seamounts are covered by carbonate reefs dominated by rhodoliths at the same “depth window” of occurrence proposed by Vecsei (2003).

Fernando de Noronha Archipelago was formed by two volcanic events with an erosive process that occurred between Mid-Miocene and Pliocene. Between the Pliocene and the Pleistocene another erosive cycle was responsible for the build of FNA insular shelf (Castro and Antonello, 2006). The FNA insular shelf is relatively narrow (around 2 km) compared with other Southwestern Atlantic areas where carbonate reefs have been described (Pereira-Filho et al., 2012; Amado-Filho et al., in press).

Here, we tested the carbonate reefs “depth window” hypothesis (Vecsei, 2003) for the narrow insular shelf of FNA describing the rhodolith beds of this area. Also, we added new information on the possible role of *M. plumieri* in the local connectivity between the shallow and mesophotic zones.

## 2. Methods

The Fernando de Noronha Archipelago is located at 3°50'10"S and 32°25'30"W, 345 km from the northeastern Brazilian mainland (Fig. 1). A preliminary survey of the archipelago was carried out in April 2007 by scuba diving. This survey captured 8 h of video recordings along the archipelago's depth gradient. At this time, five sites were surveyed: Ressureta (RE), Sapata (SA), Barro Vermelho (BV), Pedras Secas (PS) and Cabeço das Caieiras (CC) (Fig. 1). During a 10-day follow-up expedition (October 2010), a remotely operated vehicle (ROV, Video Ray Explorer) was employed to determine the distribution of rhodolith beds in the mesophotic zone down to 100 m at six other sites along the insular shelves of the archipelago (Fig. 1), capturing an additional 10 h of video recordings. The benthic habitats in the shallow and mesophotic zones at RE, SA, BV, PS and CC were also sampled by scuba diving. At each site, 10 photoquadrats (0.49 m<sup>2</sup>) were randomly dispersed along three 50-m transects situated at a depth of 15 m (except at BV and SA, where surveys took place at depths of 53 and 22 m, respectively). The Coral Point Count software v.3.6 (CPCe; Kohler and Gill, 2006) was used to analyze the images, and the structure of the rhodolith beds was described using a measure of abundance (ind m<sup>-2</sup>). The rhodolith diameter was also determined from the images by scaling the images based on the photoquadrat edge (0.7 m). The differences between rhodolith abundance (ind m<sup>-2</sup>) and rhodolith diameter among sites were compared using ANOVA, and the Tukey's post-hoc test was performed with Bonferroni correction when necessary (Zar, 1999).

In addition to the image analyses, divers randomly sampled 30 rhodoliths from each site. To record the original color of the rhodoliths, we took pictures of their up face immediately after they had been removed from the water. Rhodolith percent live surface was estimated based on a pigmentation analysis of the coralline

**Table 1**

Abundance (ind m<sup>-2</sup>) and diameter (cm) of the rhodolith beds from the Fernando de Noronha Archipelago (FNA) (mean ± SE). Letters in superscript indicate the Tukey's post-doc test for each parameter.

	Abundance	Diameter
Sapata	450.9 ± 29.8 <sup>b</sup>	3.4 ± 0.3 <sup>d</sup>
Pedras Secas	429.0 ± 31.6 <sup>b</sup>	5.2 ± 0.5 <sup>e,f</sup>
Barro Vermelho	367.5 ± 31.8 <sup>a,b</sup>	4.9 ± 0.3 <sup>f</sup>
Cabeço das Caieiras	306.1 ± 38.7 <sup>a</sup>	5.9 ± 0.5 <sup>e</sup>
Ressureta	293.6 ± 25.5 <sup>a</sup>	5.0 ± 0.3 <sup>f</sup>

algae thallus surface (Peña and Bárbara, 2008; Martin and Gattuso, 2009; Bahia et al., 2010) using CPCe software.

Identification of the crustose coralline algae species comprising the rhodoliths was based on both vegetative and reproductive characters according to, Verheij (1993), Harvey et al. (2006), Harvey and Woelkerling (2007), Villas-Boas et al. (2009), Bahia et al. (2010, 2011) and Basso et al. (2011). Formalin-preserved specimens were first decalcified in 10% nitric acid. Then, all specimens were immersed in a series of 70%, 90% and 100% ethanol solutions for a minimum of 1 h each. Specimens were subsequently immersed in Leica HistoResin infiltration medium (Leica Microsystems, Wetzlar, Germany) until they were completely infiltrated. A hardening solution was added to the infiltration medium, and the specimens were oriented in this final solution until they had set. All specimens were sectioned at a thickness of 3–8 µm using a Bright 5030 Microtome (Bright Instrument Co. Ltd., Cambs., England). Each section was removed from the microtome blade using a fine sable hair brush and transferred to a slide covered with distilled water. All slides were then placed on a hot plate until they were dry, followed by staining with 1% toluidine blue.

In addition to confirming the presence of rhodolith beds at depths between 30 and 100 m (Fig. 1), ROV operations allowed us to detect the presence of *M. plumieri* mounds at the deeper boundaries of the beds. Mixed gas technical dives (TRIMIX) were employed to conduct three 50-m video transects at the largest *M. plumieri* colony we observed on the FNA (Fig. 1). These transects were filmed 5 m from the bottom, each covering an area of 200 m<sup>2</sup>. Sequential frames were analyzed using CPCe to obtain the distances between the mounds and the area occupied by the mounds.

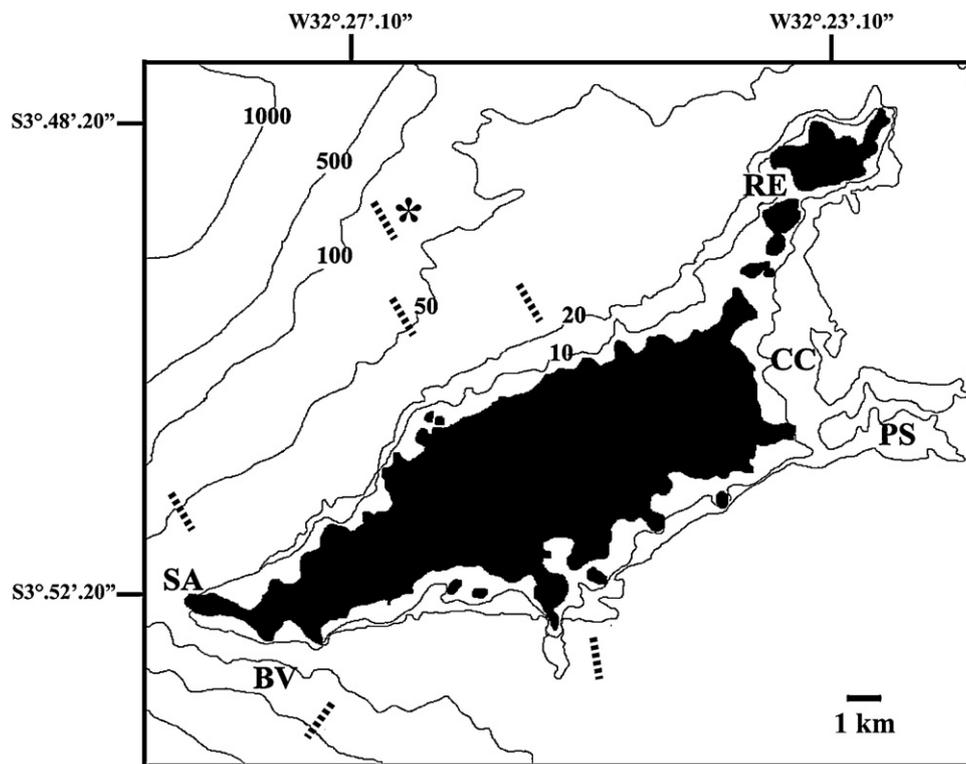
## 3. Results

Rhodolith beds were observed at all study sites (Figs. 1 and 2A), occurring at depths of 10–100 m. The presence of shallow-depth rhodolith beds depended on the availability of a flat seabed, which varied among the sites. Video analysis revealed that the depth at which the rocky shore was replaced by a soft bottom interspersed with rhodoliths ranged from 10 to 50 m (RE = 10 m, PS = 15 m, CC = 16 m, SA = 20 m, BV = 50 m).

The mean abundance of rhodoliths (ind m<sup>-2</sup>) differed among the sites (ANOVA;  $F = 4.9$ ,  $p < 0.01$ ). The Tukey test showed that rhodolith beds from SA and PS were denser ( $451 \pm 30$  and  $429 \pm 32$ , respectively; mean ± SE) than those found at CC and RE ( $306 \pm 39$  and  $294 \pm 26$ , respectively). The beds from BV were not different from the other beds (Table 1).

The diameter of the rhodoliths also differed among the sites (ANOVA;  $F = 30.6$ ,  $p < 0.001$ ; Table 1). The largest diameter was found at CC ( $5.9 \pm 0.4$  cm) and the smallest one at SA ( $3.4 \pm 0.3$  cm). Percent live surface was greater than 96% at all study sites (Fig. 2B).

Six taxa of coralline algae forming rhodoliths were identified in the sampling areas: *Hydrolithon rupestre* (Foslie) Penrose, *Lithophilum corallinae* (P.L. Crouan & H.M. Crouan) Heydrich, *Lithothamnion crispatum* Hauck, *Sporolithon episporum* (M.A. Howe) E.Y. Dawson, *Sporolithon ptychoides* Heydrich and *Mesophyllum engelhartii* (Foslie) Adey (voucher specimens, including slides, were deposited



**Fig. 1.** Bathymetry of the Fernando de Noronha Archipelago (FNA) indicating the sites sampled for rhodolith beds. RE–Ressureta, SA – Sapata, BV – Barro Vermelho, PS – Pedras Secas and CC – Cabeça das Caieiras. Dotted lines indicate sites surveyed by the Remotely Operated Vehicle (ROV). The asterisk indicates the largest *Malacanthus plumieri* colony known in the FNA.

in the herbarium of the Rio de Janeiro Botanical Garden: RB 510349, 511655, 504934, 511654, 510350 and 510627, respectively). According to our observations, most of the rhodoliths were monospecific and associated with a warty or lumpy growth form. *L. crispatum*, *H. rupestre* and *S. ptychoides* were the most common species in the beds.

Fig. 2C–E shows rhodolith mounds associated with sand tilefish (*M. plumieri*) at the sample site (Fig. 1). They were more frequent at the deepest boundary of the bed (approximately 55 m deep). At this site, mounds were observed up to 40 m from the boundary of the bed. The mean distance between two mounds was  $6.6 \pm 0.7$  m, and it was possible to observe up to 5 mounds in an area of  $5 \text{ m}^2$  (Fig. 2D). The mean diameter of the mounds was  $2.0 \pm 0.2$  m.

#### 4. Discussion

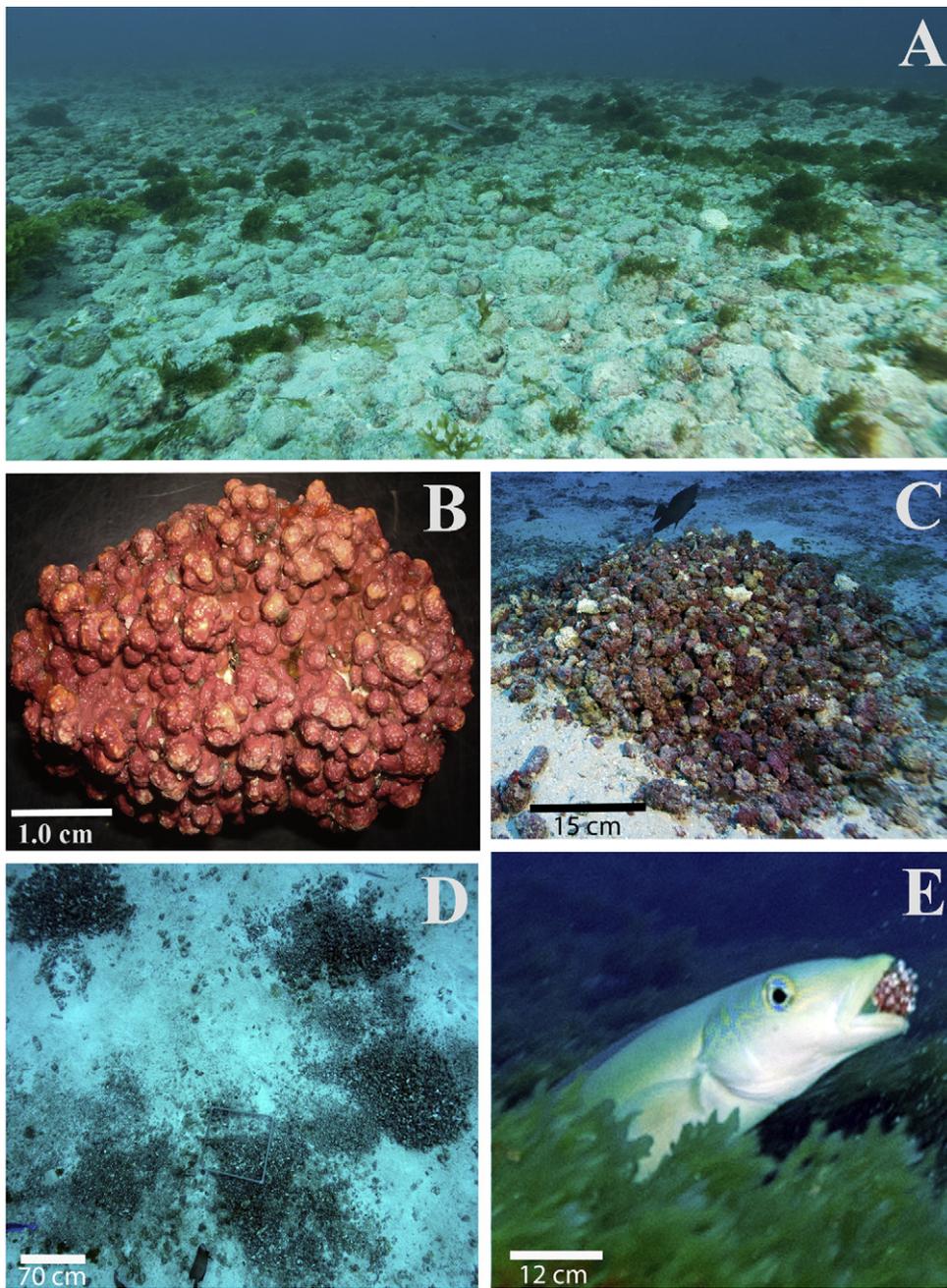
The rhodolith beds of the FNA were found between depths of 10 and 100 m. Until 14 k.a. BP the sea-level ranged between 125 and 70 m below the present level (Vecsei, 2000). Vecsei (2003) suggested that only a few summits must have been available as substrate for carbonate production at that time. When the sea-level reached depths shallower than the present level of 70 m, the available substrate increased and also the sea-level rate decreased which provided favorable conditions to the increase in carbonate production in these areas. In addition to the recently obtained data (Amado-Filho et al., 2007, in press; Riul et al., 2009; Bahia et al., 2010; Pereira-Filho et al., 2012), our results indicate that the Southwestern Atlantic Ocean carbonate banks occur in the same depth window (0–70 m depth) pointed by Vecsei (2000, 2003, 2004).

All six rhodolith-forming CCA species identified represent new records for the FNA flora. These species were previously recorded in rhodolith beds from both the Brazilian continental shelf and seamounts from the Vitória-Trindade Chain (Villas-Boas et al.,

2009; Amado-Filho et al., 2010, in press; Bahia et al., 2010, 2011; Pereira-Filho et al., 2012). This indicates similarity in the CCA composition among rhodolith beds from southwestern Atlantic areas. Considering a *stepping-stone* hypothesis for the dispersal of species (Wilson and Kaufmann, 1987), dispersal between the FNA and the Brazilian continental shelf could be facilitated by the presence of seamounts and islands in the Fernando de Noronha Chain. Although the FNA macroalgal flora is similar to the Caribbean flora (Villaça et al., 2006), *S. episporum* is the only CCA identified in the present study found in both regions (Littler and Littler, 2000). For the other five CCA species, the FNA represents the northernmost limit in the western Atlantic Ocean. Most of the rhodoliths from the FNA were monospecific, unlike what has been observed for the majority of other Brazilian rhodolith beds, where it is common for each rhodolith to be composed of two or more CCA species (Amado-Filho et al., 2007, 2010; Bahia et al., 2010; Riul et al., 2009).

For coralline reefs dominated by corals, the most profound changes caused by anthropogenic impacts are described for reefs occurring shallower than 20 m, whereas reefs deeper than 30 m (the mesophotic zone) have been observed to be free from the majority of these impacts (Bak et al., 2005; Lesser et al., 2009; Kahng et al., 2010). Therefore, reefs from the mesophotic zone could serve as important refugia for species that inhabit shallow reefs. These mesophotic zone reefs must be considered in conservation policies.

Our results indicated that there were no differences in percent live surface between sample sites, with each site exhibiting values higher than 96%. There have been few studies on the proportion of living vs. dead rhodoliths (e.g., Figueiredo et al., 2007; Peña and Bárbara, 2008; Bahia et al., 2010). Rhodoliths from the Brazilian continental shelf show a percent live surface of approximately 20% in beds from 10 to 20 m in depth (Figueiredo et al., 2007; Bahia et al., 2010). These reefs are exposed to sedimentation due to continental influences that cause an increase in water turbidity (Bahia et al., 2010). The oceanic



**Fig. 2.** Rhodolith beds of the Fernando de Noronha Archipelago (FNA). A – a typical rhodolith bed, B – *Lithothamnion crispatum* forming a typical rhodolith in the FNA, C – A *Malacanthus plumieri* mound from a 55-m depth, D – Five *M. plumieri* mounds at a depth of 55 m with a 0.49-m<sup>2</sup> quadrat in the center, E – *M. plumieri* transporting a rhodolith. Photos: Zaira Matheus.

position of the FNA, which is associated with low water turbidity, may be responsible for the higher percent live surface rates, similar to what was observed for southwestern Atlantic seamounts (Pereira-Filho et al., 2012).

Mounds of rhodoliths constructed by tilefish were found up to 40 m from the boundaries of the beds. Buttner (1996) found values similar for both the mean diameter and maximum distance from the reefs of such mounds in Santa Marta, Colombia. Buttner also showed that the composition of *M. plumieri* mounds varied according the availability of components (stones, coral fragments, mollusks and star barnacle shells) and that, depending on the age of the substrate, a range of organisms could be transported on them, including algae, foraminifers, bryozoans, hydroids, tunicates, tube-building polychaetes, vermetids, balanids and sponges. The great

availability of rhodoliths in the FNA insular shelf is likely related to the occurrence of rhodoliths as the main component of *M. plumieri* mounds.

Clark et al. (1998) found that the distribution of *M. plumieri* ranges from North Carolina through the Caribbean to south of Brazil, where it overlaps with rhodolith beds (Foster, 2001). Observations made by our research group during other studies have highlighted this range overlap (e.g., Amado-Filho et al., 2007, 2010; Bahia et al., 2010).

The observations made in this study indicated that *M. plumieri* is an important component influencing rhodolith bed structure on the FNA and that it is likely involved in rhodolith dispersion and connectivity among shallow and mesophotic beds, corroborating the hypothesis proposed by Prager and Ginsburg (1989).

However, how important the dispersion promoted by *M. plumieri* is for other organisms associated with rhodoliths remains a question to be answered.

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