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Front Cover: The reef crest indicator species, *Acropora palmata*, on Gaulin's Reef, San Salvador Island. Gaulin's Reef is a classic bank-barrier reef that has shown remarkable resilience following two significant disturbances: El Niño-induced warming of the sea surface in 1998 and Hurricane Floyd in September, 1999 (see Peckol et al., this volume). Photo by Janet Lauroesch.

Back Cover: The oolite shoals of Joulter's Cay, north of Andros Island, Bahamas, site of the pre-meeting field trip. Photo by Ben Greenstein.

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WHAT MODERN RHODOLITHS ALLOW US TO SAY ABOUT PAST ENVIRONMENTS: MODERN CARIBBEAN PATCH REEF RHODOLITHS AS ANALOGUES TO OLIGOCENE RHODOLITHS OF THE SUWANEE STRAITS

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ABSTRACT

Rhodoliths from the San Blas archipelago of Panama are observed in windward bank edge high-energy patch reef environments in 6 to 8 m water depths. These rhodoliths are predominantly spheroidal. They range in size from 1.6 to 11.8 cm with a mean diameter of 4.99 +/- 1.64 cm and an average density of 72 rhodoliths/m^2. The rhodoliths occur both in high-energy rippled inter-reef channels, as well as more moderate energy environments such as grass bed areas. Rhodoliths exhibit columnar and laminar concentric algal growth bands in both thin-sections and SEM preparations. Previous studies have suggested that laminar growth represents a deeper (~100 m) water morphological trait.

Fossil rhodoliths occur in abundance in the Oligocene Bridgeboro Limestone of SW Georgia. The type locality for the Bridgeboro quarry section is a rhodolith rich limestone with 33 documented faunal species. A section of the Bridgeboro Formation was logged at the former Grady Aggregate Company (GAC) quarry north of Cairo, GA. Rhodoliths of the basal unit at GAC are similar in density (327/m^2) and size (~5 cm) to the lower Bridgeboro. However a much thicker siliceous lens, at the top of the section, contains a higher density (499/m^2) and a smaller size (1-3 cm) rhodolith assemblage. A fine laminar boundstone feature is also found at GAC. This unit is similar to the Florala member of the Bridgeboro Fm. as identified in Florida. The rhodoliths of GAC are found associated with a typical bank-edge patch reef environment and faunal assemblage. All these features, along with layers of medium to coarse-grained shell hash, would indicate a paleoenvironment that is much shallower than the previously suggested depth based on the section interpretation at Bridgeboro (~100 m). Based on our studies, the GAC paleoenvironment appears to be directly analogous to the present shallow patch reef conditions in Panama.

Results from the present study, along with previous published investigations, strongly suggest that rhodolith morphology, growth form and texture cannot be used as paleoenvironmental indicators of relative wave energy and bathymetry. More reliable interpretations could be made based on faunal assemblages and visible diagenetic alterations.

INTRODUCTION

Geographic and Geologic Setting

In this study a comparison of modern rhodoliths and the substrate on which they occur from San Blas, Panama (Fig. 1A; Fig. 2A-D) with fossil (Oligocene) rhodoliths of South Georgia, USA (Fig. 1B; Fig. 2E-H) was undertaken. The San Blas archipelago is located off the northern coast of Panama (9°35' N, 78°59' W) (Fig. 1A). The specific area studied is a windward bank edge high-energy tropical patch reef (upper fore-reef) environment in 6 to 8 m water depths called Reef 1-2-3 (Fig. 1A and 2A, B). Reef 1-2-3 occupies an area approximately 100 m long by 50 m wide. Rhodoliths from Reef 1-2-3 are predominantly spheroidal according to the Zingg (1935) classification. They range in size from 1.6 to 11.8 cm with a mean diameter of 4.99 +/- 1.64 cm. The rhodoliths occur both in high-energy rippled inter-reef channels (Fig. 2B), as well as in the more moderate energy environments of the grass bed areas (Fig. 2A). Rhodoliths exhibit columnar and laminar concentric algal growth bands in both thin-sections and SEM preparations. Previous studies have suggested that laminar growth represents a deeper (~100 m) water morphological trait (Littler et al., 1991).

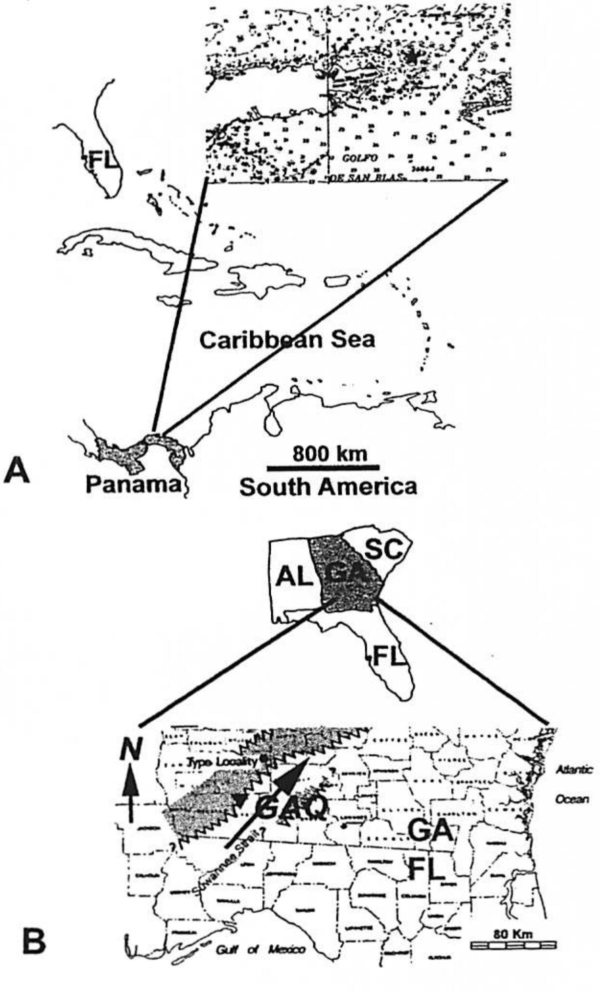

Figure 1. A) Location map of Reef 1-2-3 (indicated by the gray star) in the San Blas archipelago (9°35' N, 78°59' W) off San Blas Point in Panama; B) Location map of the old Grady Aggregate Company quarry in Grady County, Georgia.

The former Grady Aggregate Company (GAC) quarry in south Georgia is located north of Cairo, GA, off of Harrell Rd in Grady County (31°03' N, 84°17' W) (Fig. 1B). The quarry was active during the past 10 to 12 years, but has been abandoned since the late 1990ís. The measured section at the quarry is approximately 16 m (Fig. 2G), the lower contact was not observed. The rock unit is the Oligocene (Vicksburgian age) Bridgeboro Formation as described by Huddlestun (1981). The type locality, as described by Manker and Carter (1987), is located near the town of Bridgeboro, GA (Fig. 1B, Fig. 2H). It is a >20 m thick; rhodolithic limestone in a bioclastic calcarenite matrix (Fig. 2H). Manker and Carter (1987) have described the Bridgeboro Fm. as a shelf break unit bordering the relatively deep Oligocene Suwannee Strait (Fig. 1B). The top of the section at GAC contains a fine laminar encrusting algal layer (Fig.

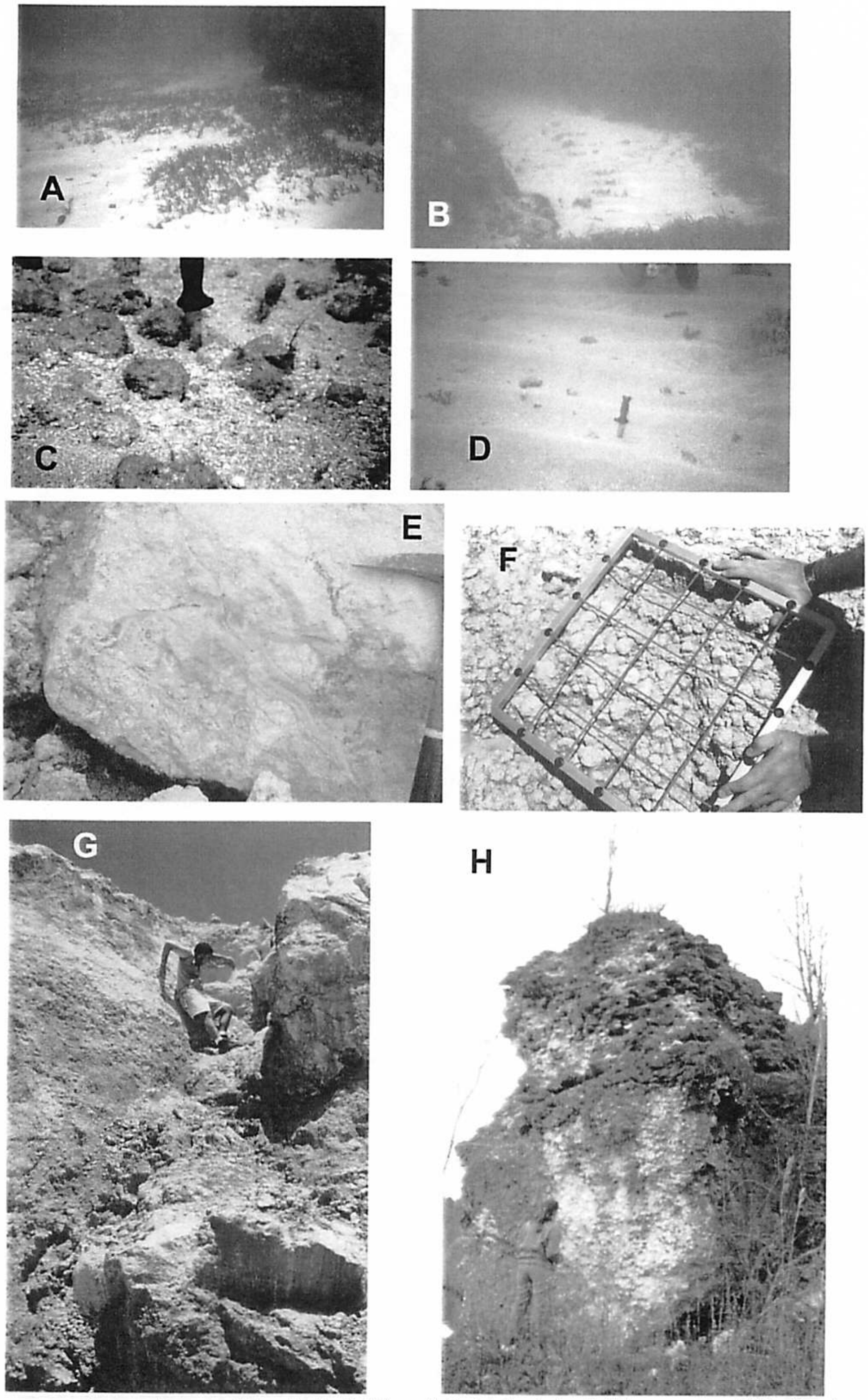

Figure 2. Representative modern and fossil rhodoliths. A) Spherical rhodoliths on top of Thallassia grass beds, Reef 1-2-3, San Blas, Panama; B) Spherical rhodoliths in the rippled coarse-grained sand channel area, Reef 1-2-3, San Blas, Panama; C) In situ *rhodoliths from Reef 1-2-3, San Blas, Panama. Dive knife for scale; D) Rhodoliths within the troughs of rippled coarse-grained sand channel area, Reef 1-2-3, San Blas, Panama. Dive knife in foreground for scale; E) Boundstone from top section at Grady Aggregate Company quarry, south Georgia containing fine laminar encrusting algal layers; F) Oligocene fossil rhodoliths from South Georgia, USA. Quadrat (50cm2) used for density measurements used as a scale. Note the high density of rhodoliths present; G) Measured section from Grady Aggregate Company quarry, South Georgia. The student is pointing at an* in situ *colonial coral location at the top of the section; H) Type locality of the Oligocene Bridgeboro Formation, near Bridgeboro, Georgia.*

2E) and is characterized by a decrease in mean rhodolith size. Huddlestun (1993) interprets this as a deeper water facies, possibly laterally equivalent to the Florala Mbr. of the Bridgeboro Fm. exposed in northern Florida. The rhodoliths of the Bridgeboro are also predominantly spheroidal. They range in size from 2.1 to 8.2 cm with a mean diameter of 4.59 +/- 1.27 cm. Rhodoliths exhibit both columnar and laminar concentric algal growth bands in both thin-sections and SEM.

For this study rhodolith density using a 50 cm^2 quadrat, and mean size and shape, by measuring the long, intermediate and short axes with a caliper, were calculated. General algal growth morphology, columnar vs. laminar, was observed using both petrographic thin-sections and SEM microscopy. The results were compared and the associated faunal assemblages were also evaluated. We thus assessed the degree to which rhodolith shape, size and morphology was related to a known environment of deposition and bathymetry (Panama) and concluded that without analyzing other parameters, principally the associated faunal assemblage, rhodoliths could not be successfully used as depth indicators as other studies have attempted. When assessing ancient environments of deposition and paleobathymetry, other parameters must be employed.

Background

Definition: What is a Rhodolith?

Rhodoliths are nodules composed of algae belonging to division Rhodophyta (red algae). Corallinaceae or Peyssonneliaceae are the two families within the Rhodophyta that are associated with rhodolith formation. Historically the shape, texture, morphology, and growth patterns of rhodoliths have been used as environmental indicators for both bathymetry and relative wave energy. However, this generalization may not be applicable in all situations. Reid and MacIntyre (1988) have argued that in the eastern Caribbean, paleoecologic indicators such as nodule formation do not have a direct correlation with specific environmental conditions.

Calcareous nodules have been described in the literature as oddities for over 200 years (e.g. Ellis and Solander, 1786). The term nodule has historically been used to describe a smooth, lump-shaped growth form. The algal nodules describe herein and in the literature may be smooth or have a knobby appearance. The term rhodolith was first used to describe unattached branched growths with a nodular form composed primarily of the Mg-calcite secreting red coralline algae (Family Corallinaceae; Barnes et al., 1970; Toomey, 1975). However, nodules of aragonite secreting Peyssonnelids (Family Peyssonneliaceae) have also been recently described in the literature (Ballantine et al., 2000; Hills and Jones, 2000).

The literature on rhodoliths is vast. Rhodolith research has been particularly fruitful over the last 30 years. Bosence (1983a) proposed a classification for rhodoliths and provided a comprehensive literature review. Recently Ballantine et al. (2000) revisited the literature and documented the first occurrence of rhodoliths in a shallow-water (<1 m) reef environment in the warm western Atlantic and Caribbean region. The present study re-affirms the position of Ballantine et al. (2000) that rhodoliths are a feature frequently encountered in the shallow (<8 m) western Atlantic and

Caribbean.

Previous names for rhodoliths have included rhodolites (Bosellini & Ginsburg, 1971), rhodoids (Peryt, 1983) and oncolites (McMaster and Conover, 1966). However this last term, oncolith or oncolite, is exclusively used for cyanobacteria (blue-green algae) stromatolitic structures and thus has not been re-used to describe red algal nodules. Currently, some investigators still use the term rhodolite in the literature. In recent studies, Clarke and colleagues (1996) used the term rhodolite to describe some cool water rhodoliths on the coast of southern Australia. The term rhodolite is not preferred, because its original use is for a pyrope-almandite garnet (Hurlbut and Klein, 1977).

Some of the more common coralline algal genera that form rhodoliths are *Lithothamnium*, found only in arctic waters or in deep subtropical waters; *Lithophyllum* found in shallow tropical waters 0-60 m, but mainly between 25-40 m; *Neogoniolithon* also found in shallow tropical waters 0-55 m, but mainly between 5-20 m; and *Archaeolithothamnium* found in deeper tropical waters >40 m, along with *Lithoporella* and *Mesophyllum* (found in waters >45 m). The Peyssonnelids that have been described as rhodolith formers are *Peyssonnelia* (Hills and Jones, 2000) and *Cruoriella* (Ballantine et al., 2000) both from very shallow waters (<14 m and <1 m, respectively).

Formation and Distribution of Rhodoliths

An extensive body of literature exists regarding the formation of rhodoliths (Adey and MacIntyre, 1973; Ballantine et al., 2000; Basso, 1998; Bosellini and Ginsburg, 1971; Bosence, 1976, 1983a,b, 1985; Bosence and Pedley, 1982; Bourrouilh-le Jan et al., 1988; Boyd, 1986; Focke and Gebelein, 1978; Hills and Jones, 2000; Littler et al., 1991; Montaggioni, 1979; Piller and Rasser 1996, Prager and Ginsburg, 1989; Reid and MacIntyre, 1988; Scoffin et al., 1985; Toomey, 1975; Wilber et al., 1988; Yoshihiro, 1993). Most investigators have made inferences about the relative wave and current energy of the environment and the resulting morphology exhibited by the nodule. In general, a consensus is reached that encrustation by carbonate producing or sediment-trapping organisms (Prager and Ginsburg, 1989) is the most commonly suggested mechanism for formation. In general the "active" side is the underside (Ballantine et al., 2000; Littler et al., 1991) and repeated turning of the surfaces being encrusted (Prager and Ginsburg, 1989) forms the nodule. Previous studies of rhodoliths show their depth distribution is primarily controlled by light, secondarily by temperature, and salinity being somewhat less important (Adey and MacIntyre 1973). Rhodoliths are found growing on substrates varying from mud to gravel.

Rhodoliths have been described from all latitudes and depths. They have been reported primarily from tropical waters, but they are probably more abundant in temperate and polar seas (Bosellini and Ginsburg, 1971). Their distribution is governed by the genera of red algae that forms the nodules. *Lithothamnium* has been documented as the primary nodule former in polar seas. In these areas, referred to as Maerl, the nodules are found primarily in rocky slope environments (Bosence 1976, 1983b; Olson 1964). The literature contains numerous references to rhodolith formation in tropical waters. Authors cite rhodolith formation in tropical shelf environments (Reid & MacIntyre 1988), fore reef environments (Montaggioni, 1979), reef flat and channels environments (Pollock, 1928) as well as tropical back reef environments (Bosellini and Ginsburg, 1971; Ballantine et al., 2000). Rhodoliths have been described from all depths ranging from very shallow <1 m (Ballantine et al., 2000) back reef environments to very deep ~290 m (Littler et al., 1991) slope environments. Their widespread distribution is due to ambient light, temperature, depth, salinity, substrate and energy conditions present that control their distribution (Bosence, 1983b).

Manker and Carter (1987) state that the primary algae forming the Bridgeboro rhodoliths are *Archaeolithothamnium* and *Lithoporella*, which, as previously stated, are found in deeper tropical waters >40 m. These two genera have been proposed as indicators of deeper (>40 m) tropical water conditions. Manker and Carter (1987) have established, based in part on this criteria, that the Bridgeboro Fm. was deposited in a tropical shelf break environment at a depth of approximately 100 m. The aim of this paper is to access the reliability of rhodolith data as a sole paleobathymetric indicator.

METHODS

The density, mean size, shape, and algal growth morphology of the rhodoliths were ascertained to determine if these parameters are reliable for characterizing past environmental conditions. Marked differences should be observed in rhodolith morphology between the Bridgeboro rhodoliths (100 m) and Panamanian rhodoliths (<8 m) if wave energy and bathymetry are major factors influencing nodule growth.

Density

Density counts were performed using a 50 cm^2 quadrat. The quadrat was randomly place over sand and grass patches around Reef 1-2-3 in Panama as well as placed in randomly picked vertical sections along the exposed outcrop of the Bridgeboro Fm. in Georgia.

Size

Size of the nodules is based on the arithmetic mean diameter. The mean diameter is calculated using the relationship between the long (L), intermediate (I) and short (S) axes as described by the equation $[(L+I+S)/3]$. The long, intermediate and short axes from 158 rhodoliths from the Bridgeboro Fm. and 87 rhodoliths from Panama were measured using a caliper.

Shape

Some investigators believe that substrates control rhodolith shape. Bosence (1983a) has classified shapes of rhodoliths as spheroidal, discoidal or ellipsoidal using a modified ternary diagram after Sneed and Folk (1958). In this classification, the sphericity of a nodule is obtained by measuring the long (L), intermediate (I) and short (S) axes and applying Sneed and Folk's (1958) maximum projection sphericity formula ($\sqrt[3]{S^2/LI}$). An alternative shape classification scheme used is a modified Zingg (1935) diagram. This scheme uses four shape classifications spherical (equant), discoidal (disk), flat (bladed) and elliptical (prolate or roller) to describe nodule form. Both of these shape-classification schemes were employed in this study.

Morphology

In general, rhodolith algal-growth morphology can be divided into two distinct growth forms. The first form is characterized by a columnar, primarily non-branching, morphology. The second is defined by a laminar concentric growth pattern. These morphological attributes can be observed on the outside of the nodule either as a smooth (Fig. 3A) outer rind or a knobby crust (Fig. 3B, C). Very rarely are rhodoliths strictly composed of either columnar (Fig. 3D, K) or laminar (Fig. 3J) growth patterns. Most rhodolith specimens contain both growth patterns within the same nodule (Fig. 3F, G). Some rhodoliths exhibit internal structures consisting of a series of constructional voids (Fig. 3D). These voids are packed and infilled by loose or cemented sediment in other rhodoliths (Fig. 3F).

It is thought that columnar discoidal forms are more common in muddy substrates, while laminar spherical forms are thought to form on sandy or hard substrates (Bosence 1983b; Bosellini and Ginsburg 1971).

Sediment Characterization

The sediment substrate from Reef 1-2-3 was characterized by point counting five thin-sections from both the high-energy rippled and the grass bed areas as well as performing a sieve analysis to obtain mean grain size and distribution. The substrate matrix at the quarry in South Georgia was characterized by point counting two thin-sections from different stratigraphic levels along the quarry wall.

Mineralogy

Carbonate mineralogy was analyzed by X-ray diffraction, scanning the interval from 25°-33° 2Θ (Cu-Kα) at 1° per minute. All samples were run on a Phillips XRD at Georgia State University. The relative amounts of aragonite, calcite and magnesian calcite were quantified using the peak-area method of Milliman and Bornhold (1973). X-ray diffraction was employed to determine if mineral composition of rhodoliths may vary in relation to environment as well as to determine the algal species based on the mole-percent $MgCO_3$ (Milliman et al., 1971). However, secondary mineralization of rhodoliths in the Bridgeboro must be considered when comparing Oligocene rhodoliths with recent specimens from Panama.

RESULTS

Reef 1-2-3 Panama

The mobile substrate of Reef 1-2-3 is characterized by skeletal sands composed of corals (range 20.9-37.6%; mean 27.7% (+/-6.1%), coralline algae (range 19.6-29.7%; mean 24.4% (+/- 3.3%), molluscs (range 6.4-13.1%, mean 9.9% (+/- 2.2%), echinoids (range 2.3-6.4%, mean 2.9% (+/- 1.7%), *Halimeda* (range 1.3-14%, mean 9.22 (+/- 4.7%), forams (range 0-8.3%, mean 3.2 (+/- 3%) and skeletal aggregate grains (range 2.8-20.3%, mean 9.7 (+/- 6.4). Other constituent grains were observed but not quantified. These include the foraminifer *Homotrema rubrum*, crustacean parts, and phosphatized grains. *In situ* cementation of some of these grains and incipient alteration and diagenesis of

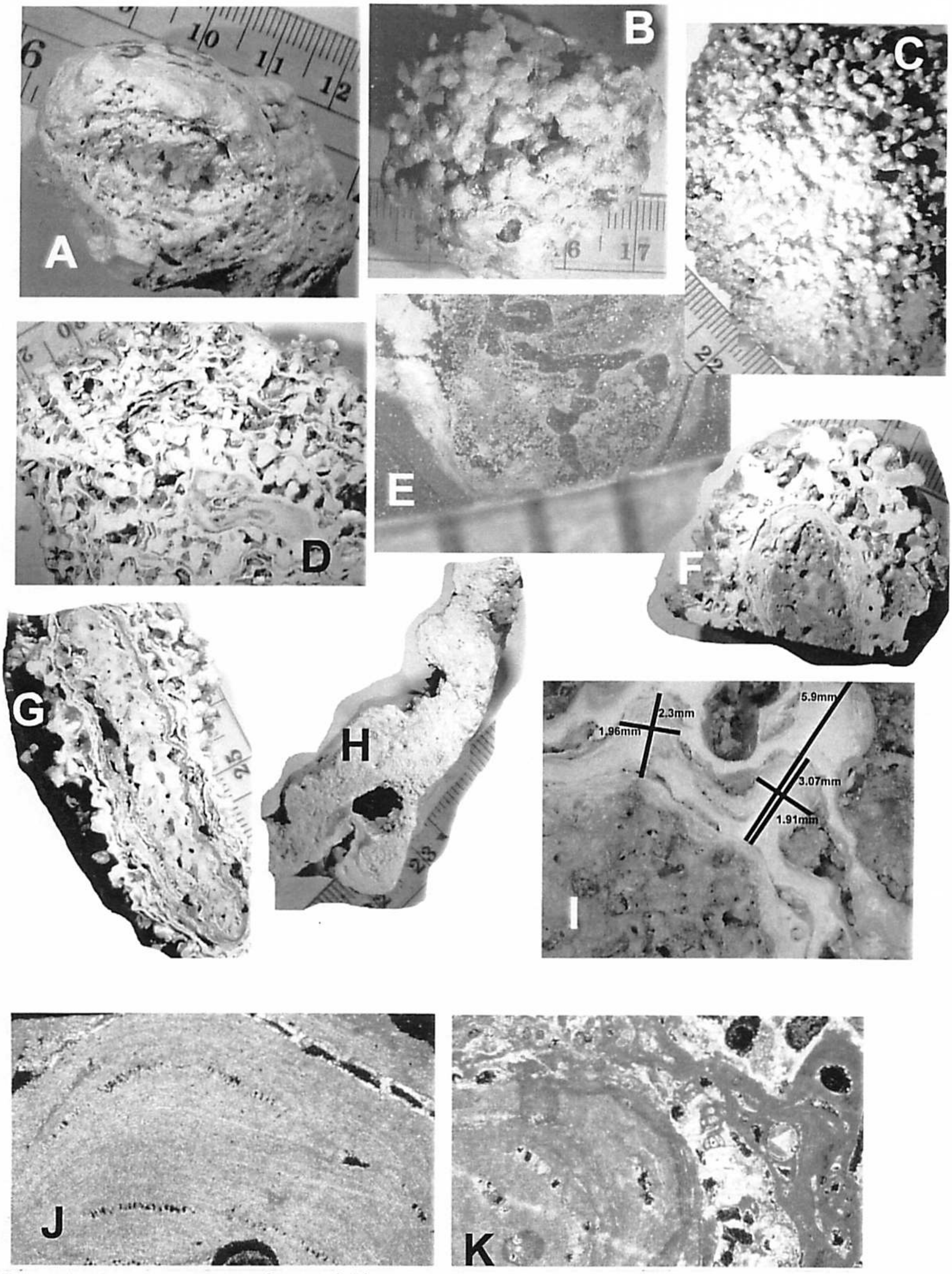

Figure 3. Representative modern and Oligocene rhodoliths. A) Smooth outer rind of spheroidal Oligocene rhodolith from the Bridgeboro; B, C) Knobby external texture of spheroidal Panamanian rhodolith; D) Cross-section of a Panamanian rhodolith showing columnar growth pattern, and numerous constructional voids; E) Acetate peel of Panamanian rhodolith showing internal borings; F) Cross-section of Panamanian rhodolith with laminar and columnar growth pattern- note laminar growth pattern around a distinct nucleus and the numerous infilled constructional voids; G) Laminar growth pattern from a Panamanian rhodolith. Note a distinct nucleus (coral) and progression from laminar to a columnar growth pattern; H) Discoidal shaped Panamanian rhodolith; I) Measurements of Panamanian rhodolith columnar growth patterns; J) Laminar algal growth pattern observed in an Oligocene rhodolith (x 40) from the Bridgeboro Formation; K) Columnar growth pattern of a Oligocene rhodolith (x 40) from south Georgia.

the grains is also apparent as would be expected in a shallow tropical environment. Borings are frequently encountered (Fig. 3E). Cements (1.5% (+/- 0.1%) and non-skeletal grains (5.2% +/- 3%) account for the remainder of the grains.

The rhodoliths in Reef 1-2-3 are found in two distinct areas: 1) within sparse *Thallassia* grass beds (Fig 2A); and; 2) within the rippled coarse-grained sand channel area (Fig. 2B, D). The sediment of the grass beds is predominantly finer grained than the channel area (grass beds-78% of sediment <500 μm), but it is not a muddy substrate. The rippled channel surface is predominantly a very coarse grained sand (73% >1000 μm). Both substrates are mobile. The rippled channel represents a higher energy environment than the grass beds.

Rhodoliths

Counts performed using a 50 cm^2 quadrat showed that the density of rhodoliths ranged from $32/m^2$ to $88/m^2$ with a mean number of $72/m^2$. The long (L), intermediate (I) and short (S) axes of 87 rhodoliths collected from Reef 1-2-3 were measured and the results tabulated and computed using the Sneed and Folk (1958) and Zingg (1935) equations. The computed mathematical mean [(L+I+S)/3] diameter of the rhodoliths is 4.84 +/- 1.32cm. This figure excludes two irregular- shaped aggregate-rhodoliths having a mean diameter of 11.8 cm and 11 cm; otherwise the mathematical mean diameter would be 4.99 +/- 1.64 cm. Using the Sneed & Folk (1958) classification scheme, the rhodoliths were found to fall predominantly within the compact to compact-platy, -bladed and -elongated forms (54%) (Table 1). If the Zingg (1935) classification scheme is used then the majority would fall in the spheroidal to discoidal (78%) category (Fig. 4A). Using the modified scheme by Bosence and Pedley (1982), most rhodoliths would be spheroidal (74%). Bladed shapes are 3 to 4 times more prevalent in the very small (1.58-2.75 cm) or very large (6.82-11.81 cm) mean rhodolith diameter nodules. Also within one standard deviation of the mean, the rhodoliths tend to be primarily (82.5%) equant (Fig. 3A) to disk (Fig. 3H) shaped.

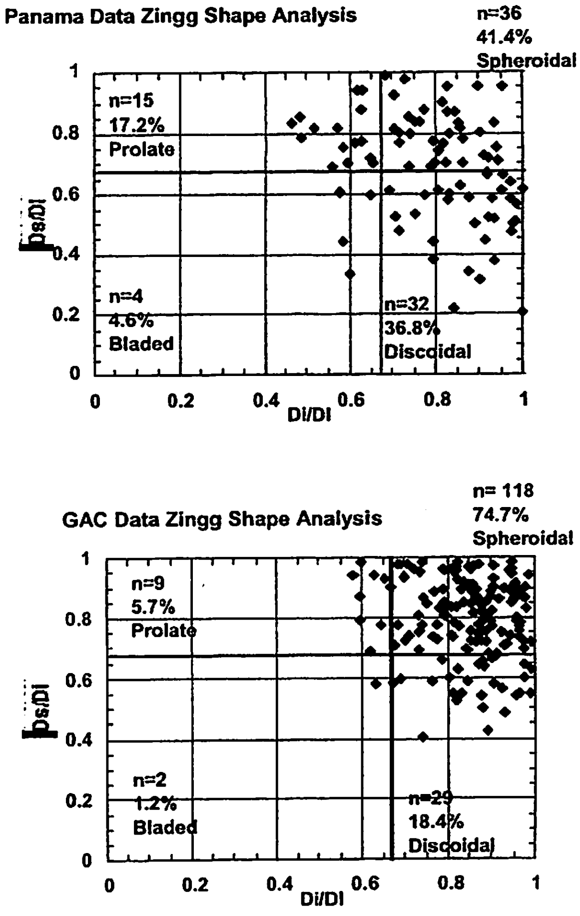

Figure 4. Zingg (1935) shape analysis of modern Panamanian (top) and Oligocene rhodoliths from Georgia (bottom).

The internal structure of the rho-

SIZE	PANAMA (n=87)	S. GEORGIA (n=158)
Mean Dl	6.26 +/- 2.10	5.22 +/- 1.63
Mean Di	4.86 +/- 1.58	4.33+/- 1.38
Mean Ds	3.00 +/- 1.32	3.39 +/- 1.08
Mean D	4.99 +/- 1.64	4.59 +/- 1.27
Range	1.58-11.82	2.07-8.17
SHAPE		
Compact*	18%	39%
Compact Platy*	15%	13%
Compact Bladed*	11%	17%
Compact Elongated*	10%	12%
Spheroidal**	74%	92%
Ellipsoidal**	13.5%	05%
Discoidal**	12.5%	03%

*Table 1. Size and shape comparison between Panama and S. Georgia rhodoliths. Size measurements given in centimeters. *Sneed and Folk (1958); **Bosence and Pedley, (1982).*

doliths exhibit both columnar and laminar concentric growth. In general, the rhodoliths start accreting in a laminar fashion around a nucleus and then pro gress to a columnar structure (Fig. 3F, G). It appears that several genera of algae make up the rhodoliths.

In addition to SEM and petrographic analysis, the mineralogy of the rhodoliths was obtained using an XRD. Using the graphical method of Goldsmith and Graf (1958), it was determined that the rhodoliths exhibited anywhere from 10 to 24 mole % $MgCO_3$ and contained up to 40% aragonite. The higher the mole-percent $MgCO_3$ the higher the water temperature (Milliman et al., 1971). The genera that tend to secrete the higher mole-percent $MgCO_3$ are, in order of decreasing mole percent, *Porolithon* (14-16%), *Goniolithon* (13-16%), *Jania* (11-14%) and *Lithophyllum* (11%). The aragonite found in the specimens is more than would be expected just by additional sediment trapping. We assume that some of this aragonite is due to the aragonitic red Peysonnelids algae. However, this idea has not been verified by an accurate taxonomic identification. Morphologically it also appears that some of the algal thalli belong to *Peyssonnelia.*

South Georgia Quarry

The rhodoliths from the old Grady Aggregate Company quarry are found within a bioclastic matrix of skeletal fragments composed of corals (range 2.2-5.0%), coralline algae (range 30.6-54.7%), molluscs (range 0.8-1.4%), echinoids (range 4.0-5.4%), forams (range 0.4-1.2%) and cements (37.2-50.2%). Other constituent grains were observed but not quantified. These include the foraminifera *Lepidocyclina*, crustacean parts, and medium to coarse grained shell hash. The associated fauna (Table 2) at GAC is a low diversity fauna. It includes common occurrences of the

Foraminifera	
*Lepidocyclina**	Common
Gastropods	
*Conus**	Uncommon
*Turritella**	Common
Bivales	
*Chlamys**	Common
*Ostrea**	Uncommon
*Pitar?**	Rare
Malacostracan crustaceans	
Spiny lobster appendages**	Common***
Cnidaria	
*Trochocyathus**	Rare
Unidentified colonial coral*	Rare/Recurrent
Echinoidea	
Clypeasteroids*	Common
Chlorophyta	
Halimeda (?)**	Rare
Dasycladacean?*	Rare
Chordata	
*Carcharocles***	Rare

*Table 2. Faunal assemblage from the South Georgia Quarry. *also found by Manker and Carter (1987) at Bridgeboro; **never previously described from Bridgeboro; ***common within cave system in quarry, not visible on quarry walls.*

echinoid *Clypeaster cotteaui*, the bivalve *Chlamys* and crustacean appendages and carapaces, as well as a rare occurrence of a *Carcharocles auriculatus* tooth.The rhodoliths in the old GAC quarry are found in a massive high density rhodolith rich (Fig 2F, H) calcarenitic grainstone-rudstone that is in part silicified. The top of the section exhibits characteristics of a boundstone (Fig. 2E).

Rhodoliths

Rhodolith density of the basal unit, where the larger rhodoliths (>5 cm) are found, is 327/m^2 +/- 56/ m^2. The rhodolith density in the upper unit, where the smaller rhodoliths (1-3 cm) are present, is 499/m^2 73/m^2.

The long (L), intermediate (I) and short (S) axes of 158 rhodoliths collected from GAC were measured. The computed mathematical mean diameter [(L+I+S)/3] of the rhodoliths is 4.59 1.27cm. The shape analysis, determined by the equations of Sneed and Folk (1958) and Zingg (1935) showed that the rhodoliths are predominantly compact to compact-type forms (81%) (Table 1) or equant to discoidal (93%) using the Zingg classification (1935) (Fig. 4B) or spheroidal (92%), using the modified scheme by Bosence and Pedley (1982). The smaller rhodoliths (<3.32 cm) are three times as likely to be prolate (rollers) as compared to the mean diameter and two times as likely to be discoidal shaped. If the mean diameter within one standard deviation is taken then rhodoliths at GAC are >80% spheroidal (equant) while the smaller rhodoliths tend to be <55% spheroidal (equant).

The internal structure of the rhodoliths exhibit both columnar and laminar concentric growth. However laminar forms tend to be more common. In general the rhodoliths start accreting in a laminar fashion around a nucleus and then progress to a columnar structure (Fig. 3K). Several of the rhodoliths at GAC show active borings by bivalves that tend to obliterate any evidence of a nucleus or growth pattern type. It appears that perhaps a few different genera of algae make up the rhodoliths. Manker and Carter (1987) identified *Archaeolithothamnium* as the primary genus of rhodolith formation but *Lithoporella* was also common.

In addition to SEM and petrographic analysis, the mineralogy of the rhodoliths was obtained using an XRD. Using the graphical method of Goldsmith and Graf (1958), it was determined that the rhodoliths were primarily calcite with some containing ~8 mole% $MgCO_3$. No aragonite was found within the nodules, as would be expected from diagenesis. The low percentages of $MgCO_3$ are probably also the result of diagenetic transformations to low-Mg calcite.

DISCUSSION

The similarity in size, shape and algal growth pattern between the shallow (<8 m) patch reef rhodoliths of Reef 1-2-3 in Panama and the rhodoliths of the Bridgeboro Fm. bordering the deep Oligocene Suwannee Strait of Georgia is evident. The faunal assemblages between the two sites are also analogous. Depth, therefore, is not the sole factor nor the most important factor in rhodolith growth and form.

A potential caveat when using rhodoliths as depth indicators is determination of the optimum depth of formation. It is debatable that an optimum depth of formation even exists. Depth is an illusive quantity. It is always defined in relation to another point of reference, usually mean sea level. In the case of a marine environment, that point of reference may be relative to the platform or basin that the rhodoliths are found in. This is the only option one would have using rhodoliths as paleoenvironmental indicators. In contrast, most studies of extant rhodoliths use actual measured depths as a frame of reference for rhodolith formation. Wilber and colleagues (1988) indicated that modern rhodoliths may dominate broad areas of any one platform. Their study suggests the widespread occurrence of rhodolith-rich bottoms are indicative of generally deep (>20 m) shelves and platforms of the Caribbean. For Wilber and colleagues (1988) then, >20 m is considered deep. On the other hand, Adey and MacIntyre (1973) considered rhodoliths a characteristic element of the sea floor at depths of about 50 to 150 m. For their study, deep signified anything greater than 50 m. Similarly, Prager and Ginsburg (1989), documented rhodolith nodule growth on Floridaís outer shelf. In this case, nodules formed in a relatively deep (35-65 m), quiet water setting. Finally, Piller and Rasser, (1996), described a rich rhodolith growth zone from the Northern Bay of Safaga in a relatively low energy shallow-water area (maximum depth of 55 m). Calcareous red algae are photosynthetic and are limited by the photic zone (<200 m). The maximum photic limit would therefore be 200 m (very deep) while 50 m would be considered shallow and 20 m very shallow. This classification is based on the shaky assumption that depth is the only factor influencing the photic zone.

A second problem arises when trying to interpret what is considered deep and what is considered shallow. According to Adey and MacIntyre (1973) 50 m is considered deep in a tropical environment. In contrast, Piller and Rasser (1996) consider 55 m to be a shallow-water area. Clearly, there is no clear classification of what we consider to be deep or shallow based on extant studies. With this in mind, consider how confounding it would be to estimate water depth for an Oligocene system where we lack any frame of reference for depth. Manker and Carterís (1987) statement that "the presence of *Archaeolithothamnium*, a dasycladacean algae, and *Lithoporella* suggests that water depth was moderately shallow (i.e., less than 100 m)" is then questionable.

Their assertion that "moderately shallow (i.e., less than 100 m)" waters were present during Bridgeboro deposition should be suspect. Other factors, the presence of a boundstone at the top of the section, the many crustacean appendages, the shell hash layers and the abundant whole echinoids, would tend to indicate a shallower setting, maybe even one analogous to the Panamanian rhodolith environment.

One assumes that light, which is the primary environmental factor influencing rhodolith growth, is directly correlated with depth. However, other environmental conditions such as proximity to land, which would increase turbidity or amounts of dissolved organic acids, could greatly influence the amount and quality of light available for algal growth. There are other situations where deeper, clearer water may allow enough light to support a robust bed of rhodoliths. In the case of rhodolith growth, a combination of temperature or changes in salinity (both secondary influences on rhodolith growth) at a microenvironmental scale may be significant. In either case, more studies of environmental factors influencing rhodolith growth are needed before we can use rhodoliths as a singular indicator of past environmental conditions.

CONCLUSIONS

Previous literature and this study show that rhodolith morphology, growth form and texture cannot be exclusively used to indicate relative energy and bathymetry of a paleoenvironment. Various algal morphological growth patterns, shapes and sizes exist for extant rhodoliths found at different depth. Our study suggests that a number of environmental factors appear to influence the growth form and internal structure of rhodoliths. This makes morphology, growth form, and texture questionable indicators of depth and relative energy. Ideally, a feature that serves as an environmental indicator must primarily be influenced by the environmental factor it supposedly reflects. Although rhodolith formation may be linked with depth and relative energy, we found no strong indications that depth and relative energy were the primary environmental factors influencing rhodolith growth.

The present study also suggests that placing a strong emphasis on one paleoenvironmental indicator is undesirable. We suggest that rhodoliths do aid in estimating past environments. However, they can be misleading when used as a singular paleoenvironmental indicator. We suggest combining rhodolith data with faunal assemblages and associated sedimentary (organic and inorganic) structures when interpreting paleoenvironments.

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