Modern Rhodolith-dominated carbonates at Punta Chivato, Mexico

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ABSTRACT
Rhodolith-dominated carbonate environments, characterized by high abundances of free-living coralline algae, have been described globally from a wide range of Recent and fossil shallow marine settings. In the present-day warm-temperate Gulf of California, Mexico, rhodolith-dominated systems

are important contributors to carbonate production. One of the most prolific rhodolith factories is located on the Punta Chivato shelf, in the central Gulf of California, where due to a lack of input of terrigenous material from the arid hinterland, carbonate content averages 79%. Punta Chivato rhodoliths thrive above the shallow euphotic zone under normal saline, warm-temperate and meso- to eutrophic conditions. A detailed sedimentologic study combined with acoustic seafloor mapping indicates the presence of extensive rhodolith-dominated facies at subtidal water depth covering an area of >17 km². Additional facies, surrounding the rhodolith-dominated facies include a fine-grained molluscan, a transitional bivalve-rhodolith and a bivalve facies. While the Punta Chivato shelf yields average abundances of 38% rhodolith-derived coralline algal components in the gravel-sized sediment fraction, the rhodolith facies itself is characterized by more than 60% coralline algal components. Other important carbonate producers at Punta Chivato include bivalves (35%), bryozoa (11%) and gastropods (8%). The present study shows that acoustic sediment mapping yields highly resolved continuous coverage of the seafloor and can distinguish modern rhodolith facies from surrounding sediment. This has important implications for quantifying rhodolith-dominated settings globally, as well as for ecological and conservation studies.

KEY WORDS
Gulf of California,
coralline algae,
acoustic mapping,
rhodalgal.

RÉSUMÉ

Les faciès carbonatés actuels à rhodolithes de Punta Chivato, Mexique.

Des exemples d'environnements carbonatés à rhodolithes dominants, caractérisés par la grande abondance des algues corallines, ont été répertoriés au sein d'une large gamme d'environnements marins peu profonds, modernes ou fossiles. Aujourd'hui, dans les eaux chaudes du golfe de Californie (Mexique), ces systèmes contribuent de façon significative à la production carbonatée. Une des « fabriques » à rhodolithes parmi les plus productrices est située sur la plate-forme de Punta Chivato, dans la partie centrale du golfe de Californie, là où, l'aridité de l'arrière-pays limitant fortement les apports terrigènes, la proportion de carbonates tourne autour de 79 %. Les rhodolithes de Punta Chivato prospèrent dans la zone euphotique peu profonde, dans des eaux chaudes à salinité normale, et dans des conditions méso- à eutrophiques. Une étude sédimentologique détaillée combinée à une cartographie acoustique indique que les zones à rhodolithes dominants s'étendent dans la zone subtidale sur une surface supérieure à 17 km². À la périphérie des secteurs à rhodolithes dominants, on observe d'autres types de faciès : 1) un faciès sablonneux à mollusques ; 2) un faciès à mollusques bivalves et rhodolithes ; et 3) un faciès à mollusques bivalves seuls. Si nous considérons alors, sur la plate-forme de Punta Chivato dans son grand ensemble, qu'en moyenne 38 % des débris d'origine algaire se rangent dans la catégorie granulométrique des graviers et galets, cette fraction dépasse 60 % pour le faciès à rhodolithes. Les mollusques bivalves (35 %), les Bryozoaires (11 %) et les Gastéropodes (6 %) complètent le tableau. Notre étude montre que la cartographie acoustique des sédiments fournit une couverture continue à haute résolution du fond marin et permet de distinguer les faciès à rhodolithes des sédiments qui les encadrent. Cette approche est intéressante pour qui voudrait quantifier les zones à rhodolithes, tant à des fins écologiques que pour leur préservation.

MOTS CLÉS
golfe de Californie,
algues corallines,
cartographie acoustique,
faciès rhodalgal.

INTRODUCTION

Global occurrences of modern rhodolith-dominated carbonate systems (rhodoliths = free-living coralline algae) have been compiled by Bosence (1983) and Foster (2001). In many of these systems, rhodoliths exhibit patchy distribution patterns and are found in distinct so-called "rhodolith beds", which are loosely defined as accumulations of living and dead unattached coralline algae (Steller & Foster 1995; Foster *et al.* 1997). While a modern rhodolith environment is considered a "bed" when rhodolith cover exceeds 10% (Steller *et al.* 2009) the minimum spatial extent for a rhodolith accumulation to be considered a "bed" has not been defined. Accordingly, the spatial extent of "beds" described in the literature varies from less than a few hundred m^2 to several km^2. Only the larger "beds" (e.g., >1 km^2) would likely be recognized as a distinct facies in ancient deposits. In the fossil record, the term "Rhodalgal" lithofacies – dominated by encrusting coralline algae (Rhodophyta) which often form rhodoliths – has commonly been applied (Carannante *et al.* 1988). Fossil analogues of modern rhodalgal carbonate sediments are widespread globally (Halfar & Mutti 2005) and in the Gulf of California (Johnson *et al.* 2009) and have frequently been reported from numerous outcrops from the Paleotethys region (Bosence & Pedley 1979; Carannante *et al.* 1988; Esteban 1996; Fornos & Ahr 1997; Betzler *et al.* 1997; Wilson 2002; Rasser & Piller 2004; Pomar *et al.* 2004; Basso *et al.* 2006, 2008; Nalin *et al.* 2008).

Rhodolith systems support a high biodiversity of associated species and are characterized by slow growth and accumulation rates (Blake & Maggs 2003; Bosence & Wilson 2003). Few attempts have been made to quantify the spatial extent of modern rhodolith facies, despite their importance and common occurrence (Hetzinger *et al.* 2006). Since the development of modern acoustic ground discrimination systems, which allow the distinction of different sediment types based on their geophysical properties (Riegl & Purkis 2005), a limited number of studies have quantified rhodolith facies extent (Birkett *et al.* 1998; Hetzinger *et al.* 2006).

The goals of the present study are: 1) to conduct quantitative acoustic mapping of the largest rhodolith-dominated shelf area in the Gulf of California using an acoustic ground discrimination system; 2) to correlate acoustic mapping with sediment data; and 3) to characterize physical conditions favorable for development of the rhodalgal carbonates. The functioning of the applied acoustic mapping method has important implications for quantifying rhodolith carbonate production in other regions, and can be applied to studies focusing on ecological and conservation aspects.

REGIONAL SETTING

The Gulf of California, Mexico, is one of the best studied regions globally with respect to extensively developed modern rhodolith-dominated carbonates (Steller & Foster 1995; Foster *et al.* 1997; Reyes-Bonilla *et al.* 1997; Marrack 1999; Riosmena-Rodríguez *et al.* 1999; Steller *et al.* 2003; Hetzinger *et al.* 2006). With its latitudinal extent from 23°N to 30°N, the evaporative basin of the Gulf of California spans the warm-temperate/subtropical realm, is characterized by seasonal upwelling and encompasses nutrient regimes from oligo-mesotrophic in the south to eutrophic in the north (Alvarez-Borrego 2010; Fig. 1). Carbonate production ranges from coral-reef dominated shallow-water areas in the south to rhodolith-dominated, inner shelf carbonate production in the central gulf, and to molluscan-bryozoan inner- to outer-shelf environments in the northern Gulf (Halfar *et al.* 2006b).

In the central Gulf of California modern rhodolith-dominated carbonate factories develop under meso- to eutrophic conditions (Halfar *et al.* 2006a). Punta Chivato is the northernmost of a series of well-developed rhodolith-dominated settings in the Gulf of California. Restricted rhodolith beds, however, are found throughout the entire gulf (Steller *et al.* 2009; Riosmena-Rodríguez *et al.* 2010), but no reports of extensive beds (e.g., >1 km^2) contributing significant amounts of carbonate sediment exist from the extreme north and south of the gulf. The southernmost extensive Gulf of California rhodolith-dominated seafloor environ-

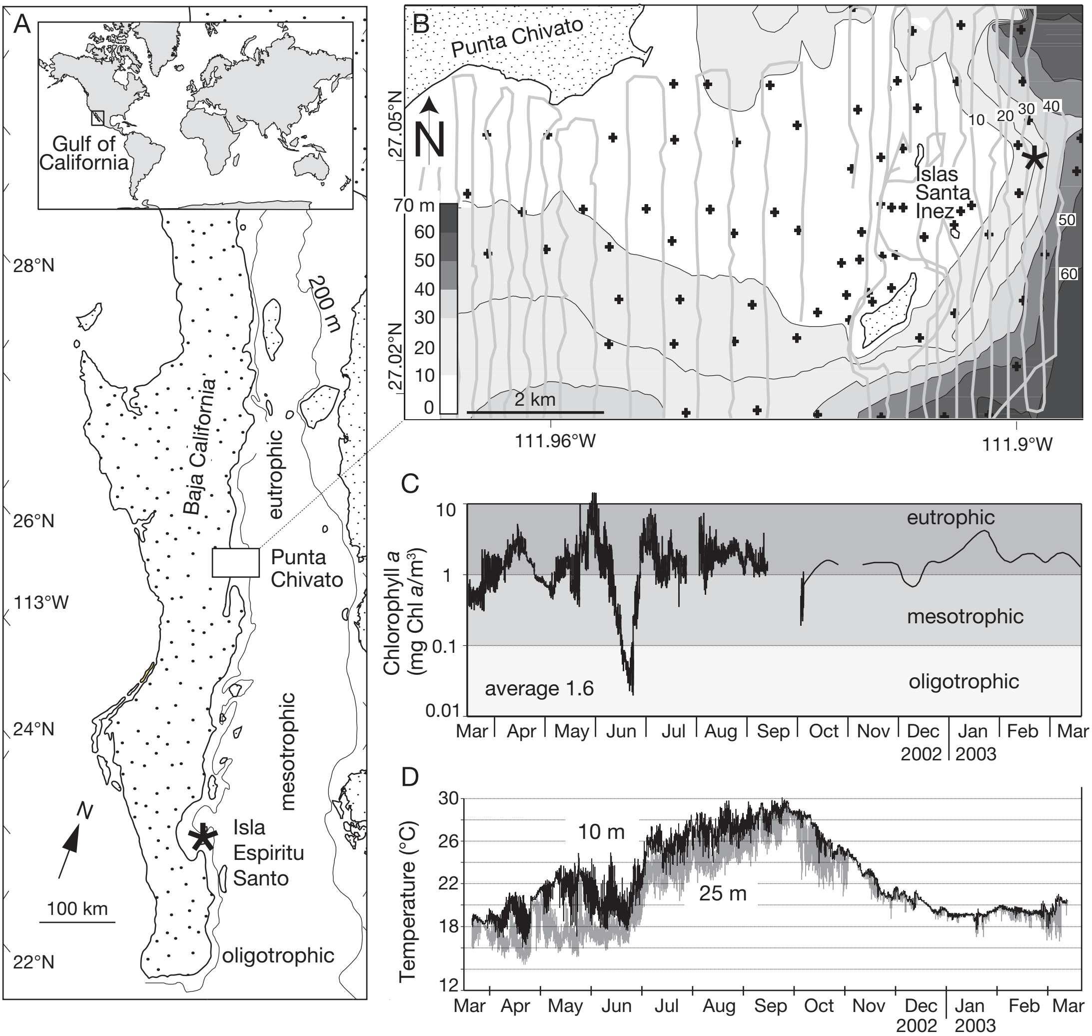

FIG. 1. — The Punta Chivato study site in the central Gulf of California: **A**, asterisk indicates location of southernmost extensive rhodolith bed described in Gulf of California (Marrack 1999); **B**, Punta Chivato bathymetry with sampling locations (**+**) and acoustic sediment mapping transects; asterisk indicates position of oceanographic mooring; **C**, Chl *a* measurements (10 m water depth – *in situ* measurements March-September; SeaWiFS data October-March); **D**, high-resolution *in situ* temperatures (from Halfar *et al.* 2006a).

ment described is located near Isla Espiritu Santo 400 km to the south of Punta Chivato (Marrack 1999) occupying an area of 20 km² (Halfar *et al.* 2001; Fig. 1).

Punta Chivato itself is a small headland in the middle of the east coast of the Baja California Peninsula that extends several kilometers into the Gulf of California (Libbey & Johnson 1997). The shelf of Punta Chivato is flat with a mean depth of 13 m west of Islas Santa Inez (Fig. 1). Even though partly protected by this group of three islands and the headland of Punta Chivato to the north, the studied shelf is subjected to seasonally shifting winds and high wave energies from the north, east and south (Simian & Johnson 1997; Johnson & Ledesma-Vasquez 1999). A brief overview of the

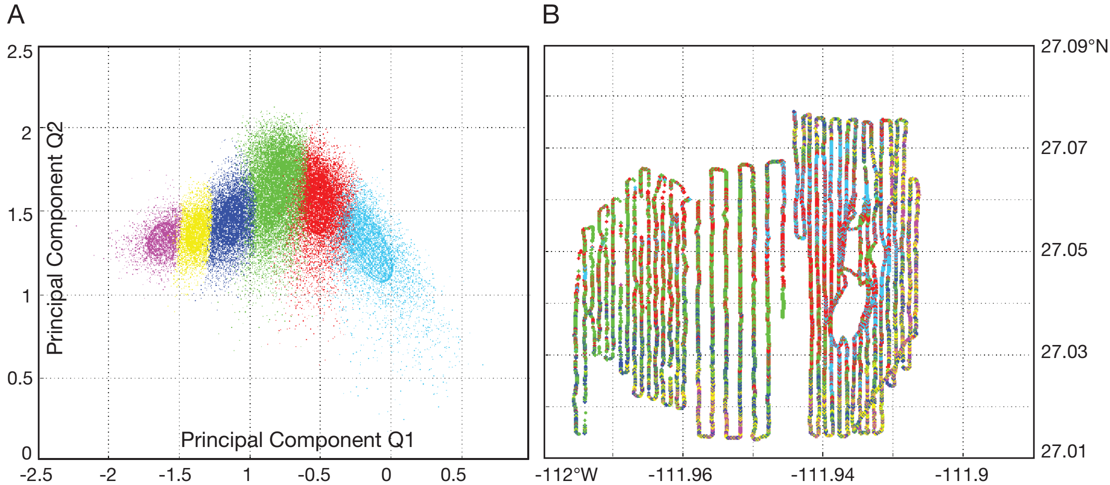

FIG. 2. — **A**, scatterplot of acoustic diversity of survey data; each datapoint represents principle component loadings of an acoustic waveform characterized by a variety of descriptors (see methods); data cloud was split into a predetermined optimal number of clusters (see Methods); cluster centroids are shown; **B**, spatial distribution of classified data.

Punta Chivato carbonate factory has been given by Halfar *et al.* (2006a), while the molluscan fauna associated with the rhodolith bed has been characterized by Cintra-Buenrostro *et al.* (2002) and free-living bryozoans (bryoliths) have been described by James *et al.* (2006).

METHODS

OCEANOGRAPHY

An oceanographic mooring with a near-surface buoy was positioned at 25 m depth for a one-year period from March 2002 to March 2003 containing Stowaway Tidbit temperature loggers at 25 m and 10 m and a self-contained underwater fluorometer (SCUFA, Turner Designs) at 10 m – the depth of prolific rhodolith formation – for recording chlorophyll *a* (Chl *a*) a proxy for nutrients and an indicator of seafloor light conditions (location of mooring indicated on Figure 1). All equipment logged data at hourly intervals. In addition, due to equipment failure after 7 months of deployment *in situ* Chl *a* data were supplemented with remote-sensed SeaWiFS information, which was obtained for each site at weekly resolution from http://seawifs.gsfc.nasa.gov. Secchi disk light-penetration depths were measured at *c.* 3-month intervals at noon from March 2002 to March 2003. At the same time, a salinometer (37SM MicroCAT, Sea-Bird Electronics) was deployed logging salinity profiles to 50 m depth in 1-m intervals.

SEDIMENTOLOGY

Surface sediment grab samples (n = 79) were collected using a Van Veen clam-shell benthic grab sampler across the entire Punta Chivato study area in water depths ranging from shallow subtidal to 65 m (Fig. 1). Sediments were separated into three size fractions (< 63 µm; 63 µm-2 mm; > 2 mm); each size fraction was weighed to give an approximation of grain size distribution. Groups of carbonate-producing organisms were distinguished during point counting of 40 sediment samples (150 points per sample, > 2 mm fraction). In addition, rhodoliths and fragments were grouped according to growth morphologies defined by Woelkerling *et al.* (1993) after observation under a binocular microscope. Carbonate content of all samples collected (bulk sample) was determined using a coulometer following procedures outlined in John *et al.* (2003).

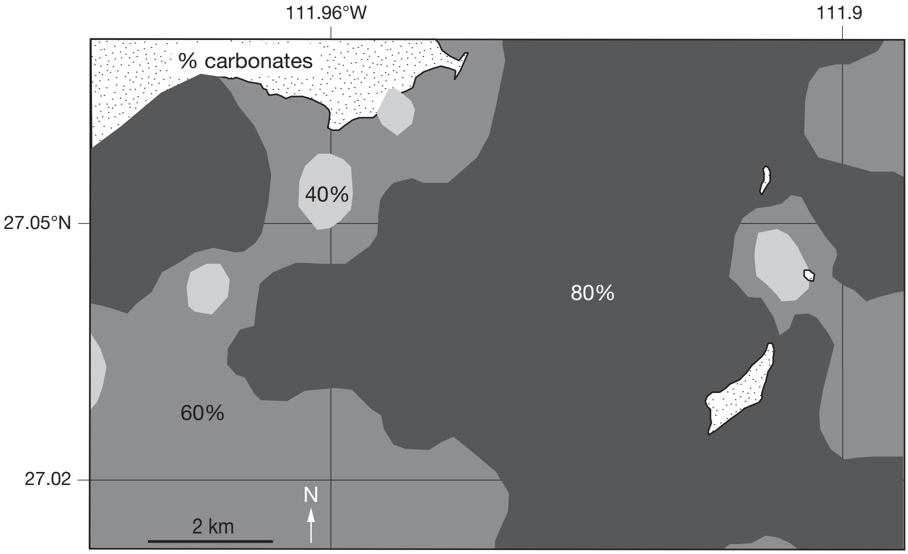

FIG. 3. — Percent carbonate content of samples (all size fractions combined).

ACOUSTIC MAPPING

Acoustic mapping was conducted using a computer-based QTC View mapping system (Quester Tangent Corporation) in conjunction with a single beam echosounder. The system interprets the characteristics of the returning waveform reflected from the seafloor to generate signal classifications based on the diversity of acoustic responses of different seafloor types. Hence, as discussed in detail by Riegl & Purkis (2005) and Riegl *et al.* (2007) it is sensitive to sediment composition and/or benthic assemblages (e.g., signal differs between hard vs soft bottom). For the identification of facies this study concentrated on using 200 kHz echosounder data. This relatively high-frequency and short wave-length signal enters little into the substratum and is primarily reflected at the sediment surface. Rugose surfaces create strong scatter, which tends to be well-visible when total acoustic diversity is evaluated (Moyer *et al.* 2005). Since rhodolith-dominated seafloor environments are relatively rugose structures, it was reasoned that acoustic diversity above rhodolith-dominated environments would be strongly influenced by a scatter component. 170 km of transect lines were acquired at a cruise speed of 5 knots and line spacing was 200 m (400 m in the center of the study area; Fig. 1). In QTC Impact software, the echoes were digitized, subjected to Fourier and wavelet analysis and were analyzed for kurtosis, area under the curve, spectral moments, and other variables by the acquisition software (Legendre *et al.* 2002). After being normalized they were subjected to principal components analysis (PCA) in order to eliminate redundancies and noise. The first three principal components of each echo were retained (called Q values), as they contain the majority of the information (Fig. 2). Datapoints were projected into pseudo-three-dimensional space along these three components, where they were then subjected to cluster analysis using a Bayesian approach. In clustering, the user decides on the number of desirable clusters and also chooses which cluster to split and how often. Decisions are based on a series of indices that allow detection of optimal number of clusters (Legendre *et al.* 2002; Riegl & Purkis 2005). The class-categorized data were imported into a Geographic Information System (ESRI ArcGIS™ 8.2) with the objective to map the distribution of the different clusters spatially over the surveyed area (Fig. 2). After regridding the irregular survey data to a regular grid, nearest-neighbour interpolation was used to provide full coverage of acoustic

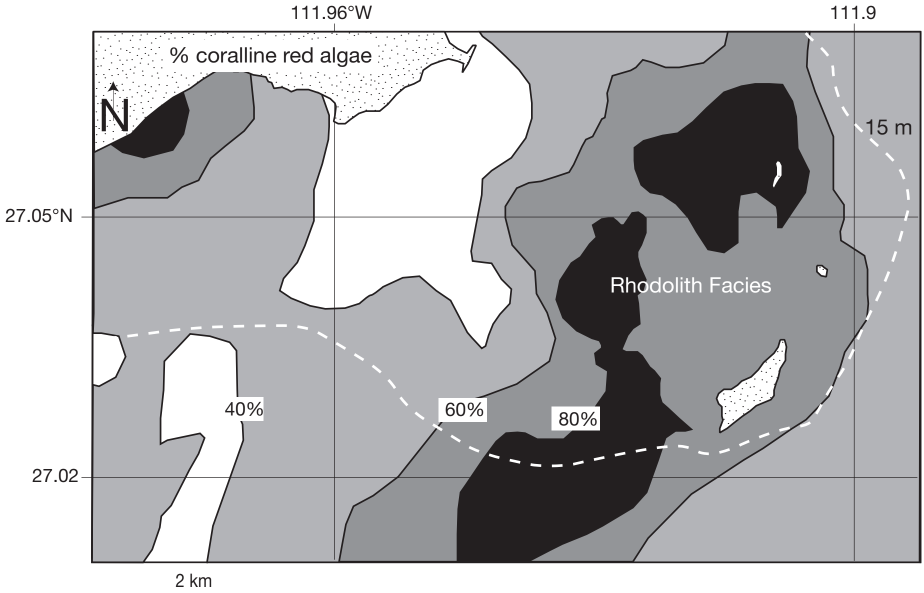

FIG. 4. — Distribution of rhodolith components (> 60% rhodolith components in > 2 mm fraction). Dashed white line shows 15-m depth contour.

data also in between survey lines (Hetzinger *et al.* 2006). In order to allow for gradations between the classes, they were arranged in a logical order so that fractional classes could be seen as gradations along a surface roughness ramp (class 1-6 decreasing surface roughness). Spatially interpolated data were compared to qualitative groundtruthing information, which was obtained from sediment samples and by using an underwater video camera and SCUBA at selected locations.

RESULTS

OCEANOGRAPHY

Based on quarterly measurements to 30 m depth, salinity at each of the four carbonate producing settings fluctuated little throughout the year and was centered at 35.2‰ (Table 1). A shallow thermocline was present from April through October with thermocline depths varying between 14 and 27 m (Fig. 1; Table 1). Ocean temperatures above the thermocline ranged from 17 to 30°C and are characteristic of the warm-temperate realm. Chlorophyll *a* concentrations fluctuated widely throughout the year and within individual months ranging from oligotrophic through eutrophic conditions (Fig. 1). For most of the year, however, eutrophic conditions prevailed (average 1.6 mg Chl a/m^3) with high phytoplankton biomass restricting depth of light penetration as evidenced by a minimum Secchi disk depth of 8 m (range 8-18 m; Table 1). Similar Secchi disk depths of 9-15 m have been reported from the Bahía Concepción rhodolith bed 50 km to the south of Punta Chivato (Foster *et al.* 1997). Double Secchi disc depth (e.g., minimum 16 m at Punta Chivato) commonly defines the depth of the euphotic zone where < 1% of surface irradiance penetrates (Holmes 1970).

The Punta Chivato carbonate factory

Owing to a lack of input of terrigenous material from the arid Baja California Peninsula, carbonate content averages 79% in all bulk samples (Fig. 3). Coralline algae in the form of rhodoliths were the most abundant carbonate constituents in the > 2 mm-fraction (38% of total carbonate producers). Entire living and fragmented rhodoliths were encountered throughout the study area, however,

TABLE 1. — Physical oceanographic parameters measured at Punta Chivato.

	Salinity above thermocline (‰)	Thermocline depth (m)	Temperature at 10 m (°C)	Temperature at 25 m (°C)	Chlorophyll *a* (mg Chl *a*/m³)	Secchi Disk depth (m)
March 2002	35.2	27	19	18	0.8	9.5
Aug 2002	35.3	14	28	25	3	8
Nov 2002	35.3	> 50	26	25	1	9
Jan 2003	35.3	> 50	19	19	4	18
March 2003	35.3	> 50	20	19	2	11

they were widespread from the shallow subtidal zone to inner shelf depth (to 20 m). With concentrations of > 60% of total carbonate producers rhodolith material was most abundant west of Islas Santa Inez and close to the shore in the northwestern part of the Punta Chivato shelf at water depths < 10 m (Fig. 4). An exception was the southern part of the Punta Chivato shelf where an accumulation of more than 60% rhodolith fragments (out of total % carbonate producers) reached to 40 m water depth. Rhodolith growth morphologies – indicators of environmental conditions and energy regimes – can be grouped according to a classification scheme modified from Woelkerling *et al.* (1993) into 85% fruticose (branching) growth forms, 9% lumpy (crowded, contiguous and rarely branched) forms and 6% fragile foliose (lamellate branch) forms (Fig. 5). While the fruticose forms were evenly distributed throughout the study area, fragments of small lumpy rhodoliths were found in more than 60 m water depth east of Islas Santa Inez. In general the occurrences of fruticose and lumpy rhodoliths were inversely correlated. Foliose rhodoliths were concentrated in the south and encrusting coralline algae are found mainly along the rocky shoreline of Punta Chivato.

Bivalves made up 35% of all carbonate producers, whereas gastropods accounted for 8% of the carbonates (Fig. 5). 11% of the carbonate constituents were bryozoans, most of which were located in the deeper part of the study area east of Islas Santa Inez. Hence, bryozoan abundance was strongly controlled by depth, reaching >40% below 30 m and > 60% below 50 m (out of total % carbonate producers). Encrusting, branching and free-living (Cupuladriid) bryozoans represented the most common growth morphologies. Carbonate producers such as serpulids, zooxanthellate corals and barnacles made up less than 2% each of total carbonate producers (Fig. 5). The predominant grain size range on the Punta Chivato shelf was from > 63 μm-2 mm (sand fraction). Only in locations where rhodoliths and their fragments made up > 60% of the carbonate biota did the sand fraction account for less than 60% of the total sediment, while gravel size components comprised > 40% of the sediment (Fig. 6). Hence, coarse grain sizes were correlated with high abundances of rhodoliths and rhodolith-derived fragments.

PUNTA CHIVATO RHODOLITH FACIES

The above shown abundance and distribution data of rhodoliths and rhodolith-derived fragments allowed for delimiting an extensive area of dense coverage of rhodoliths (defined here as >60% rhodoliths and fragments in the > 2 mm-fraction – based on total carbonate producers) west of Islas Santa Inez (Fig. 4). According to a spatial interpolation of the percentage of coralline algae, most of the Punta Chivato rhodoliths are largely confined to the 15 m depth contour, except for a tongue of rhodolith sediment extending to the south below 15 m (Fig. 4). A region of high abundances of rhodoliths near the coastline along the northwestern part of Punta Chivato was not well defined due to low sample coverage (n = 2) and bottom observations did not reveal significant amounts of living rhodoliths (Fig. 4).

ACOUSTIC MAPPING

Based on sediment characteristic and seafloor observations in combination with principal component analysis of acoustic return signals, six acoustic seafloor facies were distinguished (Fig. 7; Table 2). Acoustic facies 1 to 3 were dominated by rho-

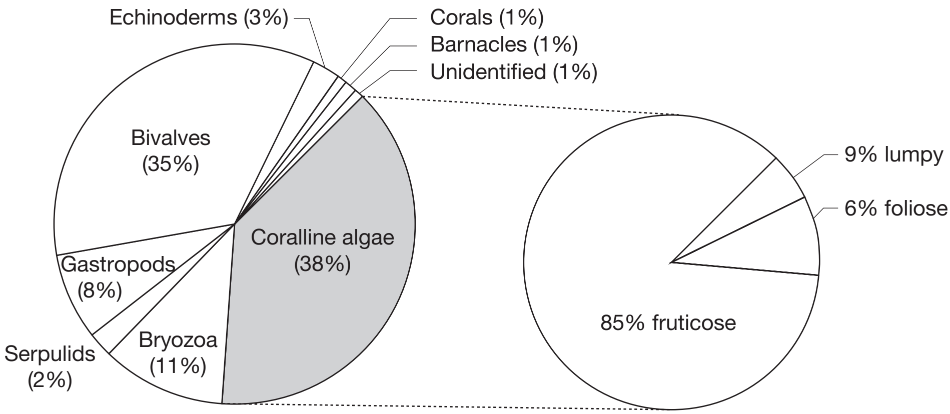

FIG. 5. — Average percentages of biogenic constituents of Punta Chivato and composition of rhodolith subcategories (> 2 mm fraction, n = 40).

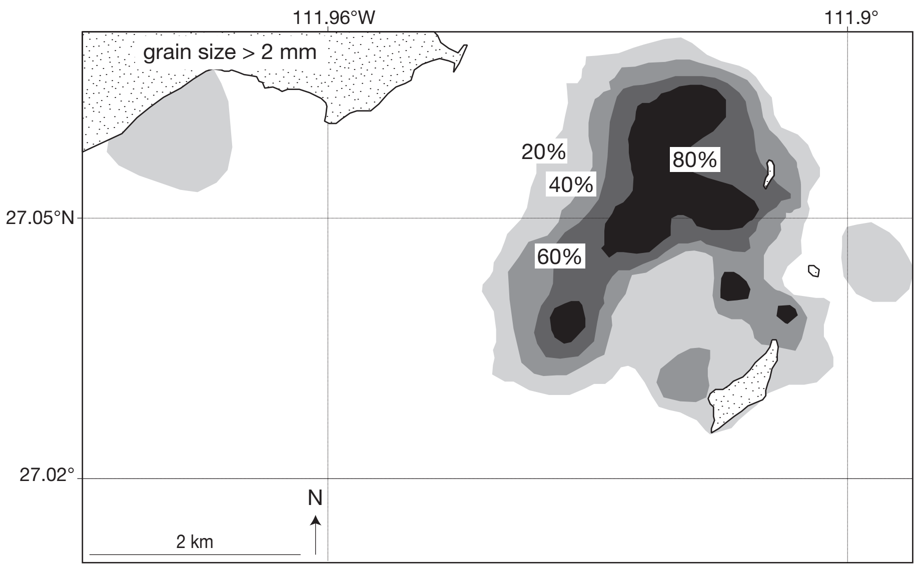

FIG. 6. — Distribution of sediment fraction > 2 mm. Coarse fraction gives indication on location of rhodolith beds.

doliths and surrounded the islands of Santa Inez. These facies largely overlapped with the location of the rhodolith-dominated seafloor environment as defined by sediment analysis. All three facies had a high carbonate content (>93%) and were characterized by their coarse grain size. Even though actual differences in the three acoustic facies were subtle, acoustic facies 2 represented the center of the rhodolith-dominated area with highest amounts of rhodolith material. Acoustic facies 1 and 2 exhibited the coarsest material. Groundtruthing indicated that living rhodoliths were abundant in these two acoustic facies. Acoustic facies 1, which was closely associated with the group of three islands, differed from facies 2 in the frequent occurrence of rocky nearshore outcrops, causing a difference in the reflected acoustic signal. Facies 2 was defined as a rhodolith-dominated facies, whereas facies 1 was a combined rhodolith-dominated – hard-substrate facies. Facies 3 surrounded the rhodolith-dominated facies and was termed a marginal rhodolith-dominated facies. This facies was characterized by lower abundances of rhodoliths and higher percentages of bivalves. Hence, facies 3 outlined the limits of the rhodolith-dominated area and likely contained material transported from acoustic facies 1 and 2. Together, facies 1 to 3 occupy 21% of the mapped area or 17 km^2. Facies 4 to 6 showed a distinctly different acoustic return signal and represented areas of high abundances of bivalves mixed with up to 31% fine non-carbonate material. These facies together occupied more than ¾ of the Punta Chivato shelf and were found close to shore (facies 5) or largely in deeper water (facies 4). Acoustic facies 3 was also present south of the headland of Punta Chivato, however, in the absence of extensive rhodolith cover (as observed by groundtruthing and sediment sampling; sediment consists of 86% bivalves and 6% rhodolith material) this appeared to largely be an erroneous interpolation of the acoustic data set.

DISCUSSION

Acoustic mapping and sedimentology of the Punta Chivato carbonate system

The carbonate factory occupies an area of 80 km^2 and is therefore the most extensive carbonate factory in the Gulf of California known to date. Due to an arid hinterland, and low terrigenous input siliciclastic material is negligible at this site away from the coastlines and above 40 m depth, which is the maximum depth of prolific carbonate formation. The associations of carbonate producing organisms on the Punta Chivato shelf are dominated by rhodoliths and can be defined as rhodalgal carbonates *sensu* Carannante *et al.* (1988).

Acoustic mapping shows that the rhodolith–dominated area occupies *c.* 21% or 17 km^2 of the study area (facies 1-3). The location of the acoustically mapped rhodolith-dominated area closely corresponds to the distribution of coarse grain sizes >2 mm. While both the acoustic map and the coarse grain size map overlap, there is a discrepancy with the spatial distribution of rhodoliths and rhodolith fragments, which extends to the south (Figs 4-7). The reason for the poor overlap is that the southern tongue of high percentages of rhodoliths represents allochthonous and broken up rhodolith material, that contains few living rhodoliths, and high numbers of fragments >2 mm. This material is interpreted as having been transported by currents and storms from the north and east away from the living rhodolith bed and redeposited downcurrent in up to 40 m water depth. This interpretation is confirmed by bottom observations during groundtruthing, indicating low coverage of living rhodoliths on the deeper shelf. Hence, both the grain size distribution and the acoustic map give a better representation of the position and extent of the rhodolith-dominated area than the distribution of rhodoliths and rhodolith-derived fragments as determined by point counting. Reasons are that the predominant grain size has an important influence on the acoustic return signal (Legendre *et al.* 2002; Riegl & Purkis 2005). Sediments containing entire rhodoliths will therefore have a different acoustic character as sediments with mainly rhodolith fragments, or sediments dominated by molluscs or bryozoa. In fact, acoustic sediment mapping has previously been shown to be an excellent approach for detecting and delimiting the extent of rhodolith facies (Birkett *et al.* 1998; Hetzinger *et al.* 2006; Ierodiaconou *et al.* 2011).

Punta Chivato rhodolith environment

While modern rhodolith beds of varying size have been described from throughout the modern Gulf of California (see distribution map in Steller *et al.* 2009 and Riosmena-Rodríguez *et al.* 2010), sediment-forming rhodolith-dominated environments are restricted to the central portion between Punta Chivato and Isla Espiritu Santo (Halfar *et al.* 2006; Fig. 1). Gulf of California rhodoliths generally occur in two main settings: 1) gently sloping, subtidal soft bottoms with moderate wave action (wave beds; <12 m deep); and 2) relatively level bottoms in channels with tidal currents (current beds; >12 m) (Foster *et al.* 1997). In both settings, rhodoliths are protected from smothering by fine sediments through tidal currents or wave action (Marrack 1999). The majority of the Punta Chivato rhodolith

TABLE 2. — Characteristics of acoustic facies.

Acoustic Facies	1	2	3	4	5	6
Depth range	5-25 m	5-15 m	0-45 m	15- > 65 m	0-25 m	0-10 m
Main carbonate producers	Rhodoliths bryozoa	Rhodoliths bryozoa bivalves	Rhodoliths bivalves	Bivalves rhodoliths gastropods bryozoa	Bivalves rhodoliths	Bivalves rhodoliths
Average carbonate content	93%	94%	94%	79%	79%	79%
Dominant grain size	> 2 mm	> 2 mm	63 µm-2 mm	63 µm-2 mm	63 µm-2 mm	63 µm-2 mm
Median grain size (ϕ)	–2 to –1	–2	0	1-2	1-2	1-2
Spatial coverage	2%	13%	6%	47%	30%	3%
Facies name	Rhodolith-hard substrate	Rhodolith-dominated	Marginal rhodolith-dominated	Fine-grained molluscan	Transitional bivalve-rhodolith	Bivalve

bed is shallower than 15 m, and can be classified as a wave-dominated rhodolith bed. This finding is in contrast to Cintra-Buenrostro *et al.* (2002) who describe the Punta Chivato rhodolith beds as generally occurring below 12 m, without, however, giving quantitative or bathymetric data on rhodolith distribution. On a global scale, the majority of rhodolith beds are most commonly found in less than 30 m water depth (e.g., Bosellini & Ginsburg 1971; Freiwald & Henrich 1994; Piller & Rasser 1996; Perry 2005; Basso *et al.* 2009).

Rhodolith growth forms and structure can be used as environmental indicators (Bosence 1983; Basso 1998; Steller *et al.* 2003; Basso *et al.* 2009). Most of the fruticose rhodoliths – the most common growth form in the study area – are fragmented by water motion. The fact that only fruticose forms are fragmented is an indication for weak water motion. While protuberance degree (Basso *et al.* 2009) and thickness of individual branches generally decreases with increasing water depth and decreasing energy (Steller *et al.* 2003), there is no depth-related trend in occurrences of fruticose rhodoliths in our study. This is further evidence for low-energy conditions in shallow-water. Fruticose massive morphologies were found within the rhodolith facies, but also in deeper samples. Lumpy forms usually occur in shallow-water only, where they are resistant to wave energy (Foster *et al.* 1997). The abundance of these forms in deeper water at Punta Chivato most likely reflects the allochthonous character of redeposited rhodoliths.

The associated calcareous fauna of the rhodolith-dominated settings in the Gulf of California exhibits a north-south gradient (Halfar *et al.* 2006a). The transition from cold, nutrient-enriched, to warmer, nutrient-impoverished regions, is manifested in rhodolith settings in the northern gulf exhibiting higher abundances of bivalves and bryozoa, whereas rhodoliths in the south are frequently associated with zooxanthellate corals (Reyes-Bonilla *et al.* 1997; Hetzinger *et al.* 2006). As minimum monthly sea surface temperatures (SSTs) between Punta Chivato (16°C) and Isla Espiritu Santo (16.5°C – the location of the southermost described extensive rhodolith bed in the Gulf of California; Marrack 1999) are similar, they are unlikely to be responsible for the different percentages of associated calcifiers.

Nutrients, however, play a significant role in the distribution pattern of Gulf of California rhodoliths and associated carbonate producers, due to their effect on light-penetration. While nutrients themselves are not limiting the development of rhodolith facies (Steller *et al.* 2009), increased nutrients stimulate phytoplankton growth. This is reflected by increased Chl *a* values under high-nutrient conditions. Phytoplankton abundance in turn exerts a significant influence on light reaching the seafloor and, hence, the growth of light-dependent rhodoliths (Halfar *et al.* 2006). In fact, there is an

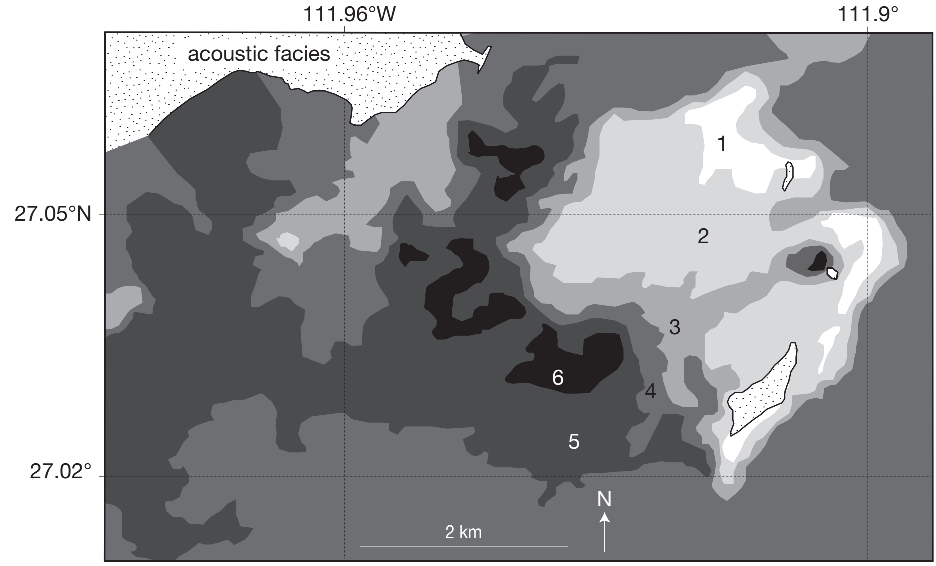

FIG. 7. — Spatial distribution of acoustic facies and respective characteristics (gradations along a surface roughness ramp – class 1-6 decreasing surface roughness). Facies description shown in Table 2.

intimate link between nutrients and depth of the light-dependent euphotic zone (Hallock 1987). The decreasing depth of the euphotic zone in the Gulf of California (average depth of euphotic zone in the south is 26 m; in the north 16 m; Halfar *et al.* 2006a) is accompanied by increasing concentrations of chlorophyll *a* (Halfar *et al.* 2006a). Living rhodoliths only occur where light on the seafloor is suitable for growth (Steller *et al.* 2009; Riosmena-Rodríguez *et al.* 2010). Generally, the maximum depth for growth is assumed to be at the limit of the euphotic zone (Foster *et al.* 1997), which has a minimum depth of 16 m (average 22 m) at Punta Chivato. Accordingly, the maximum average depth of the spatially extensive rhodolith-dominated acoustic facies 2 at Punta Chivato is 15 m.

As light penetration decreases with increasing nutrients and phytoplankton biomass in the northwestern gulf (Alvarez-Borrego 2010), shallow seafloor environments suitable for development of extensive rhodolith facies become sparse along this steep rift-basin ocean margin. In contrast, the deepest Gulf of California rhodolith occurrences are found in the south (Riosmena-Rodríguez *et al.* 2010) where nutrients are lowest and light penetration is highest. In the southernmost gulf, however, the absence of extensive and carbonate-sediment producing rhodolith-dominated facies is due to the presence of fast-growing zooxanthellate corals, which can dominate rhodoliths for space under high temperature and low-nutrient conditions (Riosmena-Rodríguez *et al.* 2010).

CONCLUSION

The Punta Chivato rhodalgal carbonate factory is dominated by an extensive wave-dominated rhodolith facies forming within the euphotic zone in less than 15 m water depth. The location of the acoustically mapped rhodolith-dominated facies closely corresponds to the distribution of coarse grain sizes >2 mm due to the predominant grain size having an important influence on the acoustic return signal. Hence, entire rhodoliths have an acoustic character distinct from surrounding sediments. Acoustic seafloor mapping can therefore be used to rapidly and accurately map and quantify seafloor rhodolith environments. This is important, as rhodolith environments globally have been recognized as complex habitats supporting rich and diverse benthic communities, including commercially exploited species, and are being considered as marine conservation areas in different regions of the world (Steller *et al.* 2009).

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