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Shallow rocky bottom benthic assemblages as calcium carbonate producers in the Alboran Sea (southwestern Mediterranean)

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Abstract – Zonation patterns and species composition of the different assemblages encountered along the bathymetric axis are considered in order to quantify the biomass and calcium carbonate content of communities thriving in rocky bottoms of La Herradura (southwestern Mediterranean) between 0 and 50 m depth. Algal biomass is lower but total biomass is slightly higher to values recorded in other Mediterranean areas due to the high biomass of suspension feeders. Since most of the animals and algae with high biomass have calcareous skeletons, the calcimass is rather high (1 100 to 2 400 $g{\cdot}CaCO_3{\cdot}m^{-2}$) when compared to other temperate and Mediterranean sites. A tentative estimate of yearly carbonate production yields 1 000 $g{\cdot}CaCO_3{\cdot}m^{-2}{\cdot}y^{-1}$ for the rocky bottoms of the infralittoral zone and 680 $g{\cdot}CaCO_3{\cdot}m^{-2}{\cdot}y^{-1}$ for the circalittoral zone. This relatively high carbonate production may be related to the particular hydrographic processes which take place in this area (mixing of Mediterranean and Atlantic waters, upwelling of Mediterranean deep waters). © 2000 Ifremer/CNRS/IRD/Éditions scientifiques et médicales Elsevier SAS

calcium carbonate / rocky bottoms / benthic assemblages / production / Mediterranean Sea

Résumé – Les communautés benthiques des fonds rocheux littoraux comme producteurs de carbonate de calcium dans la mer d'Alboran (Méditerranée sud-occidentale). La zonation et la composition spécifique des différentes communautés rencontrées sur un profil bathymétrique sont utilisées pour quantifier la biomasse et la teneur en carbonate de calcium des fonds rocheux littoraux de La Herradura (Méditerranée sud–occidentale), entre 0 et 50 m de profondeur. La biomasse algale est moindre mais la biomasse totale est légèrement supérieure à celles rapportées pour d'autres zones de Méditerranée, en raison de la forte biomasse des organismes suspensivores. Puisque la plupart des animaux et des algues à forte biomasse possèdent des squelettes carbonatés, la « calcimasse » est assez élevée (1 100 jusqu'à 2 400 $g{\cdot}CaCO_3{\cdot}m^{-2}$) quand on la compare avec d'autres données provenant des mers tempérées ou de la Méditerranée. Une estimation de la production annuelle de calcaire conduit à des valeurs proches de 1 000 $g{\cdot}CaCO_3{\cdot}m^{-2}{\cdot}an^{-1}$ pour les fonds rocheux infralittoraux et 680 $g{\cdot}CaCO_3{\cdot}m^{-2}{\cdot}an^{-1}$ pour les fonds circalittoraux. Cette production carbonatée rélativement importante peut être mise en rapport avec les processus océaniques particuliers qui ont lieu dans cette zone de la Méditerranée: mélange des eaux méditerranéenne et atlantique, remontée des eaux méditerranéennes profondes. © 2000 Ifremer/CNRS/IRD/Éditions scientifiques et médicales Elsevier SAS

carbonate / fonds rocheux / communautés benthiques / production / mer Méditerranée

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1. INTRODUCTION

It has been estimated that half of the total calcium carbonate fixed in the oceans arises from benthic organisms [32]. Benthic communities from shallow waters have high primary production and carbonate deposition rates when compared to deep water assemblages [8]. Benthic calcium carbonate is hence one of the major components of sediment in mid and low latitude shelves, its presence in significant amounts on high latitude shelves being more exceptional [36].

In contrast with coral reef settings [2, 38, 46], carbonate production, export and accumulation on continental shelves are poorly documented although it has been suggested that global carbonate production on shelves may be at least one order of magnitude lower than that reported for coral reefs [31, 32]. Since a global mean of 1 500 $g \cdot m^{-2} \cdot y^{-1}$ of calcium carbonate production seems to be a fairly good estimate for coral reefs [44], a mean value close to 150 $g \cdot m^{-2} \cdot y^{-1}$ should be acceptable for continental shelves. Limiting factors for shallow-marine carbonate sedimentation are considered to be upwelling, terrigenous clastic input, cool temperatures, and light reflection, according to the classical view [50].

The Mediterranean is an enclosed sea with various deep sub-basins surrounded by continental shelves of different amplitudes, with depths of less than 150 m occupying the 17.2 % of the seafloor [23]. The physiographic complexity of the Mediterranean Sea is in accordance with its high species richness and habitat diversity [49]. Also, differences in the sediment composition from Mediterranean continental shelves are acute and distinctions between terrigenous, mixed and carbonate shelves have been made [9, 26]. This physiographic complexity, which encompasses the watershed, habitat diversity and climatic factors, is at the origin of the observed sedimentary variability.

The geographical location of the Alboran Sea as the first Mediterranean basin for the inflowing Atlantic Water (AW) through the Strait of Gibraltar along its path into the Mediterranean Sea, makes its study a subject of prime importance for any well-based research on the gradients and variability of benthic carbonate production in the Mediterranean Sea. Because of its strong Atlantic influence, the Alboran Sea has been described as, "the most Atlantic of the Mediterranean basins".

While carbonate sedimentation in the Mediterranean Sea has been described in the offshore banks from the Alboran Sea [33] and in the Balearic inner shelf [16], and carbonate content is known for several Mediterranean communities [5, 24], carbonate production has been only estimated in the Balearic shelf, where [8] reported a mean production rate around 100 $g \cdot CaCO_3 \cdot m^{-2} \cdot y^{-1}$ for the phytobenthic assemblages over the upper 100 m of water depth.

Since there are outstanding differences between the Western Mediterranean shelves in the Alboran Sea and the Balearic islands, both in terms of physiography (shelf connected to mainland versus island platform) and oceanography (inflow of surface Atlantic waters with frontal structures and upwelling versus saltier Algero-Balearic mixed-surface water with Intermediate Western Mediterranean Water at deeper levels and intense summer thermal stratification), differences in the species composition and thus in the rate of carbonate production from benthic assemblages between the two zones were expected. Following the work by Canals and Ballesteros [8] in the Balearic islands, we describe here the benthic communities developing on rocky bottoms and quantify the calcimass of both algae and animals from 0 to 50 m depth in La Herradura, a coastal locality from the northern Alboran Sea. A preliminary estimate of carbonate production is also established considering the yearly turn-over rates of the calcareous species.

The aim of this work is to increase knowledge of the carbonate production in the continental shelves of the Mediterranean in order to quantify its contribution to sediment formation, thus helping to improve global carbonate budgets and the interpretation of ancient carbonates in similar settings.

1.1. Hydrographic setting

In general terms, the superficial waters in the Alboran Sea are of Atlantic origin. The water entering through the Strait of Gibraltar is made of Superficial Atlantic Water (from 0 to 100 m depth), with salinities between 36.4 and 36 and, below, North Atlantic Central Water (from 100 to 1 000 m depth), which shows a diminution of salinity and temperature with depth (36.2 to 35.4, and 16 to 9 °C). Since these two Atlantic waters mix progressively as a function of

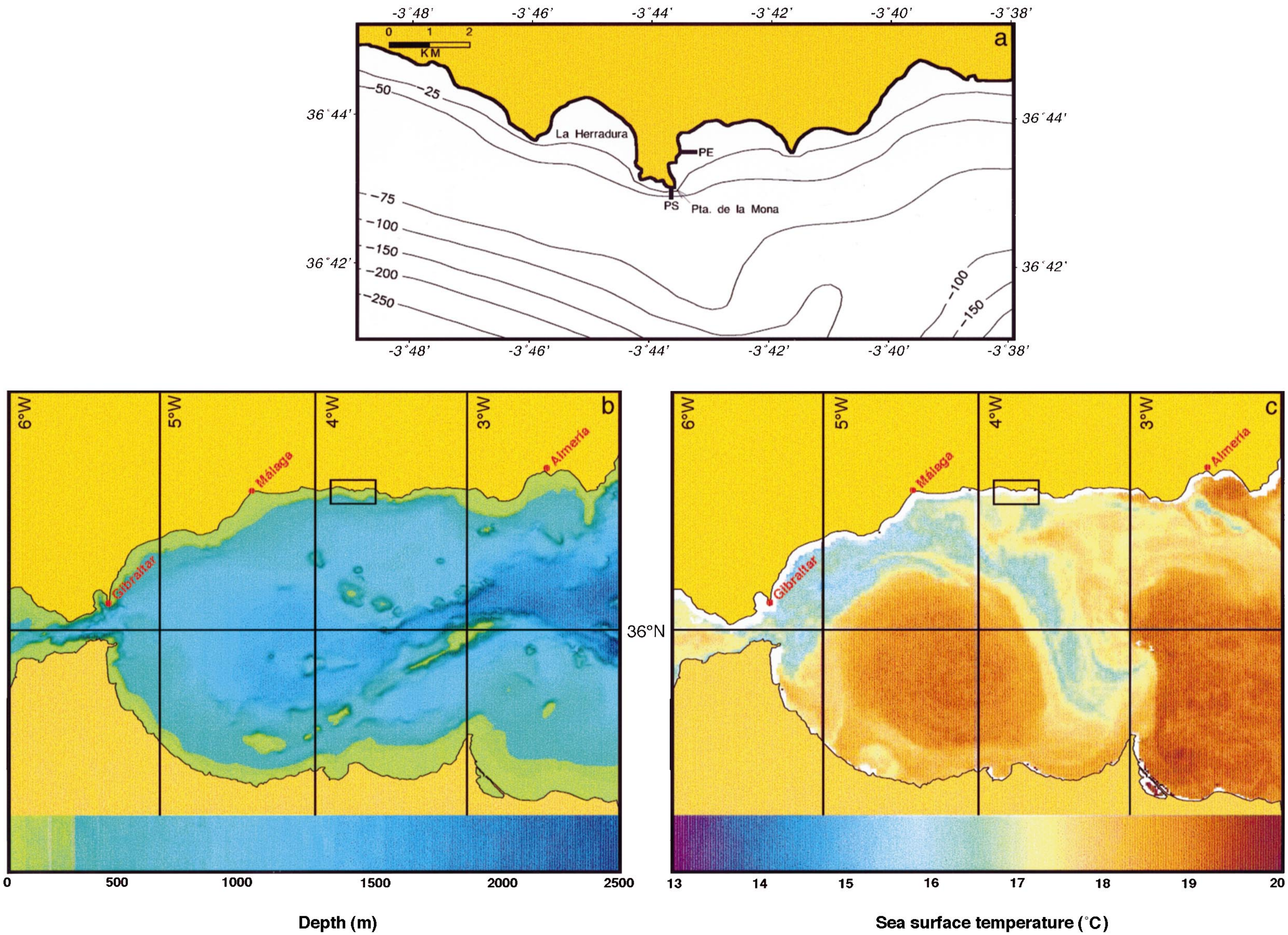

Figure 1. Location of La Herradura in the Alboran Sea, surface water temperatures of the Alboran Sea in a typical cyclonic hydrographic structure that promotes upwelling of deep waters in coastal waters south of Spain, and situation of the transects in La Herradura.

their residence time and circulation paths in the Alboran Sea, it becomes increasingly difficult to differentiate between them. For that reason, in the Alboran Sea, waters having a salinity < 37.5 are considered simply 'Atlantic waters' [20]. Thus, the depth of the 37.5 isohaline corresponds to the thickness of the layer of Atlantic waters. The jet of Atlantic water forms two large anticyclonic gyres, known as the Western Alboran gyre, of permanent nature, and the Eastern Alboran gyre, of a more episodic character. The zone between Malaga and Almeria, where La Herradura lies, is usually occupied by a cyclonic counter-circulation, that can promote the ascent of deeper waters thus causing superficial salinity values close to 37.5. This means, in practice, that there may be almost no Atlantic waters over the continental shelf in that zone. Around La Herradura, the measured thickness of Atlantic waters generally ranges between 5 and 25 m, and tends to be smaller towards the coast, even disappearing completely [19; M. Vargas, pers. comm.]. The thickness of the Atlantic layer changes seasonally, particularly in the coastal area, with a tendency towards minimum thicknesses in winter and maximum thicknesses in autumn months [20].

Mean monthly temperature of superficial waters in the La Herradura area for the period 1980–1990 ranges from 14.65 °C in February to 23.68 °C in August [10, 19]. Secchi disk values range from 5.8 to 15 m depth, with lower values measured in May and July (data from Caleta de Vélez; M. Vargas pers. comm.), suggesting the presence of strong upwelling periods in late spring and early summer. In May–July, the period when our field work was done, measurements from a station close to La Herradura show salinity values ranging between 37.0 and 37.8 for surface waters, and 37.9 to 38.5 at 75 m depth, and temperatures moving from 16 to 17 °C [20]. In summer, a seasonal thermocline forms that may reach 60 to 70 m depth, well below the depth of the Atlantic waters over the continental shelf. On top of the thermocline there is an homogeneous layer 5 to 25 m thick. The thermal characteristics of the superficial layers are also influenced by wind regimes, specially in coastal areas, with fast temperature changes of up to 5 °C in spring–summer [20]. The dominant winds in the Alboran Sea are from the east and the west. West winds favour the entrance of Atlantic waters, with the main water jet following roughly the 36° N parallel. This leaves a broad passage between the jet and the coastline, thus allowing the formation of the cyclonic eddies mentioned above. East winds brake the jet of Atlantic waters and the Western Alboran anticyclonic gyre occupies the whole western sub-basin without any space left for the formation of the coastal cyclonic eddies. In parallel, the rise of deeper waters weakens or even disappears [20].

2. MATERIALS AND METHODS

The pronounced biogeographical differences between the Atlantic Ocean and the Mediterranean Sea [12, 22, 29, 39] affect the zonation patterns of benthic communities in La Herradura, which are very different to those reported for other Mediterranean localities [11]. Previous floristic and faunistic studies performed in this area have shown that depth is the main axis of variation in the species composition of the rocky benthic communities [11]. Three major groups of communities can be distinguished: shallow water assemblages (SWA, 0 to 5 m depth), mid water assemblages (MWA, 5 to 25 m depth), and deep water assemblages (DWA, 25 to 50 m depth), which correspond to shallow infralittoral, lower infralittoral and circalittoral communities [11].

In order to account for this bathymetric variation, transects were performed between 0 and 50 m depth with Scuba diving techniques in Punta de la Mona-south and Punta de la Mona-east (*figure 1*). Two different sampling methods were used to estimate the abundances of the species along the bathymetric axis. Small, abundant species were quantified by scraping off all organisms from four 20 cm × 20 cm quadrats for each assemblage and transect. Samples were sealed in individual plastic bags, and fixed in 4 % formalin:sea water for later sorting and classification in the laboratory. The abundance of algal species and invertebrates was quantified as biomass (g per dw mass) after drying at 105–110 °C for 12–24 h [4]. The abundance of large organisms was quantified by means of 25 cm × 25 cm quadrats, divided into 25 subquadrats of 5 cm × 5 cm [40]. Thirty-two quadrats (total area of 2 m^2) were randomly positioned within each assemblage at both transects and the number of sub-

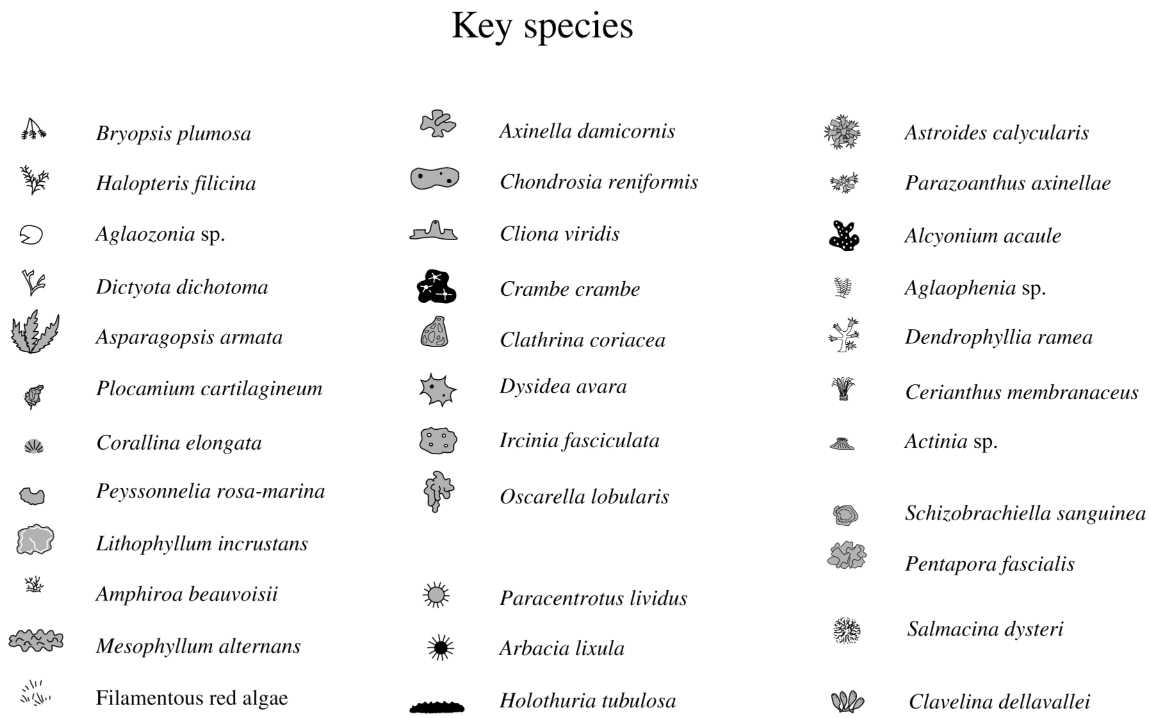

Figure 2. Legend for species diagrams shown in *figures 3* and *4.*

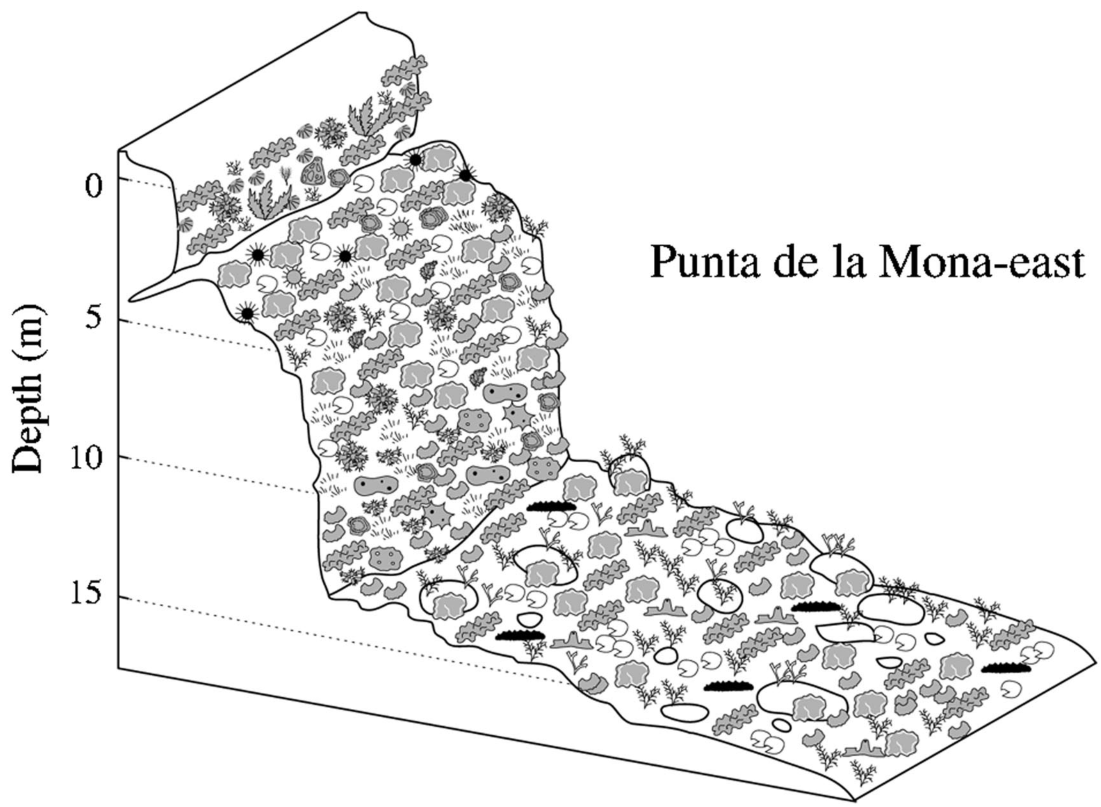

Figure 3. Diagrammatic representation of Punta de la Mona-east transect.

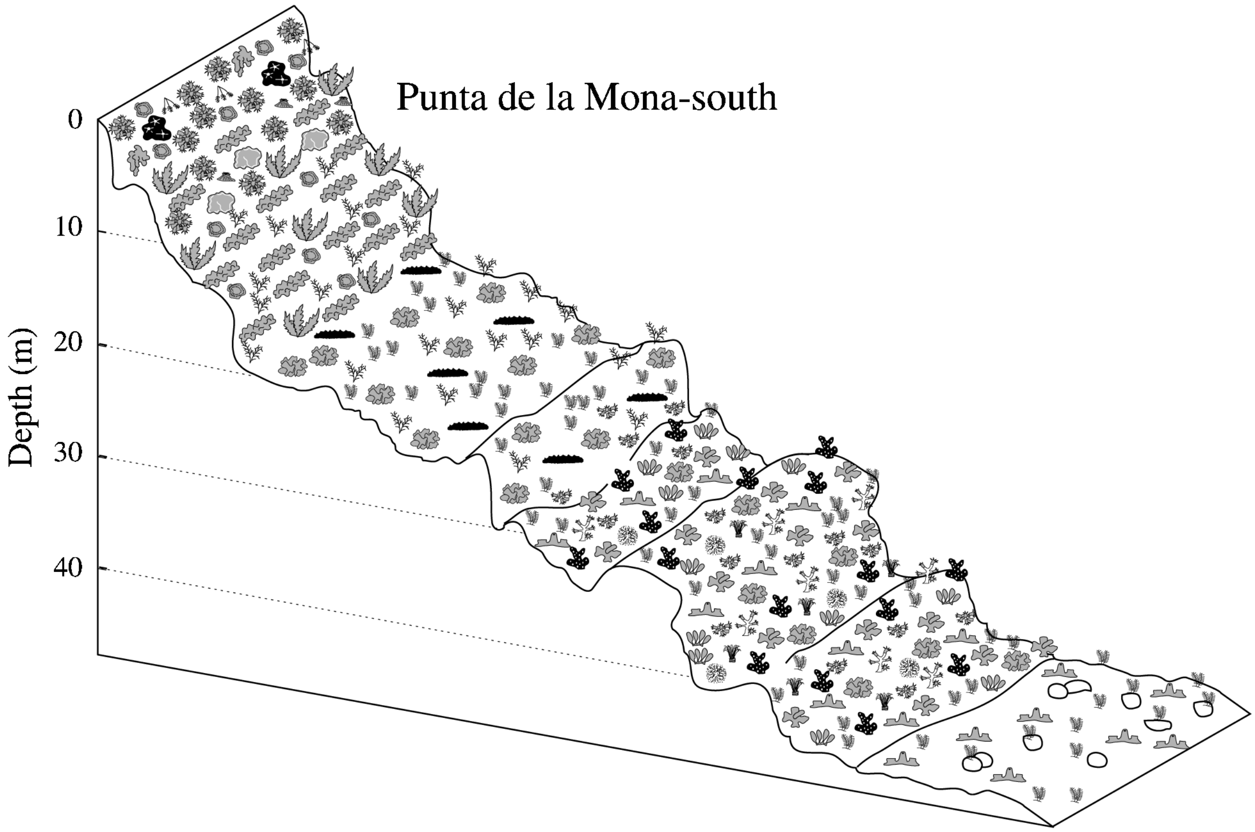

Figure 4. Diagrammatic representation of Punta de la Mona-south transect.

quadrats in which each species appeared was recorded and used as unit of measure. Conversion factors to estimate biomass from coverage data recorded in the field were obtained for each species in the laboratory. Biomass data obtained by the two methods were gathered together and normalised to 1 m^2 surfaces.

Amongst the calcareous species, several specimens of different sizes were collected and preserved for further carbonate content evaluation in the laboratory by the CO_2-gasometry method [41]. Total living calcimass of each assemblage was estimated by considering the living biomass of all calcareous organisms and its carbonate content. Tentative estimations of carbonate production were calculated taking into account the mean carbonate content of each species at each assemblage and its yearly turn-over rates obtained from references in the literature. For species lacking turn-over rate estimates in the literature, values obtained for morphologically similar species with similar ecological requirements were used.

3. RESULTS

3.1. Assemblages (*figures 2–4*)

Punta de la Mona-south is representative of exposed areas with a wide bathymetric range. The upper sublittoral fringe is characterized by a dense population of barnacles (*Balanus perforatus*). Below 1 m depth, and down to 12 m depth, encrusting calcareous algae (*Mesophyllum alternans*, *Lithophyllum incrustans*, *Peyssonnelia rosa-marina*), the erect red alga *Asparagopsis armata* and the bryozoan *Schizobrachiella sanguinea* are very abundant. Sciaphilic algae (*Mesophyllum alternans* and *Aphanocladia stichidiosa*) and the star coral *Astroides calycularis* are the dominant species between 12 and 23 m depth. The abundance of algae decreases below 23 m depth and suspension feeders become more prominent (*Pentapora fascialis*, *Aglaophenia* spp.); below 30 m depth algae are not relevant and suspension feeders constitute a highly diverse epifaunal community, with sponges (*Dysidea avara* and *Geodia* sp.), cnidarians (*Parazoanthus axinellae*, *Dendrophyllia ramea*), bry-ozoans (*Pentapora fascialis*, *Rhynchozoon* sp.) and polychaetes (*Salmacina dysteri*). The detritic muddy bottom situated around 50 m depth is colonized by some suspension-feeders growing on the detritic cobbles: *Dendrophyllia ramea*, *Balanus perforatus*, *Rynchozoon* sp. and *Salmacina dysteri*.

Punta de la Mona-east represents sheltered, shallow areas. In the upper part of the transect, between 0 and 2 m depth, coralline algae (*Mesophyllum alternans*, *Corallina elongata*, *Amphiroa beauvoisii*) dominate, with some colonies of *Astroides calycularis* and the encrusting bryozoan *Schizobrachiella sanguinea*. Below 2 m and down to 4 m depth, there is an overgrazing platform of the sea urchins *Arbacia lixula* and *Paracentrotus lividus*, with a high coverage of the calcareous algae *Lithophyllum incrustans* and *Peyssonnelia rosa-marina*. *Astroides calycularis* is extremely abundant between 4 and 10 m depth, in a diverse community with encrusting calcareous algae, and *Ircinia variabilis* is also a main component of the macrofauna. At the lower part of the wall, between 10 and 18 m depth, only sciaphilic encrusting algae (*Mesophyllum alternans*, *Peyssonnelia rosa-marina*) are abundant. Sponges (e.g. *Dysidea avara*, *Ircinia variabilis)*, cnidarians (*Astroides calycularis*) and bryozoans (*Schizobrachiella sanguinea*, *Rynchozoon sp.*) are the most prominent macrofauna.

3.2. Biomass (*table I*)

Total biomasses do not show a great variation with depth, although there is an increasing trend related to depth. Algae and animals co-dominate in shallow waters but the importance of algae is much lower in deep water assemblages, where cnidarians, bryozoans and polychaetes dominate. The sheltered transect assemblages display slightly higher biomass values than assemblages thriving at the exposed transect. Most of the dominant organisms or, at least, those which contribute the most to the living biomass have calcareous skeletons.

3.3. Calcimass

The average carbonate content for the studied assemblages ranges between 1 116 and 2 413 $g \cdot m^{-2}$. The different assemblages display similar carbonate contents although there are major depth-related differences in the taxonomic groups responsible for the production of calcium carbonate (*table II*).

Algae are fundamental in shallow environments, with contributions situated at nearly 40 % of the total carbonate content. Bryozoans and cnidarians substitute the algae as the most important calcareous organisms in deep water assemblages, with algae remaining at very low levels. Cnidarians are the animals which contribute the most to total carbonate content. Therefore, a decrease in their relative abundance is reflected in a carbonate content decrease; this is the case for mid water assemblage in Punta de la Mona-south.

4. DISCUSSION

Algal biomass in the infralittoral bottoms (SWA and MWA) of La Herradura is usually lower to values from northwestern Mediterranean communities where [6] reported 1 000–2 800 $g \cdot m^{-2}$ for the shallow infralittoral (around 1 100 $g\ m^{-2}$ in La Herradura) and 1 400–2 100 $g \cdot m^{-2}$ for the deep infralittoral communities (900 to 1 200 $g \cdot m^{-2}$ in La Herradura). However, animal biomass in the infralittoral northwestern Mediterranean communities almost always represent less than 10 % of total biomass, while in La Herradura animals account for roughly 50 % (44 to 69 %) of total biomass. Therefore, animal biomass in infralittoral rocky bottoms is much larger in La Herradura than in the northwestern Mediterranean resulting in a slightly higher total biomass: 1 490 to 2 930 $g \cdot m^{-2}$ in northwestern Mediterranean versus 2 870 to 2 960 $g \cdot m^{-2}$ in La Herradura for SWA; 1 530 to 2 160 $g \cdot m^{-2}$ in the northwestern Mediterranean versus 1 650 to 3 890 $g \cdot m^{-2}$ in La Herradura for MWA. Total biomass in circalittoral communities from the northwestern Mediterranean amounts to 2 000 $g \cdot m^{-2}$ (1 650 to 1 975 $g \cdot m^{-2}$; [6, 21]), which is

Table I. Biomass in $g \cdot dw \cdot m^{-2}$ of the more abundant species (>25 $g \cdot dw \cdot m^{-2}$) of all the different assemblages of La Herradura[a].

Transect	Punta de la Mona-south			Punta de la Mona-east	
Species	0–5 m	5–25 m	25–50 m	0–5 m	0–15 m
Algae					
Amphiroa beauvoisii[b]				29.4	
Aphanocladia stichidiosa	8.2	30.1			
Asparagopsis armata	130.6	6.4			
Corallina elongata[b]		28.6		99.1	3.5
Lithophyllum frondosum				26.2	
Lithophyllum incrustans[b]	379.1	191.0		343.9	100.2
Mesophyllum alternans[b]	51.9	573.7	43.1	322.7	207.5
Peyssonnelia squamaria					80.9
Peyssonnelia bornetii[b]					85.6
Peyssonnelia coriacea				1.3	54.0
Peyssonnelia harveyana[b]					53.0
Peyssonnelia rosa marina[b]	537.6	32.2		227.5	330.8
Peyssonnelia rubra[b]					210.3
Others	30.9	48.8	49.9	60.5	54.1
Sub Total	1138.2	910.7	93.0	1110.4	1179.9
Sponges					
Dysidea avara			64.8		59.7
Geodia sp.			79.6		
Ircinia oros					26.5
Ircinia variabilis	5.1	38.6		13.5	168.9
Sarcotragus spinosula	28.5	5.5		71.1	110.1
Spongia virgultosa					68.6
Others	2.2	5.5	21.8	5.9	58.8
Sub Total	35.8	49.6	166.2	90.5	492.7
Bryozoans					
Myriapora truncata[b]		19.9	146.5		82.9
Pentapora fascialis[b]		223.3	225.9		
Smittina cervicornis[b]					46.5
Rhynchozoon sp.[b]			237.0	23.6	
Schiobrachiella sanguinea[b]	211.3	24.4		132.4	133.3
Others	0.0	21.0	11.9	16.5	33.3
Sub Total	211.3	288.7	621.3	172.5	296.0
Cnidarians					
Astroides calycularis[b]	1218.8	73.7		1160.4	1510.9
Dendrophyllia ramea[b]			1131.4		
Parazoanthus axinellae			26.2		
Polycyathus muellerae[b]					61.8
Others	5.0	5.1	34.2	30.1	40.0
Sub Total	1223.8	78.8	1191.7	1190.5	1612.7
Polychaetes					
Protula sp.[b]				8.0	60.7
Salmacina dysteri[b]	62.8	65.5	180.6	73.9	90.6
Serpulidae[b]	142.4	99.5	169.5	21.5	27.8
Others	11.9	99.7	139.4	20.1	19.5
Sub Total	217.1	264.7	489.5	123.5	198.5
Molluscs					
Mollusca unidentified	118.8	44.8	43.1	161.7	103.7
Sub Total:	118.8	44.8	43.1	161.7	103.7
Crustaceans					
Balanus perforatus[b]	14.7	12.9	93.5	20.4	5.4
Sub Total	14.7	12.9	93.5	20.4	5.4
TOTAL	2959.8	1650.2	2698.3	2869.5	3889.0

[a] In shallow water assemblages (0–5 m), mid water assemblages (5–25 m), deep water assemblages (25–50 m).
[b] Calcareous species.

Table II. Carbonate content, expresed in g·$CaCO_3$·m^{-2} by phylum for each assemblage.

	Punta de la Mona-south			Punta de la Mona-east	
	0–5 m	5–25 m	25–50 m	0–5 m	5–25 m
Algae	755	674	34	848	676
Bryozoans	149	234	527	131	236
Cnidarians	1027	62	1032	978	1344
Polychaetes	178	137	290	86	152
Others	11	9	68	15	4
TOTAL	2120	1116	1951	2058	2412

also lower than the 2 700 g·m^{-2} found in the DWA of La Herradura. Here too, animal biomass is much larger in La Herradura and accounts for these differences.

Most of the animals and algae with high biomass values have calcareous skeletons (*table I*). Therefore, calcimass for the different assemblages in La Herradura are high and range between 1 100 and 2 400 g·$CaCO_3$·m^{-2}. Calcimass of the phytobenthos represents between the 1 % of total calcimass for DWA up to 60 % for some MWA. Phytobenthic calcimass values are lower than those reported before for rocky infralittoral and circalittoral areas from the Balearic islands (western Mediterranean): 969–1 585 g·$CaCO_3$·m^{-2} [8]. There is no available data on animal calcimass from other Mediterranean localities, but according to data from [6] and observations made by [8], animal contribution to calcimass is low in infralittoral communities. The abundance of calcareous animals in La Herradura infralittoral communities could be related to the specific hydrological features of the area, with a persistent frontal structure further offshore and regular upwelling of Intermediate Western Mediterranean Water and Levantine Water [34, 48]. It is well known that fronts and upwellings promote shallow water primary productivity and export of suspended, organic matter-rich particles to nearby zones. Such an export towards the open ocean has been measured recently at relatively shallow depths offshore from Malaga, 25 km west of La Herradura, and should also exist towards the coastal zone (*figure 1*). The strongest particle concentrations (above of 2 000 particles mL^{-1} in the size range from 4.80 to 19.98 μm) offshore from Malaga have been measured specifically at around 50 m depth and at shallower depths [7]. Mean total mass fluxes measured by means of moored sediment traps at 500 m depth are also much higher offshore Malaga than offshore the Balearic Islands (450 to 600 mg·m^{-2}·d^{-1}, depending on the season, and 85.6 mg·m^{-2}·d^{-1}, respectively; J. Fabrés, pers. comm.). The availability of particulate organic matter may increase competition abilities of suspension feeders in front of algae, and calcareous skeletons may provide greater resistance and perdurability [49].

The product of the static term, calcimass (g·m^{-2}), and the rate term, turnover (per year), is the mass transfer term, production (g·m^{-2}·y^{-1}) [42]. According to our calcimass data and turn-over rates of diverse marine benthic organisms reported in [15, 17, 42] for algae, and [35, 42, 45, 47] for animals, we can calculate a rough estimate of $CaCO_3$ production by each phylum at each assemblage (*table III*). Infralittoral carbonate production should roughly average 1 000 g·m^{-2}·y^{-1}, while the only circalittoral assemblage estimate amounts 680 g·m^{-2}·y^{-1}. These are rather high values when compared to production values reported by [8] from the rocky bottoms of the Balearic shelf (150 to 470 g·m^{-2}·y^{-1}). Here too, the difference is mainly due to the animal carbonate production since phytobenthic carbonate production is very similar (307 g·m^{-2}·y^{-1} in SWA from La Herradura versus 290 g·m^{-2}·y^{-1} in photophilic algal communities in the Balearic islands; 350 g·m^{-2}·y^{-1} in MWA from La Herradura versus 150–470 g·m^{-2}·y^{-1} in hemisciaphilic and coralligenous communities from the Balearic islands). Carbonate production from DWA is four fold higher in La Herradura than in the Balearic islands since these animal-dominated assemblages in the central Western Mediterranean are devoid of the big calcareous organisms that dominate in La Herradura bottoms [8].

Table III. Estimates of mean yearly calcium carbonate production ($g \cdot m^{-2} \cdot y^{-1}$) for each group at each studied location.

	Punta de la Mona-south			Punta de la Mona-east	
	0–5 m	5–25 m	25–50 m	0–5 m	5–25 m
Algae	283	289	17	332	407
Bryozoans	57	83	202	50	84
Cnidarians	514	31	103	489	663
Polychaetes	178	137	290	86	152
Others	11	9	68	15	4
TOTAL	1043	549	680	972	1310

Our results show that the production rate of $CaCO_3$ in rocky sea bottoms above 50 m depth in La Herradura is higher than values reported for other temperate environments [8, 42]. The unusual combination of highly productive calcareous algae and animals in La Herradura shallow waters accounts for this relatively high calcium carbonate production. La Herradura carbonate production is, however, lower than most values from tropical reefal systems, where the combined action of coralline algae and hermatypic corals increases the fixation of calcium carbonate by one order of magnitude [2, 13, 18, 25, 43].

How much of La Herradura annual carbonate production is incorporated actually to the sediment in the surrounding areas is unknown, but sediments from La Herradura are largely dominated by terrigenous material down to 50 m depth. In a study of the sediments from the Xauen and Alboran island banks, south of the Western Alboran basin and in the centre of the Alboran Sea, respectively, Milliman et al. [33] concluded that the rich carbonate sands and gravels there do not reflect the present-day benthic assemblages but to a thanatocoenosis mostly of early Holocene age. This might suggest that, for unknown reasons, the high carbonate production in the shallow rocky bottoms from the Alboran Sea contributes very little to local sediment formation. In contrast, in other areas like the Balearic islands, lower carbonate productions contribute much more to sediment formation [8]. However, the situation in the Alboran Sea banks cannot be fully compared with that in La Herradura since the banks are isolated from the coast, and the hydrography also differs, with rare upwelling occurrences and non-existent (Xauen bank) to less intense and unstable frontal structures (Alboran island bank).

Three mechanisms, or a combination of the three, appear then as the most plausible to explain the lack of carbonate particles in La Herradura sediments: (i) transport of the lighter carbonate grains to deeper areas by near-bottom currents, gravity flows and spill-over processes; (ii) grain maceration and transport of fine resulting products by currents; and (iii) dissolution by upwelled waters.

Transport from the inner shelf to the outer shelf is supported by the distribution of carbonate sediment in the near Almeria shelf, east of our study area, where major occurrences of carbonate sediments appear in rather deep places (more than 80 m depth), like Cabo de Gata and Rodalquilar shelves, and without a shallow water counterpart, at least for the sediments [30]. Transport of carbonate grains by near-bottom currents leading to shelf-edge spillover is a well known process in the western Mediterranean carbonate shelves [1, 27, 28].

Maceration refers to the disintegration process of skeletal carbonates in the sediments into their microscropic structural elements, needles, fibres, flakes, and granules [3]. Decomposition of the organic matrix in the skeletons causes breakdown of carbonates since the mineral elements are not harmed in any way [37], thus contributing significantly to maceration. The maceration process takes place while the carbonates are exposed on the seafloor, in contact with ambient seawater. All kinds of calcareous shells and skeletons are thus transformed into cryptic lime mud which then may be further dissolved, or redeposited elsewhere. In the Alboran Sea, this seems to be the case as proved by the relatively carbonate-rich muds in slope [30, 33]. Maceration of carbonates can be a major destructive agent, causing severe depletion of calcareous organisms in the sediment record [3].

Carbonate undersaturation in upwelled waters is also a common situation that can be, in fact, closely connected with maceration, in the sense that maceration of shells and skeletons could be a by-product of carbonate dissolution. Recent studies have further demonstrated that an appreciable portion of neritic carbonates produced on banks and shelf tops is exported to the deep sea, much of which is subsequently dissolved [32], but we still do not know if this is also the case for La Herradura since Mediterranean waters have a high alkalinity and the entire water column above 2 000 m depth is oversaturated in calcite and aragonite [14]. This question deserves further study.

Our paper constitutes a contribution towards the establishment of global carbonate budgets in the Mediterranean Sea. To achieve this overall objective and since Alboran sub-basin is not a typical Mediterranean one, new areas need to be studied and carbonate production quantified, particularly in the central and eastern Mediterranean basins. Also, more detailed studies on sediment composition and age, carbonate production, export and dissolution are required for improved estimations both on the short and the long-term.

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