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Millennial-Scale Carbon Accumulation in Mediterranean Rhodolith Deposits

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Abstract. Rhodolith and maërl beds are globally relevant biogenic habitats whose long-term carbon storage capacity remains poorly quantified, particularly in the Mediterranean. To fill this gap, we investigated the formation, structure, and carbon content of a sediment deposit underlying a rhodolith bed in the Menorca Channel (Western Mediterranean). High-resolution seismo-acoustic profiling revealed a highly heterogeneous biogenic sedimentary deposit at ~60 m depth, with thickness ranging from a few centimeters to 3.7 m (mean = 0.95 m). Seven vibrocores extracted from the thickest sediment deposits were analyzed for grain size, carbonate content, bioclast composition, organic carbon, and radiocarbon age. Radiocarbon dating indicates that sediment accumulation began during the early Holocene (11,700–9,000 yr BP), when post-glacial sea-level rise transitioned the area from subaerial exposure to shallow-marine conditions. Early deposits were dominated by bivalves and dispersed coralline fragments. The establishment of modern sea level around 7,000–6,500 yr BP led to the development of dense rhodolith–maërl facies that persist today. Sediment accretion rates are low (median = 8.54 cm kyr^{-1}), reflecting very low external sediment supply, and slow growth of coralline algae. Organic carbon content in the upper 50 cm, representing the most dynamic and recently deposited carbon pool, averaged 0.57% (± 0.22), with an estimated organic carbon stock of 32.04 (± 4.18) Mg C ha^{-1}. These results show that Mediterranean rhodolith beds act as long-term organic carbon stores, forming spatially complex Holocene deposits whose contribution to carbon storage has been largely overlooked.

Keywords

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Calcareous red algae; Sediment organic carbon; organic carbon sink; Holocene; Radiocarbon dating; Mediterranean Sea.

Highlights

- Seismo-acoustic mapping of a deep rhodolith deposits revealed highly variable thickness
- Holocene sedimentation began 11,700–9,000 yr BP during post-glacial sea-level rise.
- Dense rhodolith–maërl facies formed after sea-level stabilization ~7,000 yr BP.
- Accretion rates are low (8.54 cm kyr^{-1}), very low external sediment supply and slow algal growth.
- Organic carbon averages 32.04 (± 4.18) Mg C ha^{-1} in the upper 50 cm, evidencing long-term carbon storage.

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1. INTRODUCTION

Marine habitats play a substantial role in the global carbon cycle by contributing to both organic and inorganic carbon storage. Coastal systems sequester atmospheric CO_2 through photosynthesis and the subsequent burial of sedimentary organic carbon, a process widely recognized as "blue carbon" (Barbier et al., 2011; Nellemann and Corcoran, 2009). Most knowledge of carbon burial in the coastal ocean comes from vegetated ecosystems such as mangroves, seagrass meadows and saltmarshes (Macreadie et al., 2019). In contrast, calcifying algal systems, such as rhodolith and maërl beds, remain comparatively understudied (Tuya et al., 2023). These systems are globally distributed and their deposits persist over millennia (Aguirre et al., 2016; Van der Heijden and Kamenos, 2015), suggesting a potential long-term carbon repository that has yet to be quantified at scale.

Rhodolith and maërl beds consist of free-living, non-geniculate calcareous red algae (Rhodophyta: Corallinophycidae) occurring as multi-specific assemblages (Cabrito et al., *under review*). These assemblages thrive in subtidal environments with coarse, mobile sediments under moderate hydrodynamic regimes that prevent burial while maintaining sufficient irradiance (Basso et al., 2017). They occur from shallow to mesophotic depths across tropical to polar regions (Riosmena-Rodríguez et al., 2017; Tuya et al., 2023). Despite their slow individual growth (~1 mm yr^{-1}), rhodolith accumulations can reach several meters in thickness over hundreds to thousands of years, with living rhodoliths limited to the upper few centimeters, above deposits of fragmented coralline algae and skeletal remains of bryozoans, molluscs, and echinoderms (Betzler et al., 2011; Fornós and Ahr, 1997).

Rhodolith and maërl beds have the capacity to store carbon through the long-term accumulation of thick, carbonate-rich sediments that can remain stable over centuries to millennia (Mao et al., 2020). In contrast to other well-known blue carbon habitats, their contribution to carbon storage is not driven by short-term biological processes but result from the long-term accumulation of biogenic deposits and the trapping and retention of organic carbon supplied from external sources (Mao et al., 2020; Schubert et al., 2024). However, empirical data on sediment organic carbon content, depth distribution, sediment dynamics and accretion history remain limited, particularly in Mediterranean rhodolith beds. Quantifying these components is essential to evaluate the role of this ecosystem as long-term carbon reservoirs.

Large rhodolith and maërl beds are present on modern and ancient carbonate shelves around the world (Riosmena-Rodríguez et al., 2017), including the world's largest bed on the Brazilian continental shelf (21 000 km^2, Amado-Filho et al., 2012). The Mediterranean hosts the second-largest bed described to date, covering approximately 470 km^2 in the Menorca Channel, western Mediterranean (Tabone et al.,

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2024). Its development has been facilitated by the clear waters and low sediment input that characterize Mediterranean islands, allowing rhodolith beds to extend down to 90 m depth (Joher et al., 2016). However, despite their ecological importance, the functioning and carbon dynamics of Mediterranean rhodolith beds remain poorly resolved, particularly regarding organic carbon accumulation, small-scale spatial heterogeneity and the long-term evolution of these deposits.

These biogenic habitats are highly vulnerable to disturbance due to their slow growth and limited recovery capacity, and are threatened by bottom-contact fishing gears, elevated suspended sediments, and the cumulative effects of ocean warming and acidification under climate change (Trégarot et al., 2024; Tuya et al., 2023). Although Mediterranean rhodolith beds are protected under EU Regulation 1997/2006, the EU Habitats Directive, and the UNEP/MAP Action Plan (2008), conservation remains limited due to insufficient spatial coverage and ecological data. Strengthening the scientific basis for management aligns with European priorities linking biodiversity conservation, climate-change mitigation, and ecosystem restoration. In this context, improving knowledge of the organic carbon storage capacity of rhodolith beds is essential to help quantify their role in the global carbon cycle, particularly given their broad geographic distribution (de Macêdo Carneiro et al., 2021; Schubert et al., 2024).

This study quantifies the role of Mediterranean rhodolith beds as long-term organic carbon reservoirs by analyzing sedimentary organic carbon deposition since the early Holocene post-glacial sea-level rise, along with geomorphological and sedimentary characterization of a well-preserved deposit in the Menorca Channel (western Mediterranean). The Menorca Channel is a low-energy temperate carbonate shelf where rhodolith sediments have accumulated since the early Holocene, providing a unique archive to examine carbon storage over millennial timescales. Using high-resolution seismo-acoustic data and sediment cores and radiocarbon dating, we estimate the vertical distribution of organic carbon and reconstruct the depositional history through in relation with the last glacio-eustatic oscillation. We test the hypothesis that this rhodolith bed represents a persistent Holocene carbon store shaped by local environmental conditions and long-term sea-level changes, with implications for regional blue carbon assessments.

2. MATERIAL AND METHODS

2.1. Study area

The Balearic continental shelf is a temperate, low-energy oligotrophic system dominated by carbonate-producing habitats, including *Posidonia oceanica* meadows, coralligenous communities, and extensive

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rhodolith–maërl beds (Betzler et al., 2011; Canals and Ballesteros, 1997). Our study focuses on the Menorca Channel, a shallow carbonate platform (~100 m max depth) between Mallorca and Menorca, where post-glacial neritic carbonates have accumulated since the early Holocene (Alonso et al., 1988; Betzler et al., 2011). Rhodolith and maërl beds occur between 45–80 m depth on the platform (Fig. 1), interspersed with detrital sands and other macroalgae (*Laminaria rodriguezii*, *Osmundaria volubilis*, *Peyssonnelia rosa-marina*) (de Juan et al., 2023). Habitat preservation has been favored by a historical trawling exclusion zone surrounding submarine cables and, more recently, by the 2016 designation of the Menorca Channel as a Natura 2000 Site of Community Importance (SCI ESZZ16002).

We focused on a 43.6 km² area where rhodolith and maërl cover exceeds 50%, based on high-resolution mapping from the INDEMARES project (Moranta et al., 2014) and our own video surveys (Cabrito et al., 2024b). Within this area, we conducted high-resolution seismo-acoustic profiling to determine the thickness of bioclastic sediments above the acoustic basement and to identify suitable sites for recovering ≥1-m sediment cores. Potential sites were inspected with a remotely operated vehicle (ROV) to confirm rhodolith–maërl dominance, and full coverage was verified at all core locations.

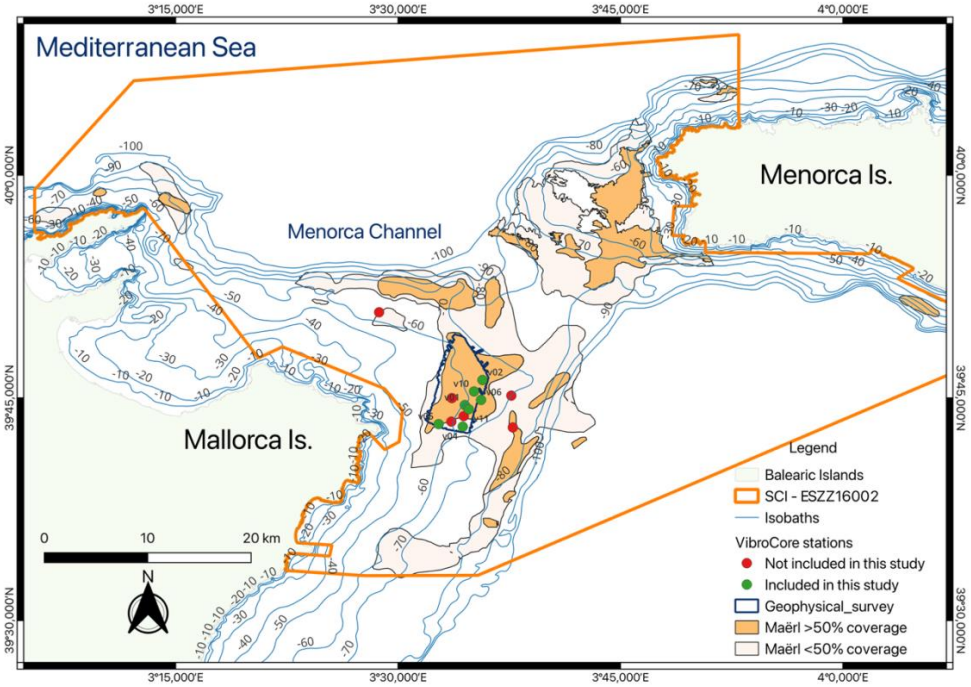

Figure 1. Study area in the Menorca Channel, located between Mallorca and Menorca islands in the western Mediterranean Sea. The map shows the area covered by the geophysical survey (dark blue polygon) and the location of VibroCore stations included (green dots) and not included (red dots) in this study. Rhodolith are represented in light and dark orange, indicating areas with 10-50% and >50% coverage, respectively. The Site of Community Importance (SCI ESZZ16002) is delineated by the dark orange boundary. Isobaths (in metres) are shown as blue contour lines. Source: modified from project INDEMARES (Moranta et al., 2014).

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2.2. Geophysical map

In May 2022, we acquired 56 high-resolution seismo-acoustic profiles in the study area (Fig. 1) during a research cruise aboard R/V *SOCIB* and using an INNOMAR Medium-100 non-linear parametric echosounder coupled with an INS SBG Navisight Ekinox and GNSS AtlasLink for positioning. Sound-speed and turbidity corrections were obtained with a Valeport SWIFT. The system emits two primary frequencies around 100 kHz, producing a secondary frequency of 5–12 kHz, with a pulse repetition rate of up to 30 s^{-1} and a beam width of ±1.8°. Non-linear parametric echosounders provide narrow, low-frequency beams with small footprints, enabling high-resolution imaging of shallow sediment deposits and precise localization of core-sampling targets (Lo Iacono et al., 2008).

Profiles were spaced 200 m apart, oriented NNE–SSW in the southern sector and NW–SE in the northern sector, intersected by perpendicular transversal profiles every 500–2000 m (supplementary material 1). Penetration depth averaged 0.8–1.0 m and reached a maximum of 3.7 m, maintaining high horizontal and vertical metric to sub-metric resolution due to the small pulse size. Seismo-acoustic data were interpreted using INNOMAR-ISE 2.9 to pick stratigraphic horizons and estimate thickness of the bioclastic deposit. Geo-referencing and isopach mapping were conducted with Global Mapper and ArcGIS.

2.3. Sediment core sampling

In May 2023, sediment cores were collected at 60–80 m depth during a research cruise aboard R/V *Sarmiento de Gamboa*. Cores' positions were selected based on geo-acoustic evidence of maximum sediment thickness within the survey polygon (Fig. 2). A vibrocorer (ASTHER I, GEOMYTSA S.A.) operating at 136 kN centrifugal force at 3 m recovered 12 PVC-lined cores (9 cm diameter, 1.4–2.8 m length; Table 1). Each core was sectioned into ≤1 m segments and stored at –20 °C for laboratory analyses. Of the 12 cores, 7 were retained for this study (Fig. 1).

Table 1 – Characteristics of the seven vibrocores obtained in the Menorca Channel (Western Mediterranean) selected for this study. Description of biocenoses based on knowledge from our own video observations (projects MaCoBioS; MARBEFES) and previous projects (INDEMARES).

Vibrocore ID	Longitude	Latitude	Sea bottom Depth (m)	core length (m)	analyses	biocenose
V1	3.5750	39.7419	61.91	1.60	+ * #	rhodoliths >75%, with Peyssonnelia and Osmundaria
V2	3.5949	39.7700	66.22	1.40	+ * $ #	rhodoliths >75%, with Laminaria
V4	3.5727	39.7177	66.08	1.80	+ * $ #	rhodoliths >60%, with Osmundaria
V5	3.5456	39.7205	60.01	2.80	+ * #	rhodoliths >60%, with Osmundaria
V6	3.5933	39.7477	64.52	1.90	+ * $ #	rhodoliths >60%, with Laminaria

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V10	3.5854	39.7572	63.28	1.45	+ * #	rhodoliths >90%, with Peyssonnelia
V11	3.5794	39.7525	63.93	1.75	+ * $ #	rhodoliths >75%, with Peyssonnelia

+ Lithology and clasts composition; * Granulometry and carbonates; $ Radiocarbon dating; # Organic carbon

Sediment core opening and visual description

Each 1-m core section was cut longitudinally for analysis. All cores were visually inspected to describe sediment composition, and subsamples were collected for grain size, radiocarbon dating, bioclast identification, and organic carbon content analyses.

Grain size and carbonate contents

The cores were sampled at 5 cm intervals for grain-size and carbonate-content analyses. Grain-size distributions were measured using a HORIBA LA-950V2 laser diffraction analyser after disaggregating and removing the biogenic fraction (10% H_2O_2), and ultrasonic dispersion; the >2 mm fraction was quantified by sieving. We calculated the weight percentages of clay, silt, sand, and gravel, as well as mean grain size (ϕ), sorting (σ), skewness (Sk), and kurtosis (kG). Carbonate content was determined from the CO_2 volume displaced by a sample of sediment treated with 20% HCl, calibrated against a 100% $CaCO_3$ standard.

Radiocarbon dating

Between two and three bioclasts (rhodoliths or bivalve shells) from different depths in four cores (Table 1) were radiocarbon-dated by Beta Analytic (Miami, USA). Dates were calibrated with BetaCal 5.0, with HPD method "MARINE20" and corrected for the local marine reservoir effect (ΔR = -112 ± 99). Sediment accretion rates (cm kyr^{-1}) were calculated by dividing the thickness of sediment between successive dated horizons along the core (kyr), taking the top most horizon as 0 yr BP.

Taxonomic identification of bioclasts

Sediment was examined under a binocular microscope at ~50 cm intervals for fauna identification. Subsamples (10–20 g) were air-dried (48 h) and sieved through 0.5 and 1 mm meshes. Between 200 and 300 clasts from the >0.5–1 mm and >1 mm fractions were inspected and assigned to major taxonomic groups (Bivalves, Gastropods, Bryozoans, Echinoids, Foraminiferans, and free-living coralline algae). Rhodoliths were classified into two morphotypes following (Basso, 1998; Basso et al., 2012): non-branched rhodoliths (including "boxwork" and "praline" forms; 1–5 cm) and branched maërl fragments (0.5–2 cm) (see also Jardim et al., 2025; Teichert, 2024).

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2.4. Organic Carbon Content

From each core, sediment samples (~21 ml) were collected using a syringe every 10 cm within the upper 50 cm, as this layer is expected to contain the highest and more dynamic carbon pool, which has not yet undergone long-term diagenesis (Middelburg, 2018). To minimize decomposition of organic matter and microbial growth, samples were kept cold (4 ºC) during 24-48 for later processing. In the laboratory, samples were weighed, freeze-dried (lyophilized) for 48-72 hours, and weighed again to determine their moisture content percentage. Finally, the samples were finely ground in an agate ball mill.

The processed samples were subsequently sent to University College Dublin to be sub-sampled for further analysis. From each 10 cm layer, ~2.0 g (±0.6 g) of homogenized sediment was subsampled for organic carbon analysis. A sub-set of the homogenized sample was then shipped to the University of Waterloo (Canada) for carbon and nitrogen analysis. The samples were analysed using an ECS 4010 Elemental Analyzer (NC Technologies, Italy) coupled to a Delta Plus XL (Thermo-Finnegan, Germany) continuous flow isotopic mass spectrometer (CRFIRMS). Samples were acid washed according to the University of Waterloo Environmental Isotope Laboratory procedures in order to remove inorganic carbon and obtain organic carbon measurements. High effervescence during acid treatment indicated a substantial carbonate fraction, resulting in a marked mass loss. The %C and %N was measured in bulk, analyzed against known certified elemental standard materials. Analytical control measures were based on the detection of major carbon (C) and nitrogen (N) peaks to ensure data consistency and calibration accuracy.

2.5. Data analysis

To evaluate whether sediment characteristics control the density of retained organic carbon, variation in organic carbon density (g/cm^3) was analysed in relation to sediment characteristics using linear mixed-effects models to account for the hierarchical structure of the sampling design, with multiple depth subsamples collected within each sediment core. Because organic carbon density values were positive and right-skewed, the response was log-transformed (log[CarDens]) and modelled assuming Gaussian errors. Core identity was included as a random intercept to accommodate non-independence among subsamples from the same core.

The following sediment characteristics that were explored as candidate fixed effects were: standardized sediment depth (cm), median grain size (d50; µm), carbonate content (%), biogenic gravel content (%), and sediment type (categorical). Owing to strong collinearity between d50 and the sand/silt fractions ($|r| \approx 0.90–0.96$), grain-size fractions were not included in models containing d50. Potential within-core

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residual dependence across depth was evaluated by fitting models with an AR(1) correlation structure along depth within each core. In addition, a random-slope formulation allowing core-specific depth trends was tested using a diagonal random-effects structure (random intercept and depth slope by core, with intercept–slope covariance constrained to zero). Models were compared using AICc, with maximum likelihood estimation used for model selection and the best-supported model refitted by restricted maximum likelihood for final parameter estimation. The intraclass correlation coefficient (ICC) was calculated from variance components to quantify the proportion of variance attributable to differences among cores. All analyses were conducted in R v4.4.2.

3. RESULTS

3.1. Seismoacoustic records

The surveyed area ranges from 57 to 68 m depth and exhibits generally smooth bathymetry, with an average slope of 0.2°. The western sector is relatively flat, gradually deepening from 57 to 60 m, while the southeast and northeast show narrow bathymetric edges with steeper slopes reaching 68 m (Fig. 2).

Geo-acoustic profiles allowed detailed mapping of the 3D architecture of the bioclastic deposit. Sediment thickness was highly heterogeneous at small scales, ranging from nearly 0 to several meters over spatial extents of hundreds of meters or less (Fig. 2, right panel; supplementary material 1). Average thickness was 0.95 m, with a maximum of 3.7 m. Thinner deposits occurred in the northern sector (down to 10 cm), whereas thicker accumulations were found in the southern and eastern sectors, including a 2 km × 1 km patch reaching 3.7 m at its depocenter.

Cores were collected at locations of maximum sediment accumulation. Of the seven cores retained for this study, V1, V2, and V10 reached the bedrock horizon; V4, V6, and V11 fell short by 0.5–1.1 m; and V5 slightly penetrated the bedrock (~1 m) (Figs. 2 and 3; supplementary material 1).

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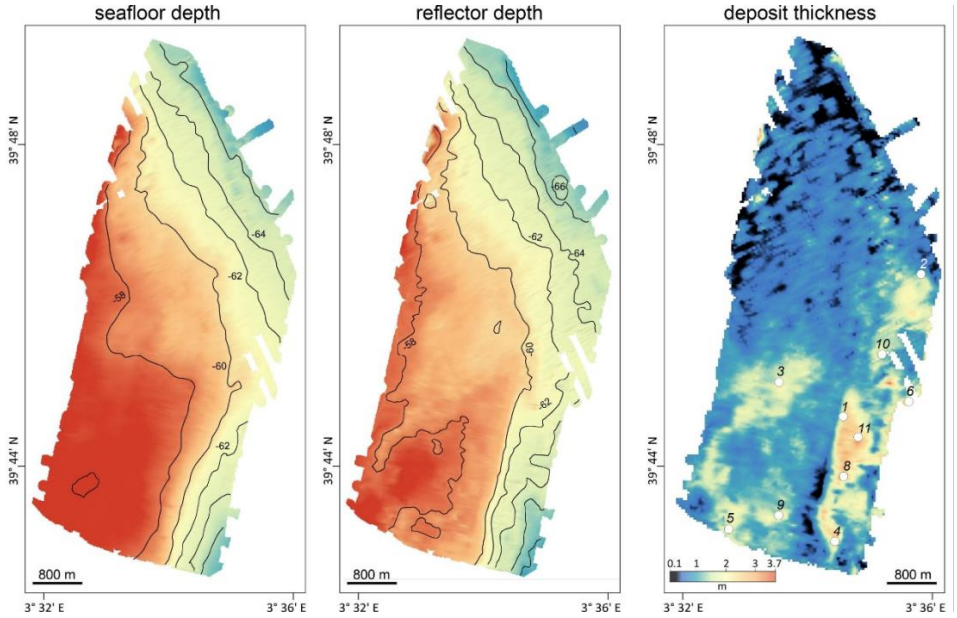

Figure 2. Results of the high-resolution profiling in the rhodolith deposit. Left panel: bathymetry, central panel: reflector depth, right panel: deposit thickness. Refer to position of geophysical survey in Fig. 1.

3.2. Sediment characteristics

Visual inspection of the cores revealed a relatively uniform composition, dominated by fine to coarse bioclastic sand with occasional horizons of gravel or silt (Fig. 3; supplementary material 2). Grain-size analysis confirmed sand as the dominant fraction (>50%), with fines occasionally higher in certain horizons (e.g., V1: 40–90 cm; V2: 30–60 cm; V4: 25–65 cm; V6: 25–60 cm; V11: 35-65cm), but never exceeding sand content. Gravel was always <25%, with the exception of V5: 40-50 cm, 50% gravel. Carbonate contents were consistently ≥90% along the cores.

Sediment composition was primarily carbonate bioclasts (75%) and, to a lesser extent, carbonate lithoclasts (8%), with variable contributions from siliciclastic grains. Stereomicroscope analysis allowed identification of 65% of clasts, mainly unattached coralline red algae (26%, branched and non-branched), bivalve fragments (22%), gastropods (13%), echinoid remains (4%), foraminifera (4%), and bryozoans (3%). Minor groups included serpulids, ostracods, and polyplacophorans. Siliciclastic grains (17%) were grey or white lithoclasts, distinguished by texture and lack of reaction to dilute HCl.

Coralline algae fragments occurred throughout the cores, whereas well-formed rhodoliths were confined to the upper ~60 cm (except V2), occurring either scattered or densely packed, particularly in V4, V5,

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and V11 (Fig. 3). Three cores (V1, V2, V6) terminated on cemented substrate, including bivalve-rich hardgrounds or reworked lithoclasts.

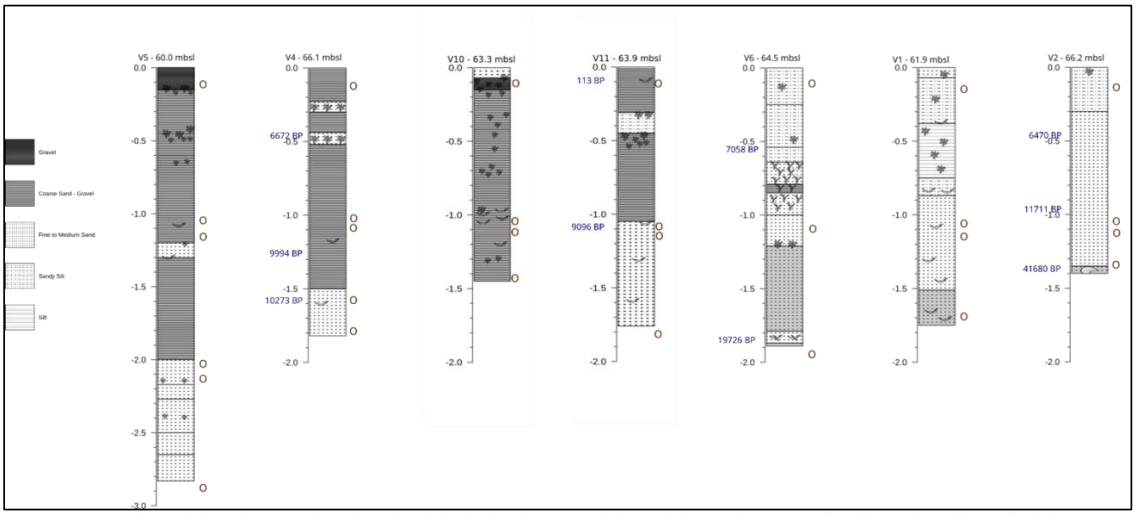

Figure 3. Stratigraphic columns showing the lithological composition of the sediment and radiocarbon dates (in blue). Circles: sampling for faunistic identification: o Clasts (only clasts > 5 cm are represented): non-branched rhodolith: branched rhodolith: entire bivalve shell: broken bivalve shell: rock fragment:

3.2.1. Radiocarbon Dating

Radiocarbon dating of rhodoliths and bivalve shells from four cores (Table 2) yielded ten age estimates. Two basal ages (41,680 yr BP in V2 and 19,726 yr BP in V6) indicate reworked pre-Holocene material from periods when the area was in an emerged sub-aerial setting. The next four oldest dates, between 11,711 and 9,096 yr BP, correspond to the end of Younger Dryas (11,711 yr BP) and the subsequent rapid sea-level rise (until 9,000 yr BP), indicating that the area was a shallow marine environment (<20 m depth) dominated by bivalves and dispersed branched rhodoliths. Some lithoclasts within these horizons indicate continental input consistent with shallow-water conditions.

Table 2. Radiocarbon dates (^{14}C) for carbonate bioclasts obtained from the testing laboratory of Beta Analytic (Miami, Fl., US), recalibrated with BetaCal 5.0 and corrected for the local marine reservoir effect (-112 ± 99).

Core	Depth (cm)	Radiocarbon Date BP	Calibrated Probability Data (2 sigma)	Calibrated years BP
V2	136	37934 ± 875	41146-38315 BC 100%	41680.5
V2	97	10490 ±30	10151-9371 BC 95.4%	11711
V2	47	6110 ± 30	4778-4261 BC 95.4%	6470
V4	160.5	9460 ± 30	8640-8006 BC 95.4%	10273
V4	117.5	9270 ± 30	8372-7716 BC 95.4%	9994
V4	46	6300 ± 30	5000-4444 BC 95.4%	6672
V6	183	28067 ± 392	30634-4918 BC 100%	19726

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V6	52	6552 ± 81	5298-4918 BC 100%	7058
V11	106	8530 ± 30	7455-6837 BC 95.4%	9096
V11	10	340 ± 30	1724-1950 BD 95.4%	113

Three younger ages, between 7,058 and 6,470 yr BP (47–52 cm depth in V2, V4, and V6), correspond to a period when the Menorca Channel was ~10–15 m below present sea level, during which well-formed, densely packed rhodoliths accumulated (Fig. 3). During this interval, continental inputs diminished, maërl became abundant, and rhodolith beds consolidated, as exemplified by V4 (~50 cm, 6,672 yr BP). Scattered rhodolith fragments occasionally occur at greater depths, but none are found in strata older than 9,096 yr BP, highlighting the onset of persistent rhodolith accumulation after postglacial transgression.

Based on these dates, sediment accretion rates range from 6.9 to 21.5 cm kyr^{-1}, with a median of 8.54 cm kyr^{-1} (Fig. 4).

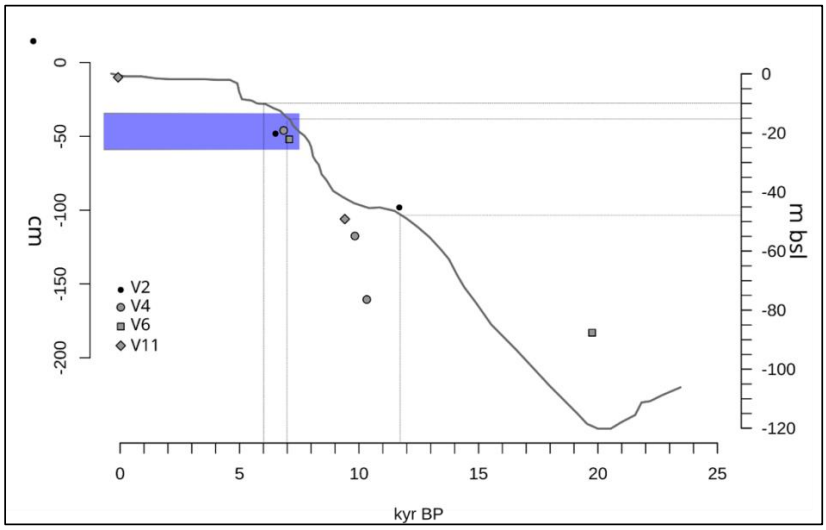

Figure 4. Age-depth plot for the dated cores (excluding one sample that yielded a date > 40 ky BP) from the rhodolith deposit of the Menorca channel. Sea-level height (m) relative to present day based on the average model from (Bianchi et al., 2012), largely based on results from (Lambeck and Bard, 2000). Relevant dates for this deposit (end of Younger Dryas at 11700 yr BP and period of sea level stabilization between 7000 and 6000 yr BP) are marked along the x-axis and the corresponding depth below current sea level on the right y-axis. Blue stripe between 35 and 60 cm core depth shows the onset of horizons with high abundance of rhodoliths.

3.3. Organic Carbon content

The average organic carbon content in the first 50 cm of sediment across all cores was 0.57% (± 0.22) (Table 3). This value remained relatively homogeneous with depth (supplementary table 1). Using these measurements, organic carbon stocks were determined for each core. Over the first 30 cm, we estimate

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an average across all the cores of 19.41 (± 4.42) Mg C ha^{-1}. Over the full 50 cm, we estimate an organic carbon stock of 32 (± 4.18) Mg C ha^{-1} across all coring sites (Table 3). Considering a median sediment accretion rate of 8.54 cm kyr^{-1}, annual organic carbon accumulation is estimated at 0.546 g C m^{-2} yr^{-1}.

The molar C/N ratios were used to assess the origin and degree of degradation of the organic matter. The average C/N ratio across all samples was 10.71 (+/-3.19), with the highest value being 18.51 (V11) and the lowest value being 7.71 (V4) indicating predominantly marine sources.

Table 3. Summary table showing the average organic carbon density, the stock over the top 30 cm and the total length of the core.

Core	Avg C Density (kg C m^{-3})	Carbon Stock Top 30 cm (Mg C ha^{-1})	Carbon Stock 50 cm (Mg C ha^{-1})
V1	5.87	24.28	29.36
V2	6.77	19.94	33.84
V4	7.75	14.92	38.74
V5	7.15	25.19	35.75
V6	6.54	20.68	32.72
V10	5.46	18.99	27.31
V11	5.031	11.82	26.54
All Cores	6.41	19.41	32.04

Mixed-effects modelling indicated that organic carbon density in the upper 50 cm was primarily explained by carbonate content and grain size (d50), with a weaker contribution from biogenic gravel content, while depth showed no consistent effect. Alternative model structures, including sediment type, random slopes for depth, and AR(1) correlation across depth, did not improve model fit and were not retained (see supplementary table 2). In the final model, d50 was positively associated with organic carbon density ($\beta = 0.177$, $p = 0.0046$) and carbonate was negatively associated with organic carbon density ($\beta = -0.306$, $p < 0.001$), whereas biogenic gravel showed a weaker positive association ($\beta = 0.098$, $p = 0.0688$) and depth was not significant ($p = 0.577$). Approximately 42% of the variability in organic carbon density was attributable to differences among cores, with the remaining variance occurring within cores and as unexplained residual variability (Fig. 5).

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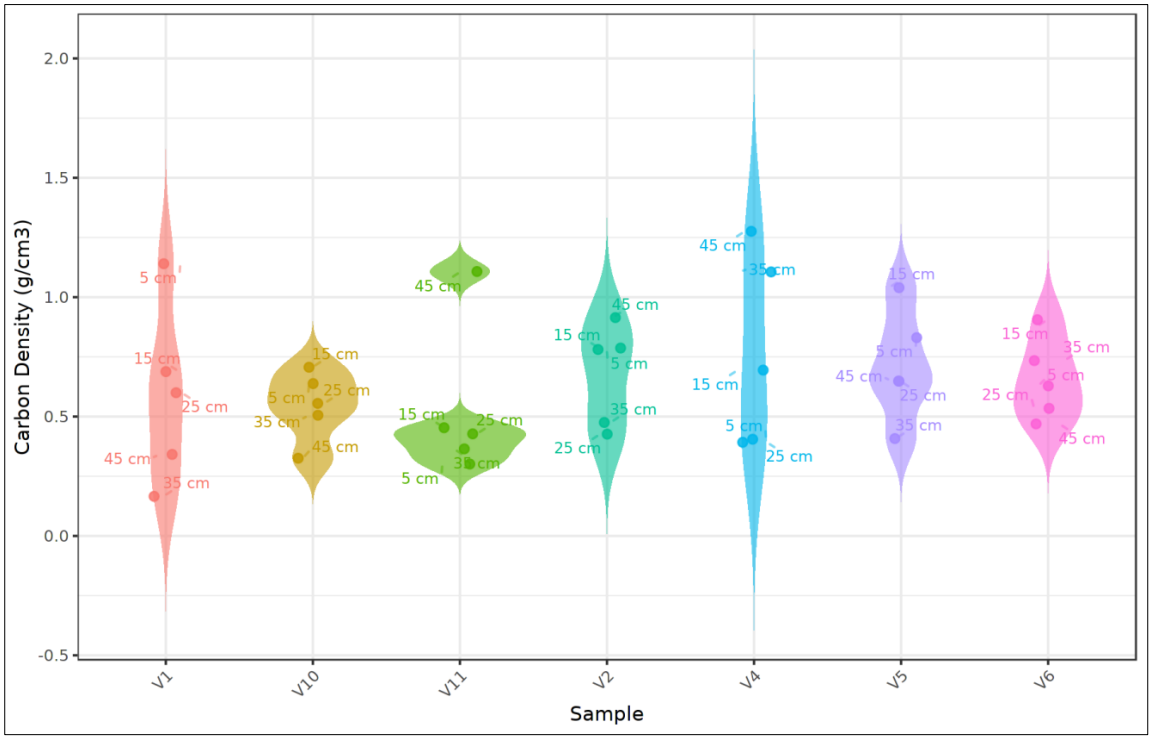

Figure 5. Organic carbon density in the sediments (g/cm^3) of the first 50 cm of corers.

4. DISCUSSION

The Holocene sedimentary deposit underlying the present-day rhodolith bed in the Menorca Channel is relatively thin and heterogeneous. It overlies an erosional unconformity formed during postglacial sea-level rise and likely includes reworked Miocene–Pliocene deposits (Guillén, 1987). Across the surveyed area (57–68 m depth range), bathymetry is generally smooth, with a gentle average slope (~0.2°): the western sector is relatively flat, while the southeast and northeast margins are marked by narrow bathymetric edges and locally steeper slopes. Sediment thickness varies markedly, from ~10 cm in the northern sector to up to 3.7 m in the south and east, with a mean value of 0.95 m. This spatial variability reflects the combined influence of variable local scale paleo-topography and hydrodynamics, as observed in other temperate carbonate continental shelves (Betzler et al., 2011; Fornós and Ahr, 1997). Mapping sediment thickness was essential to recover cores with sufficient depth to reconstruct the millennial-scale depositional history of this ecosystem.

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Radiocarbon data indicate that rhodolith assemblages in the Menorca Channel pre-date the large maërl deposits of western France (5,860–5,300 yr BP, Ehrhold et al., 2021) but are younger than the oldest known rhodoliths from the Gulf of Mexico (13,886 yr BP, Olmstead and Andrus, 2024). Early Holocene deposits, formed at the end of the Younger Dryas and during rapid postglacial sea-level rise, reflect a shallow-marine environment dominated by bivalves and dispersed branched rhodoliths. Well-formed rhodoliths only became established in the upper ~60 cm of sediment, once deeper and more stable marine conditions developed around 7,000–6,000 yr BP (Lambeck, 1995), when sea-level lowered down its rise almost reaching its actual level . This interval marks a clear transition to dense rhodolith beds, characterized by large, tightly packed rhodoliths. The expansion and persistence of rhodoliths were likely promoted by moderate hydrodynamics, reduced terrigenous input, and mesophotic depths that limit competitive pressure (Aguirre et al., 2012; Basso et al., 2017). These conditions underpin the long-term stability of these habitats in the Menorca Channel.

Present-day seafloor patterns in the Menorca Channel are characterized by patches of rhodoliths occurring at high densities (50–100%), ranging in size from ~10 m² to over 100 m², and predominantly composed of branched forms (Cabrito et al., 2024a, b), resembling the upper layers of the sediment cores. Despite being collected at similar depths and within short distances (600–1,700 m), the cores show marked spatial sedimentological variability, likely reflecting the irregularity of the basal erosive surface. Spatial differences in sediment thickness and repeated phases of erosion and deposition have shaped the present bioclastic landscape and supported the long-term development of rhodolith-rich habitats. This persistence through time underscores the capacity of these systems to maintain structural complexity over millennial timescales and act as organic carbon reservoirs, with important implications for their conservation and management. Similar patchy and heterogeneous distributions have been reported in other deep Mediterranean rhodolith beds (Bracchi et al., 2022; Rendina et al., 2020; Tabone et al., 2024).

The sediments throughout the cores are highly carbonate-rich (≥90%) and dominated by bioclastic material (~75%), including coralline algal fragments (branched and non-branched), bivalves, gastropods, echinoids, foraminifera, and bryozoans. Organic carbon in the upper 50 cm averages 0.57% and is also relatively uniform across the sampled section. In contrast, sediment thickness is highly heterogeneous at small spatial scales, ranging from a few centimeters in the northern sector to up to 3.7 m in the south and east, implying spatial variability in potential carbon storage. Reflecting these patterns, mixed-effects modelling evidenced that depth within the sediment cores had no detectable effect, and approximately 42% of the variability in organic carbon density was attributable to differences among cores, indicating

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pronounced small-scale patchiness in carbon accumulation across the rhodolith bed. The absence of depth trends could suggest relatively uniform near-surface mixing and burial, maintained by bioturbation and hydrodynamic reworking, while moderate among-core heterogeneity might reflect local patchiness in rhodolith morphology and accumulation; however, the limited number of cores prevents strong conclusions. The organic carbon density was partially explained by sediment composition, with higher carbonate content associated with lower carbon density, and coarser grain size (d50) showing a positive effect, consistent with dilution in carbonate-rich sediments and a textural control on carbon storage (Howard et al., 2018; Keil et al., 1994).

The relatively uniform organic carbon content in the upper 50 cm suggests minimal degradation over ~6,000 years, coinciding with the stabilization of the sea level. This stability likely promoted the development of well-formed rhodolith habitats, facilitating organic carbon capture and retention. Future work should examine deeper sediment layers (>50 cm) to assess carbon preservation at greater depths. We estimate an organic carbon stock of approximately 32.04 Mg C ha^{-1} within the upper 50 cm of sediment across all the cores, with an average of 19.41 (± 4.42) Mg C ha^{-1} over the top 30 cm. Considering a median sediment accretion rate of 8.54 cm kyr^{-1}, annual organic carbon accumulation is estimated at ~0.546 g C m^{-2} yr^{-1}. These values exceed previous estimates reported for coralline algal beds in temperate coastal environments. For example, Mao et al. (2020) reported average organic carbon stocks of 7.23 ± 1.30 Mg C ha^{-1} within the upper 25 cm and 12.28 ± 1.98 Mg C ha^{-1} across the full depth of carbonate deposits (~80 cm) in Scottish coastal rhodolith beds. The substantially higher carbon stocks observed in the Menorca deposit likely reflect its long-term depositional stability and slow sediment turnover. Rather than acting as a rapid carbon sink, this system functions as a millennial-scale carbon reservoir, preserving organic matter within a very slowly forming carbonate matrix and highlighting its ecological and climatic importance despite low annual productivity.

Given their extremely slow sediment accretion rates, these organic carbon deposits are highly vulnerable to physical disturbance, particularly from bottom-contact fishing such as trawling and dredging (Trégarot et al., 2024). These activities can fragment nodules, bury living rhodoliths, and alter the structure and compaction of the sediment, with impacts that persist over timescales far longer than ecosystem management schemes (Cabanellas-Reboredo et al., 2018; de Juan et al., 2013; Tauran et al., 2020). The upper few centimeters of the deposit can be disrupted by a single trawling passage, not only halting carbon sequestration but potentially remobilizing organic carbon that accumulated over thousands of years (Bernard et al., 2019). In the Mediterranean, many rhodolith beds remain exposed to such pressures,

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as they alternate with soft-sediment habitats that overlap with commercial trawling grounds (Illa-López et al., 2023; de Juan et al., 2013). In contrast, the Menorca Channel deposit has been largely protected from trawling due to the historical presence of submarine communication cables and its designation as a trawl-banned area since 2016. Evidence from this untrawled site suggests relatively uniform carbon preservation and burial under natural, undisturbed conditions. The evidence of organic carbon storage potential highlights the need for future research into rhodolith beds. In particular, this would include assessing whether organic carbon stored in sediments, as opposed to carbon produced via rhodolith calcification, is sequestered at rates that balanced or exceed calcification-related carbon release. This highlights the critical role of protection in maintaining the long-term carbon storage and ecological integrity of rhodolith habitats.

Conclusions

Rhodolith beds form the surficial sedimentary layer over millennia-old sediments in the western Menorca Channel, representing persistent carbon stocks during the Holocene, with with organic carbon averaging 0.57% in the upper 50 cm and showing minimal degradation over ~6,000 years. Although sediment accretion is slow (median 8.54 cm kyr^{-1}), the three-dimensional structure of rhodoliths create a stable matrix that traps and preserves carbon over millennial timescales, highlighting their role as long-term reservoirs rather than rapid sinks. These beds have persisted despite human impacts and environmental changes, actively storing carbon over millennia, and globally, calcified rhodolith deposits are stable over geological timescales. Given their slow growth and vulnerability to physical disturbance, protection from trawling or dredging is essential. Conserving rhodolith beds supports biodiversity, ecosystem resilience, and climate mitigation, emphasizing their often-overlooked contribution to long-term carbon storage.

Author contributions

SdJ, FM, and CL conceptualized the study. AC, MdMG, SdJ, RS, and LI conducted sample collection and processing. MdMG and CL curated the data. SdJ, RS, and AO performed the formal analysis. CL, RS, and AO developed the methodology. SdJ, FM, and CL prepared the original draft of the manuscript. HH, JG, and GC contributed to reviewing and editing the manuscript. SdJ, FM, and GC acquired funding.

Competing interests

The authors declare that they have no conflict of interest.

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