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Research paper

Sedimentological features of *Sabellaria spinulosa* biocontructions

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ABSTRACT

Sedentary polychaete *Sabellaria spinulosa* (Leukhart, 1849) is a suspension feeder that builds tubes by cementing together terrigenous particles. Under a set of environmental conditions, *S. spinulosa* can form reefs (consisting of hundreds or thousands of worm tubes) that can vary greatly in thickness, size and patchiness. The more-developed reefs form in areas with a large and continuous supply of sand, turbulent water, nutrient availability and rocky seafloor. Recently, for the first time in the Mediterranean area, a large reef of *S. spinulosa* has been discovered along the northern Gargano coast at Torre Mileto (Adriatic Sea, southern Italy). In this paper, we will detail the main sedimentological data of this worm reef. In order to evaluate the kind of terrigenous particles involved in the worm tube constructions, detailed grain-size and petrographic analyses were carried out on both reef and soft-sediment substrate samples. It is demonstrated that *S. spinulosa* selects sands on the basis of their grain size and shape, and not their composition. It is also shown that some seasonal variations of these parameters are the result of the interplay between reef growth and degradation periods mainly related to physical processes. In particular, the degradation stages seem to be induced mainly by storm wave action, while the reef growth is the result of the complex interaction between ecological and physical processes.

1. Introduction

Bioconstructions are typical examples of environments in which biological and sedimentological features are fully merged: interdisciplinary approaches (geobiological studies, *sensu* Knoll et al., 2012) are necessary to analyze these complex systems in a reliable manner. Bioconstructions are generally identified with reefs built by corals (primary frame-builders or ecosystem engineers as defined by Jones et al., 1994) and the majority of other bioconstructional forms are considered as "poor cousins" or "unsung heroes" (Naylor, 2005). This is the case of the colonial sabellariid polychaete worms, even though they are the most significant frame-builders of large bioconstructions in temperate marine areas (Fournier, 2010). Their reefs result from the aggregation of worm tubes made up of sand and shell fragments cemented-agglutinated with mucous produced by the polychaete (Wust, 2011; Fournier, 2013). From an ecological point of view, these reefs are fundamental as they provide: an increase in space availability for new species; - an accumulation of organic deposits that may be important food sources for other organisms of microhabitats; - an increment in the biodiversity (especially when reefs develop where diversity and abundances of surrounding areas are lower, Holt et al., 1998; Pandolfi et al., 1998, Desroy et al., 2011). From a sedimentological point of view, these reefs can be considered important for coastal protection because they prevent beach erosion by means of the stabilization of sediments involved in the worm tube bioconstructions (Naylor and Viles, 2000). Sabellariidae reefs and mounds are very widespread, being located along the temperate coastal sectors of all continents (*see* a complete and recent review in: Fournier, 2013). *Sabellaria alveolata* and *Sabellaria spinulosa* (Leukhart, 1849) are the most common species found along the northern European coasts as well as in the Mediterranean Sea: the former, *S. alveolata,* builds mainly intertidal and subtidal reefs, whereas the latter, *S. spinulosa* may be found only in subtidal environments as isolated tubes, short-lived crusts and, more rarely, as small reefs (Gruet, 1986; Holt et al., 1998; Nicoletti et al., 2001; Dubois et al., 2003, 2006; Delbono et al., 2003; Braithwaite et al., 2006; La Porta and Nicoletti, 2009). Previous studies have analyzed in detail many and various aspects regarding *S. alveolata* reefs: i.e. - distribution and dynamics of *S. alveolata* reefs (Gruet, 1972, 1986; Desroy et al., 2011); - detection methods using aerial

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photographs and DEM (Noernberg et al., 2010); - grain-size and mineralogy of the sands agglutinated in the worm tubes (Gruet, 1984; Naylor and Viles, 2000; Delbono et al., 2003; La Porta et al., 2006; Fournier, 2013); - relationship between tube diameter and age of the worms (Gruet, 1984); - biophysics of the cilia capturing particles (Rikmenspoel and Rudd, 1971; Dubois et al., 2005); - physical-mechanical processes related to the great strength of the worm tubes (Le Cam et al., 2011); - biochemical features of the proteinaceous cement that *S. alveolata* uses to agglutinate sand grains (Becker et al., 2012; Fournier, 2013).

However, very few studies have been carried out on *S. spinulosa*. Specific papers refer only to the laboratory modeling of *S. spinulosa* worm tubes (Davies et al., 2009) and the detection of *S. spinulosa* reefs with side scan sonar surveys (Harrison et al., 2011). Some scientific papers report public projects aimed at the detection of the *S. spinulosa* aggregations as actual reefs (Holt et al., 1998; Hendrick and Foster-Smith, 2006; Gubbay, 2007; OSPAR Commission, 2010; Limpenny et al., 2010; Pearce et al., 2011a, b; OSPAR Commission, 2013). Indeed, the term “reefiness” has been explicitly coined for *S. spinulosa* bioconstructions (Fournier, 2013) and is defined as the sum of different scores related to physical and biological parameters: some of the physical parameters are often difficult to evaluate in a quantitative and reliable manner (*see* for example, sediment consolidation score, patchiness score, *S. spinulosa* density score, etc.).

In this study, we describe some *S. spinulosa* reefs detected along the northern coastal areas of the Gargano Promontory (southern Adriatic Sea, southern Italy). These reefs represent the first example of well-developed *S. spinulosa* bioconstructions in the Mediterranean Sea (AA.VV., 2014; Lezzi et al., 2015). In the Torre Mileto area, *S. spinulosa* forms large reefs in shallow-sea environments. Preliminary ecological features of this reef have been described (AA.VV., 2014; Lezzi et al., 2015): *S. spinulosa* creates different habitats in the area, playing an important role in enhancing the local biodiversity (Moretti, 2014).

The results of a sedimentological study carried out in this area over a period of various years are presented. Principal aims of this work are to: 1) describe the occurrence of *S. spinulosa* reefs in the southern Adriatic Sea; 2) analyze and compare the textural, morphometric and mineralogical features of the sediment of the reef (in the worm tubes and between adjacent tubes) and in the surrounding soft-sediment sea bottom in order to establish the capacity of *S. spinulosa* to select specific kinds of sediment; 3) describe the seasonal variability of the reef and interpret the possible mechanisms that regulate the degradation and growth stages.

2. The northern sector of the gargano promontory

The Apulian foreland is the emerged sector of the Adriatic plate. It corresponds to a wide buckled lithospheric zone and represents the Pliocene - Pleistocene foreland of the South Apennines orogenic system (Biju-Duval et al., 1977; Royden et al., 1987). The Gargano Promontory (Fig. 1a) is the highest and most north-eastern emerged sector of the Apulian foreland, and is composed of a thick Mesozoic carbonate succession (Apulia Carbonate platform, D'Argenio, 1974; Bosellini et al., 1999) covered by thin and discontinuous Tertiary and Quaternary deposits (Pieri et al., 1997; Morsilli, 2016). The *Sabellaria spinulosa* reefs were analyzed in the northern sector of the Gargano Promontory and the most extended reef is located at the locality of Torre Mileto, along the rocky coastal sector between Lakes Lesina and Varano (Fig. 1a). Sandy beaches form along the coastal zones of the northern Gargano and are mainly fed by terrigenous materials related to the nearest delta of the Fortore River (and, in lower amounts, to the Biferno and other northeast rivers) since the local longshore drift seems to be directed from west to east (Simeoni et al., 1999; Valpreda et al., 2003 - Fig. 1a). As a result, sand composition is mixed, siliciclastic-calciclastic, owing to the erosion of Meso-cenozoic chain units (mainly made up of siliciclastic and calciclastic turbiditic units) and the repeated cannibalization of the siliciclastic and calciclastic marine and continental terraces (Tavoliere di Puglia Supersyntem, Gallicchio et al., 2014; Gioia et al., 2014) deposited in the foredeep area during a middle-late Pleistocene uplift phase. The beaches in this northern sector of the Gargano Promontory are wave-dominated and the effect of tides on the sedimentation is negligible (the entire Adriatic Sea has a microtidal regime). According to their geomorphological and sedimentological features, the beaches can be grouped into 3 main types (Fig. 1a): 1) beaches with continuous and well-developed coastal barriers (Type A beaches, Mastronuzzi and Sansò, 2002), occurring along the coastal sectors of Lakes Lesina and Varano, 2) prograding coastal barriers (Type B beaches, Mastronuzzi and Sansò, 2002), typical of the Fortore delta area, and 3) more localized mainland beaches (Type E beaches, Mastronuzzi and Sansò, 2002). The Torre Mileto reef develops in a coastal area with localized pocket beaches and large rocky shore sectors; the subtidal environments show a sandy sea floor with isolated rocky substratum.

The ondametric data in the northern sector of the Gargano Promontory can be evaluated using the online public Italian Data Buoy Network (RON, ISPRA) considering the period 1990–1995 (Fig. 1b). A complete meteo-marine study for the Torre Mileto locality (Moretti, 2014) was obtained processing data coming from the Termoli anemometric station (located 50 km to the west) during the period 1965–1998 (Fig. 1b). Highest storm waves are recorded in winter, late autumn and early spring. In every season, a NNW storm wave direction is prevailing and an eastward general longshore drift is confirmed.

3. Field and laboratory procedures

3.1. Survey and sampling

Following the first recognition of well-developed *S. spinulosa* reefs along the northern coastal sectors of the Gargano Promontory (Fig. 1a), sedimentological surveys were carried out on the widest and stablest bioconstructions located in the Torre Mileto area. 15 samples of the reef (15 × 15 × 15 cm) were collected along the central and highest part of the reef (Fig. 1c), at different water depths (about 1, 1.5, 2, 2.5, 3 m), in October 2012, February 2013, June 2013. During the sampling, a sedimentological survey, using diving techniques, was conducted. The reef was investigated by monitoring the surface and height of the worm tube bioconstruction to detect, in a qualitative way, its physical structure evolution. To evaluate the textural and mineralogical features of the sands trapped in the worm tubes of the *S. spinulosa* reefs, three transects, perpendicular to the coast, were traced: a transect located westward of the main reef area (transect A in Fig. 1d), a transect crossing the reef (transect B in Fig. 1d) and another to the east (transect C in Fig. 1d); two further small transects were traced in the same area as transect C (transects D and E in Fig. 1d) to describe also the areas where rocky and sandy substratum alternate (in the emerged and submerged sectors). Considering the longshore drift, from W to E (Fig. 1a), this distribution is consistent with the attempt to recognize the kind of selection process operated by *S. spinulosa* on the sedimentary particles, evaluating the differences and/or similarities between the sands of the beaches located to the west, the sands trapped by the worm tube accretion, and the sands located further to the east, following a series of bioconstructions. Sampling procedures were conducted along the different transects

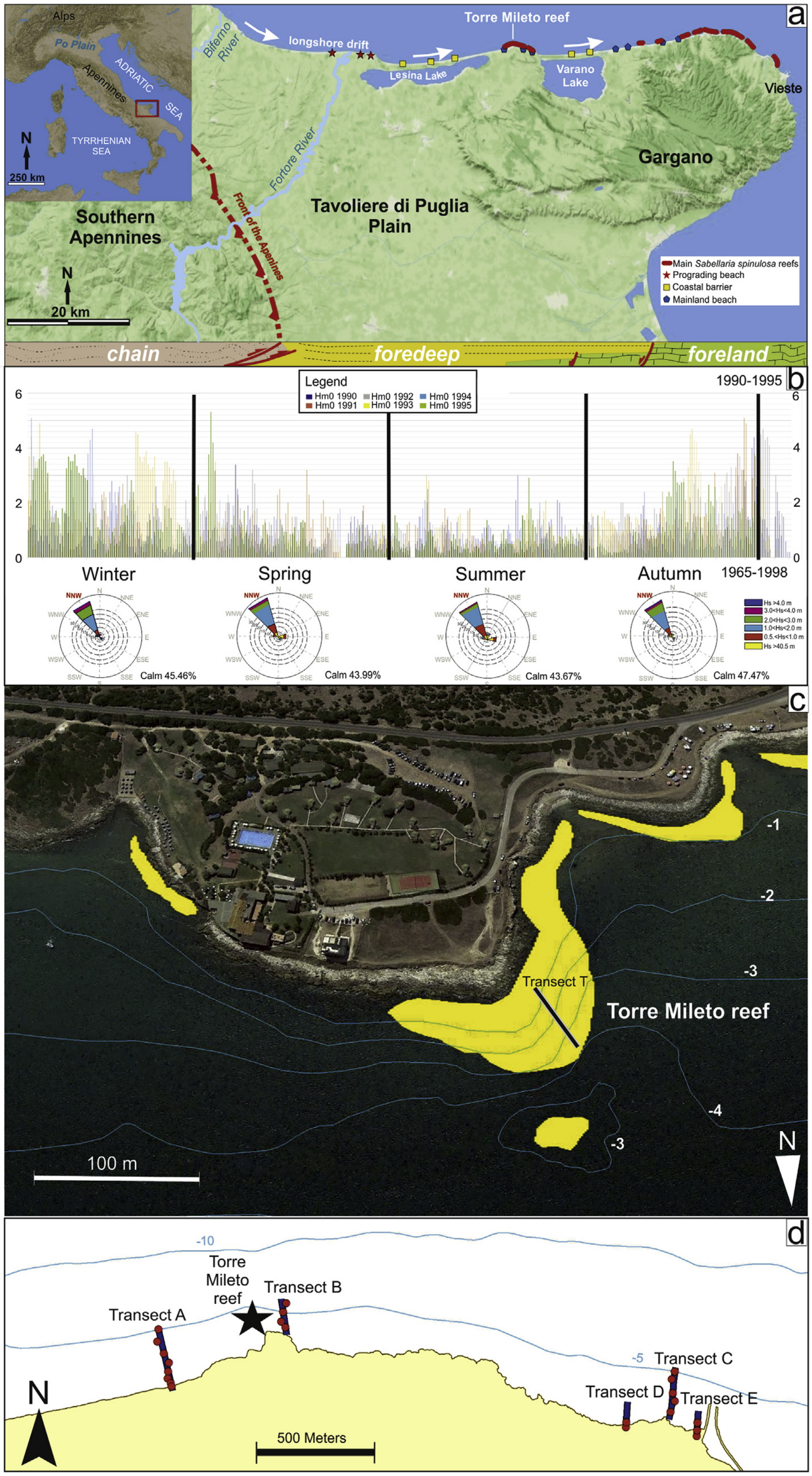


Fig. 1. a. Schematic map showing the location of the study area (Torre Mileto: 41° 56′ 00″ N; 15° 37′ 00″ E), the main structural domains and the beach types (modified from Mastronuzzi and Sansò, 2002); b. Meteomarine data; in the upper part, the record of the Italian Data Buoy Network (RON, ISPRA) is considered; in the lower part, the seasonal rose diagrams (Termoli anemometric station, 1965–1998) show a prevailing NNW storm wave direction (*modified* from Moretti, 2014). c. Extent of the Torre Mileto reef (in yellow); the approximate position of the reef sampling transects (T) along the central and highest part of the Torre Mileto bioconstruction is shown (Map Data©2016 Google). d. The sampling transects distributed westward and eastward with respect to the main reef at Torre Mileto. N.B. they are located in the backshore, foreshore and shoreface sectors (where a sandy beach is present). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

on the same day in order to consider the hydrodynamic conditions as constant. In the foreshore-shoreface area, sands were sampled at progressive 1-m water depths (0, −1, −2, etc., Fig. 1d) up to 5–6 m (corresponding to the local storm wave base). Sampling operations were also conducted in the backshore, along berms and aeolian dunes (where present). The same operational procedures were always used to keep sampling artefacts to a minimum, soft-sediment samples for grain-size analyses were collected in the first 0–2 cm below the sediment/water interface; 200–400 g of sediment, depending on grain-size and sorting of the sands, were collected in each area. These operational procedures abide by the standard sampling recommendations for marine sediments (Poppe et al., 2000).

3.2. Laboratory procedures

For grain-size analyses on soft-sediments, standard procedures were used: i.e. they were treated with hydrogen peroxide (6% solution) to remove organic matter and, later, wet-sieved to recover the fine-grained fraction (particles with diameters less than 0.062 mm), which was always negligible (less than 1–2%). The coarse-grained fraction was sieved for 10 min using a mechanical shaker and a ½ phi mesh sieve column.

For the grain-size analyses of worm tube aggregation samples, no standard procedures are available. In particular, the disaggregation of sand grains agglutinated in the worm tube seems to be a complex step: the preservation of the original grain-size distribution is a crucial focus. Nevertheless, the specific literature shows few and very different approaches (*see* Table 1). We applied the procedures described in previous papers to our samples, but did not obtain a complete disaggregation of the worm tubes (Fig. 2). To avoid textural changes due to mechanical crushing procedures, large-scale samples of worm tube reef were impregnated with low viscosity epoxy resin. In this way, image analysis procedures focusing on the calculation of main physical parameters of the worm tubes were performed without changing their original framework. Furthermore, this method allowed us to analyze the general three-dimensional morphology of the worm tubes along with some other physical features that had been neglected in previous studies. Indeed, the analysis of cemented samples allows us to accurately evaluate: 1) the percentage of areas occupied by the worm, tube and inter-tube features, and the porosity of the reef; 2) the grain-size of grains trapped in the tube and inter-tube areas; 3) the density and the dimensions of worm tubes of the *S. spinulosa* reef. For this purpose, it was necessary to obtain high-resolution images on macro-photos (on an area of about 100–150 cm^2), digitized thin sections (on an average area of about 35 cm^2 for every raster image) and microscope photos (at a x 2.5 magnification). They were then imported onto commercial and free software programs.

3.3. Image analysis procedures

To evaluate the percentage of the area occupied by the worms in the reef and the seasonal variation of this value, the raster file of both the high-resolution macro photos and digitized thin sections were imported onto ImageJ© software. Furthermore, the microscope photo images were imported onto the ArcGis software in order to draw detailed compositional maps of the sand grains throughout the different portions of the reef. The compositional classification of these sands was carried out using a simple triangular diagram (Zuffa, 1980). On the ArcGis maps, a grain-size analysis, distinguishing sand grains of the worm tubes from those of inter-tube sectors, was also carried out. The grain-size data were processed with the application Gradistat (V8) © for Microsoft Excel, obtaining the particle size distribution and the standard statistical parameters (mean, sorting, skewness, and kurtosis). On the same microscope photos, the internal diameter of the sub-circular worm tubes was measured, establishing relationships with the D50 of the sand grains agglutinated by the worm.

The ArcGis maps were imported onto ImageJ© to calculate and compare the main morphometric parameters of the sand grains: the Aspect Ratio (ratio between major axis and minor axis - AR) and the Circularity (the ratio between the area of the grain and the perimeter squared multiplied by 4π) indexes were evaluated: both parameters represent a quantitative measurement of the relative elongation of the particles.

4. The *Sabellaria spinulosa* reef at Torre Mileto

In the coastal area of the northern Gargano promontory, *S. spinulosa* forms large and stable reefs in shallow-sea environments. They are restricted to areas with a sparse rocky substrate, but develop laterally, stabilizing adjacent sandy bottom areas. Small and isolated bioconstructions develop for more than 50 km eastward along the coast, but the largest reefs are located close to the Torre Mileto locality (Fig. 1). Here, mounds and hummocks form between 1 and 4 m below mean sea level (Fig. 1c). Between 4 and 6 m below mean sea level, the thickness and the lateral continuity of the reef decrease with depth; at 6 m below mean sea level, the reef is not recognizable and only individual tubes forming incrustations or small aggregations have been reported. The Torre Mileto reef was monitored during 2012 and 2013; the *S. spinulosa* bioconstructions showed wide seasonal variability. During the period between the first ten days of spring and the first half of autumn, the largest reefs formed more or less isolated bodies with an area of some tens of m^2, covering an approximate total surface of 10,000 m^2; the maximum elevation on the sea bottom is variable

Table 1
Comparison between disaggregation procedures in literature. We have utilized all them without obtain satisfactory results: large-scale tube fragments and/or small particles aggregations were always present.

Authors	Procedure for the disaggregation of samples of worm reef	Kind of worm reef
Multer and Milliman (1967)	A sodium hypochlorite solution has been used.	*Phragmatopoma lapidosa* Kinberg reef
Rees (1976)	The sand grains of the adjacent tubes has been gently removed and, each isolated tube has been then crushed and sieved.	*Sabellaria vulgaris*
Gruet (1984)	Hydrogen peroxide has been used.	*S. alveolata*
Naylor and Viles (2000)	The worm tubes have been manually isolated as suggested by Rees (1976) and, later, disaggregated using potassium hydroxide (10% solution) followed by hydrogen peroxide (6% solution).	*S. alveolata*
Delbono *et al.* (2003)	The break up of the tubes has been obtained by shaking a mixture of deionized water and pieces of reef.	*S. alveolata*
Davies *et al.* (2009)	An ultrasonic bath has been used for 15 min to de-flocculate any clumps.	*S. spinulosa*
Le Cam *et al.* (2011)	Segments of tubes have been only washed with distilled water. After 48 h, the resulting material has been dried and mechanically sieved.	*S. alveolata*

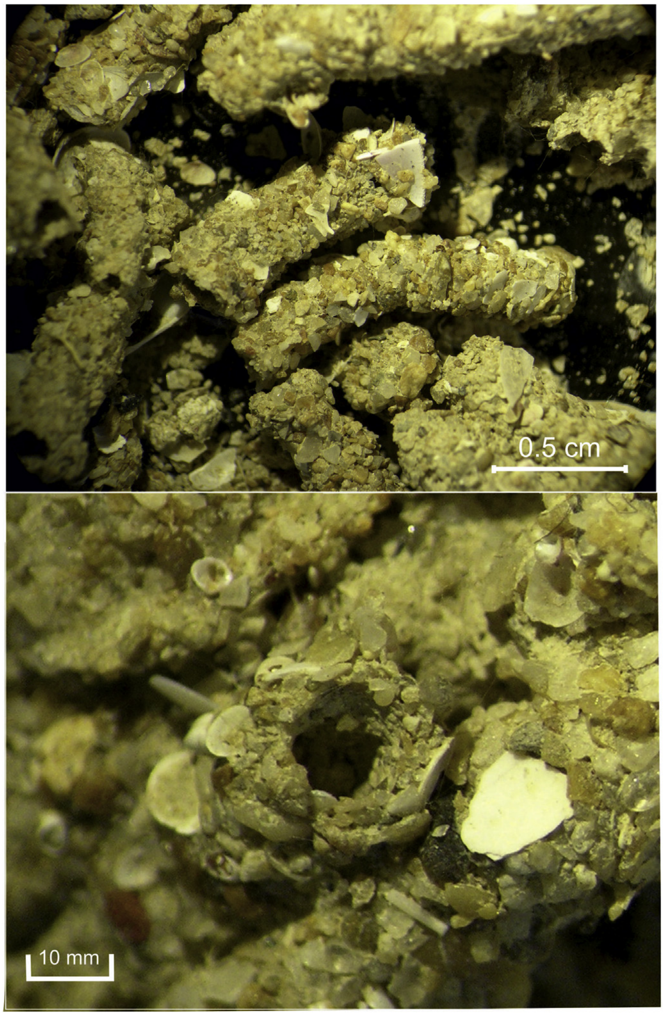


Fig. 2. Tube fragments of *Sabellaria spinulosa* after disaggregation. These reef samples were subject to: 3 repeated treatments with hydrogen peroxide (6% solution) and sodium hydroxide, an ultrasonic bath, a prolonged action of both mechanical stirrer (in a solution of sediments and distilled water) and mechanical shaker for sieve analysis. The photos show that they were almost intact.

from few tens of cm to about 0.70 m. On the contrary, during winter, the overall size of the reef dramatically decreases due to severe storm-wave action: largest colonies are restricted to localized areas (few m^2), while the residual space is occupied by dispersed worm tube aggregations that locally form thin encrustations on the sea bottom. The maximum height reaches 20–30 cm and the external morphology of the bioconstructions appears regular and locally flat (Fig. 3a, b). During winter, large reef fragments (Fig. 3c) have been recognized along the emerged sectors of the adjacent sandy beaches.

4.1. Porosity and tube density of the Sabellaria spinulosa reef

Using the ImageJ© facilities on the raster files of the high resolution photos, it is easy to calculate the total porosity of the reef (worm site and intergranular porosity) which varies from 27% to 31%. Furthermore, the worm tube density was evaluated, counting the circular voids of the reef. The results (Fig. 4) show mean values of the density of about 112,000 tubes/m^2. The table in Fig. 4 shows the seasonal variability of the worm tube number: this value ranges from 140,000 ± 16,900 tubes/m^2, in autumn, to 82,000 ± 11,200 tubes/m^2, in winter. The successive summer shows intermediate values (115,000 ± 18,200 tubes/m^2). In autumn, the worm bioconstruction is made up of tubes with varying dimensions, while the winter phase is mainly characterized by greater tube diameters and many abandoned tubes filled with sands (Fig. 4).

4.2. Sand composition in tube, intertube area and surrounding soft-sediments

More than 20 thin sections were obtained from the reef slabs, impregnated with resin along the vertical elongation of the worm tubes and perpendicularly to these planes (Fig. 5). The general framework of the reef were easily distinguished under the microscope, (Fig. 6): the tube area is made up of grains which form a circular framework around the space occupied by the worm; the elongation of these grains runs parallel to the circular development of the tube; in the intertube area, sand grains do not present a preferential orientation, being casually deposited by simple settling in the voids between adjacent tubes.

Detailed compositional maps were drawn on photos of the thin sections using ArcGis (Fig. 7) and distinguishing 4 main classes: carbonate lithoclasts, bioclastic carbonate, quartz and other components with negligible percentages (feldspar, pyroxene, amphibole, opaque mineral, etc.). We have compared sands coming from tubes, intertube area and the sands sampled in the shoreface (at −3 m below sea level in the 3 transects – Fig. 1). These sands can be classified as 'hybrid sands' of Zuffa (1980) corresponding to the 'miscellaneous sand' of Pettijohn (1975); they show only slight variations in the bioclastic content (Fig. 8).

4.3. The grain-size of tube, intertube and surrounding soft-sediments

The grain-size distribution of sediments agglutinated by the worms in the tube areas, as well as the ones trapped in the intertube area, were evaluated by using Image analysis procedures and Gradistat (V8) ©, and the cumulative curves and main statistical parameters (Fig. 8) were obtained. It was found that the tubes are composed of fine to medium grain-sized sand ($D50 = 180$ μm), while between adjacent tubes the materials were slightly coarser-grained ($D50 = 200$ μm). These data can be qualitatively compared with the grain-size distribution of the beach sands (sampled at 2 m BSL) obtained via classical sieve analysis ($D50 = 210$ μm).

In addition, a comparison between the subcircular tube diameter and the mean diameter (D50) of particles trapped by *S. spinulosa* (Fig. 9) was carried out. The point cloud distribution qualitatively suggests an increase in grain-size for larger diameters of the worm: i.e. larger tubes are made up of coarse-grained sands.

4.4. Morphometric parameters of the trapped sands

We compared the shape of the grains in the tube and intertube areas by measuring the parameters that record the relative elongation of the particles (the Aspect Ratio, AR, and the Circularity). The AR values of the tube grains are consistently lower than those of the intertube area (Fig. 9): the mean AR value of grains in the tubes is 2.7 ± 0.36, the mean AR value of grains in the intertube areas is 2.0 ± 0.2. In contrast, the values of the circularity of the grains composing the tubes are slightly lower than those of the intertube areas: the mean CIRCULARITY value of the grains in the tube is 0.6 ± 0.06, the mean CIRCULARITY value of the grains in the intertube areas is 0.7 ± 0.02.

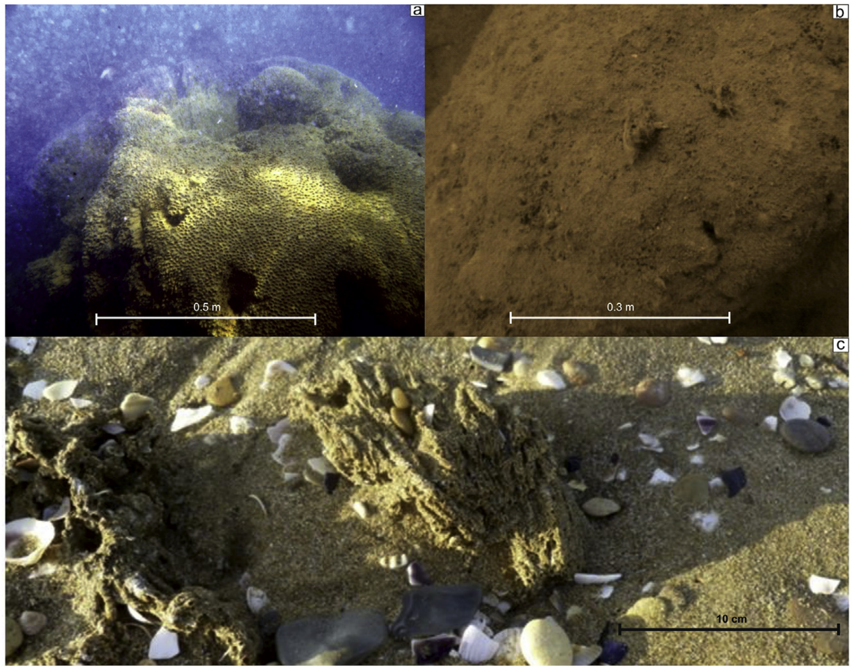
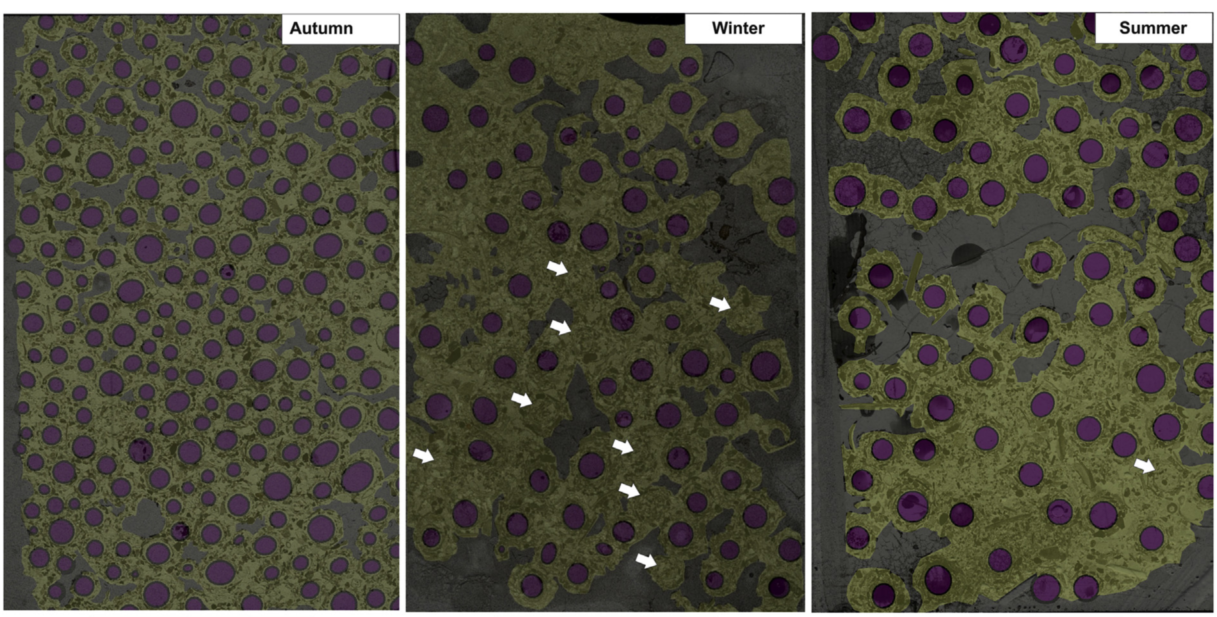


Fig. 3. Underwater photos of the reef at Torre Mileto in autumn (a) and winter (b). N.B. the levelled morphology of the reef after major winter storm-wave events. c. Reef fragments on the backshore areas after a winter storm wave event.



Autumn	AREA cm^2	n° of worm
S1	1	10.8
S2	1	14.3
S3	1	15.6
S4	1	14.1
S5	1	15.2
mean value	1 cm^2	14 ± 1.69

Number of tubes/ m^2 140,000 ± 16,900

Winter	AREA cm^2	n° of worm
R1	1	10.2
R2	1	7.9
R3	1	6.7
R4	1	8.1
R5	1	8.1
mean value	1 cm^2	8.2 ± 1.12

Number of tubes/ m^2 82,000 ± 11,200

Summer	AREA cm^2	n° of worm
1A	1	8.3
3A	1	12.1
2A	1	13.8
4A	1	12.3
5A	1	11.2
mean value	1 cm^2	11.5 ± 1.82

Number of tubes/ m^2 115,000 ± 18,200

Fig. 4. Three digitized thin sections of the reef in autumn, winter and summer. The reef is made up of tubes with varying dimensions in autumn. During the winter phase, larger tubes and abandoned tubes filled with sand (indicated by the white arrows) occur. The spring-summer phase shows large tubes, rare abandoned and filled tubes. The thin sections measure 3.2 × 2.6 cm. In the lower table, mean values and standard deviation of tube numbers during different seasons are shown. The number of worm tubes has been referred to a unit area of 1 cm^2.

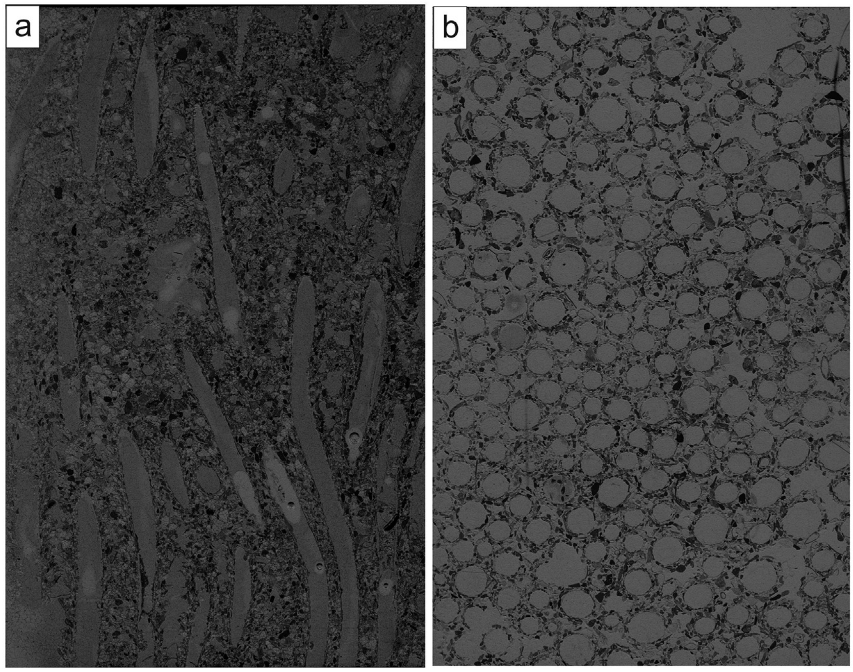


Fig. 5. Digitized thin sections showing the vertical elongation of the worm tubes (a) and the distribution of worm tubes in a horizontal plane (b). The thin sections measure 3.2 × 2.6 cm.

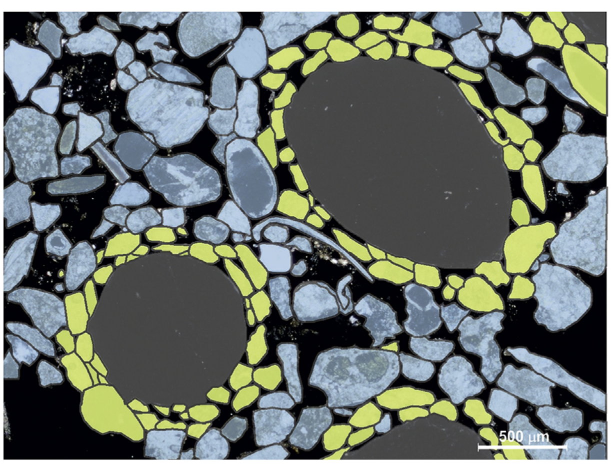


Fig. 6. Processed microscope photo. The tubes consist of sand grains (yellow) precisely distributed around the void occupied by the worm. Intertube areas contain casually oriented sand grains (light blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Discussion

The monitoring phases carried out on the largest reef of the Torre Mileto area allowed us to qualitatively define its seasonal variations. The thickness, the areal extent and the general morphology of the reef seem to be strictly influenced by the energy of the storm wave action. During the winter storm events, the reefs are partially destroyed and begin to develop during spring, reaching maximum patchiness at the end of summer and the first ten days of autumn. This interpretation is supported by the meteo-marine data (Fig. 1b) and by the abundance of reef fragments in the emerged sectors of the beaches during winter (Fig. 3c).

This process can be observed in thin section, being recorded also on a micro-scale. As a matter of fact, the number of tubes drops to a minimum during winter and increases gradually during the successive summer and autumn seasons (Fig. 4). This data is in agreement with the continuous creation of new generations up to October (Lezzi et al., 2015). Furthermore, the number of tubes is generally very high (mean value is about 112,000 tubes/m^2). The only reference value known in literature is the density score of Limpenny et al. (2010), which, however, relates to the number of individuals; obviously, this number (maximum recorded values are about 12,000 individuals/m^2 and the average reference value is around 3500 individuals/m^2) is lower than the number of tubes since part of them are empty and abandoned or filled with sands. Moreover, the values of Limpenny et al. (2010) were obtained by image analysis of ROV (Remotely Operated Vehicle) photos taken on the sea bottom and, which, consequently, have a low resolution.

A seasonal variation in the tube dimensions has been observed too. The occurrence of tubes with variable dimensions (in summer and especially in autumn, from 500 µm to 1800 µm) is related to the recruiting phase of the reef (with individuals of different ages); the winter degeneration phase of the bioconstruction is instead characterized by large tube diameters (always larger than 1000 µm, mainly adult individuals) and many abandoned tubes filled with sands. This interpretation is supported by the data of Lezzi et al. (2015) that describe new generations from April to October.

The worms do not seem to select sand grains on the basis of their compositional features: indeed, the tubes, intertube area and soft-sediments of the sea-bottom do not differ in a detectable manner, all being classifiable as hybrid sands. A small difference can be observed in the bioclastic content: the tubes seem to contain comparatively more bioclasts (average values of about 26%) than intertube (about 22%) and surrounding soft-sediments (about 14%). These data can be explained through the morphology of the trapped grains. Furthermore, the bioclastic content varies with the seasons: it seems to increase during autumn (34%) and decrease during summer and winter (21 and 22%, respectively). This is probably due to the general increase in available shells in shallow marine environments.

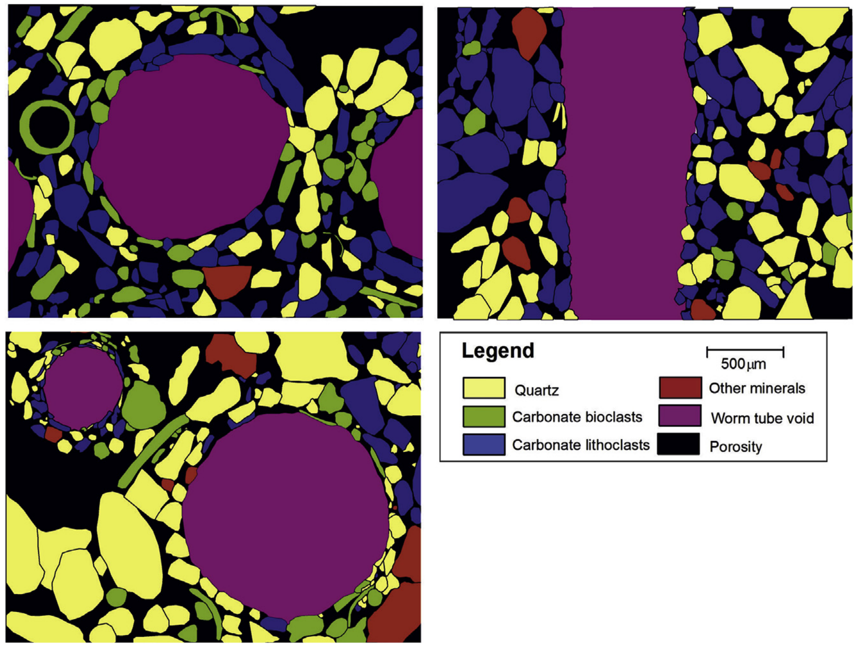


Fig. 7. ArcGis compositional maps along different worm tube orientations.

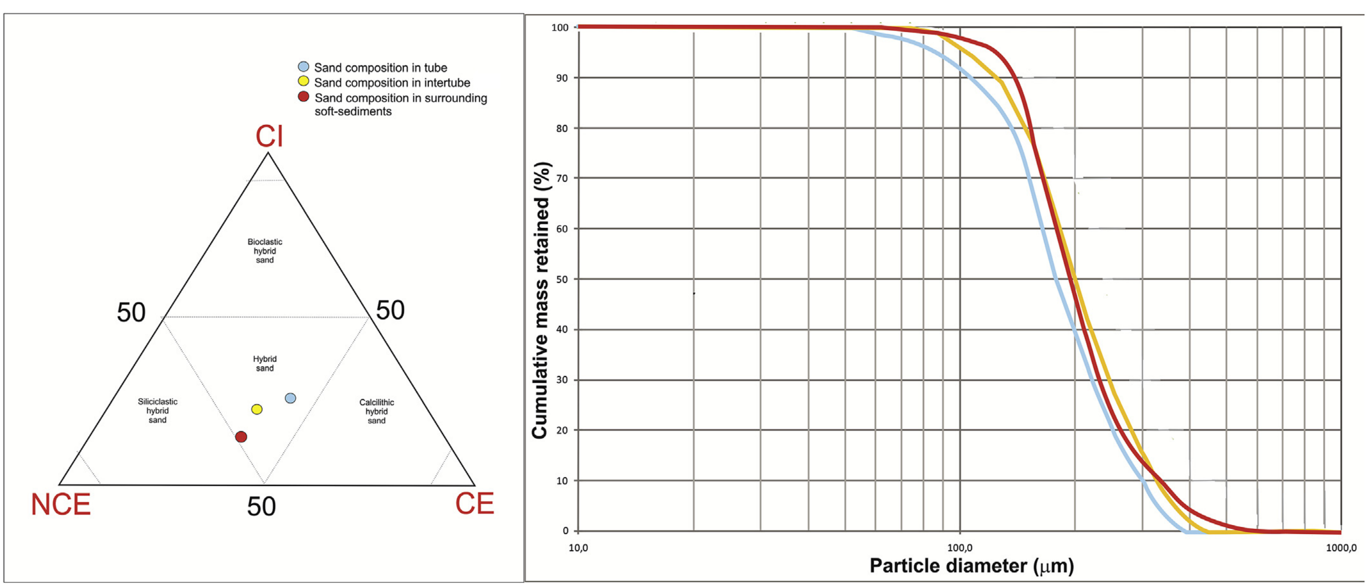


Fig. 8. On the left: the compositional classification of tube, intertube and shoreface sands shown in the triangular diagram of Zuffa (1980): carbonate lithoclasts (CE = carbonate extrarenite, corresponding to the calcilithite of Folk, 1959; i.e. older rocks fragments); - carbonate bioclasts (CI = intrarenite carbonate and calcarenite of Folk, 1959; i.e. only particles derived from present-day organisms); - non-carbonate terrigenous grains (NCE = non-carbonate extrarenite). On the right: grain-size distribution of tube (yellow), intertube (blue) and shoreface sands (red): they have similar particle size curves. The D50 of the tube sands is slightly lower than the D50 of the intertube and beach sands. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Worm tubes are generally composed of moderately sorted fine sands, while the intertube areas are mainly filled with slightly coarser-grained sands: this process is related to the large dimensions of the intertube area that can normally be filled with the largest grains, while finer-grained sand and silt are continuously removed by the wave action. The grain-size of beach sand is similar to the tube and intertube grain-size distribution: these data show that *S. spinulosa* is able to select a particular range of sand dimensions, but the grain-size of the entire reef (given by the sum of the tube and intertube areas) is not different from the general grain-size distribution of the surrounding beach sands.

Furthermore, larger tubes are made up of coarser-grained sands since they contain adult worms (the tube-building organ increases in size with age) that are able to trap larger particles (in agreement with data coming from the *Sabellaria alveolata* reefs: Gruet, 1984; Naylor and Viles, 2000).

Finally, *S. spinulosa* selects grains on the basis of their shape. In particular, flat and elongated clasts are more frequent in the tubes than in the intertube areas. Flat and elongated clasts are more frequent in the bioclastic grains and this is the reason why they are

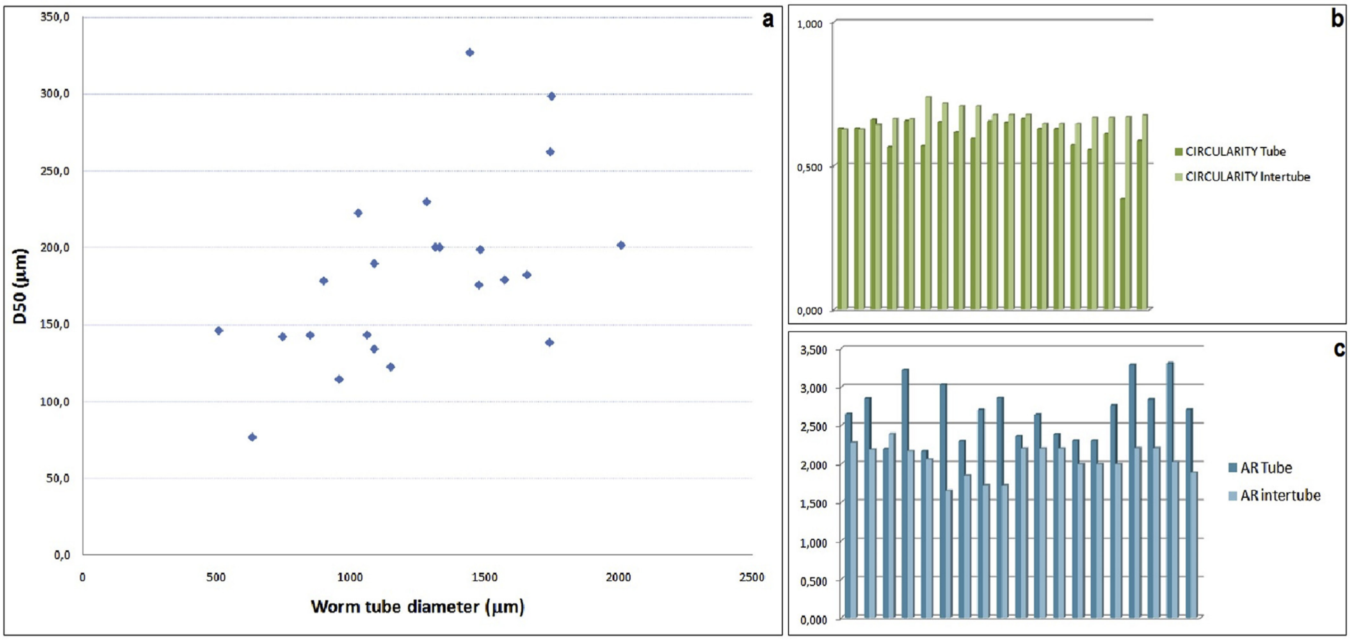


Fig. 9. a. Relationship between the tube diameters and the D50 of the sands agglutinated in the worm tube. Larger tubes seem to be associated with coarse-grained sands. On the right: morphometrical values of the sand grains forming the tube and contained in the intertube space for different raster files imported onto ImageJ©. The Aspect Ratio (AR) of the tube sands is higher than in intertube areas (b), obviously, the circularity shows an opposite relationship (c).

more frequent in the tube framework.

6. Conclusions

We report the first example of well-developed *Sabellaria spinulosa* reefs in the Mediterranean area. In the Torre Mileto locality (Southern Adriatic Sea), large build-ups of *S. spinulosa* have been identified. Main bioconstructions cover areas of some tens of m^2, and have varying thickness (20–70 cm, depending on the season). Here, *S. spinulosa* bioconstructions are restricted to the nearshore area where the action of waves provides the clastic material for the reef growth during the entire year. Degradation phases seem to be related only to the action of storm waves: during the winter storm events, the reefs are partially destroyed and the broken fragments are recognized along the backshore sectors. The bioconstructions begin to develop during spring, reaching maximum patchiness at the end of summer and the first ten days of autumn. These stages seem to reflect the meteo-marine data that show seasonal variations in the energy of the storm wave action. We document the seasonal variability on various scales (slabs, digitized thin sections and photos under the microscope). High tube-density values were documented during summer and autumn (from 115,000 tubes/m^2 to 140,000 tubes/m^2) and the lowest values during the winter degeneration phase (82,000 tubes/m^2). The reef is composed mainly of adult worm tubes (large tube diameters) in winter, while tubes with different diameters (corresponding to individuals of different ages) occur in summer and especially in autumn. Furthermore, degeneration phases are recorded by the abundance of abandoned tubes that are filled with sands. We have not analyzed the eco-biological evolution of the reef, but new generations of *S. spinulosa* are described in the same areas during the period April–October: this process certainly helps to create the conditions for the reef growth during the summer. In other words, the degeneration stages seem to be induced mainly by the storm waves action, while the reef growth is the result of the complex interaction between ecological and physical processes.

Furthermore, the *S. spinulosa* reef development in wave-dominated shallow-marine environments is favoured both by the availability of fine-to medium-sized sand grains (D50 about 180 µm) and the abundance of flat and elongated bioclasts (they have high AR values and low Circularity values). Finally, we have evaluated the porosity of the entire reef that is given by the sum of the worm tube voids and the intergranular porosity between particles that remain trapped between adjacent tubes (i.e. intertube area): we obtain porosity values that vary from 27% to 31%.

Further studies will be required in order to understand in more detail the complex interactions between ecological and physical processes, and to analyze the important role that *Sabellaria spinulosa* reefs play in coastal protection.

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