Palaeoecology of the *Pinna nobilis* biofacies along the Stirone River (Early Pleistocene, Northern Italy)

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ABSTRACT - The Stirone riverbanks (Northern Italy) host a famous Pliocene-Pleistocene marine succession, interpreted as a mosaic of shallow marine palaeoenvironments. One of the most remarkable occurrences is fossil Pinnidae in life position, here identified as Pinna nobilis *Linnaeus, 1758. It is an endemic Mediterranean bivalve, commonly reported from within* Posidonia *or* Cymodocea *meadows, or more rarely from other unvegetated shallow sedimentary bottoms, and even under hypoxic conditions. Few reports are found in the fossil record because of the low preservation potential of this large, semi-infaunal, fragile nacreous bivalve. Although already mentioned in the literature, no detailed palaeoecological investigation has been conducted on the mollusc association of the Pinnidae biofacies outcropping at the Stirone River. Four replicas of bulk sediment (2 l each) have been collected from the Pinnidae biofacies, in order to conduct a palaeontological and palaeoecological analysis, aimed at defining the composition and structure of the mollusc fossil assemblage, for the reconstruction of the associated palaeoenvironmental setting. The associated sediment, rich in tiny plant frustules, is a poorly sorted fine to very fine sand, with a bimodal distribution of sand and mud together with a coarse bioclastic fraction. The mollusc fossil assemblage is formed by a mixing of species which are related to both infralittoral vegetated and unvegetated bottoms, together with species with an affinity for both mud and coarse detritic sediments. One of the most common and abundant species is* Corbula gibba, *a bivalve considered of high ecological importance due to its opportunistic nature and reported as tolerant to elevated organic mud input, bottom hypoxia and unstable sedimentation rate. The fossil assemblage and the associated sediment point to a likely colonisation by* Cymodocea, *although the occurrence of mosaic facies of unvegetated and vegetated bottoms, with both* Cymodocea *and sparse* Posidonia, *cannot be ruled out. The bottom was strictly infralittoral (shallower than 15 m of water depth), with pulses of mud by fluvial transport, supporting the mixing of infralittoral and mud-loving deeper species, and the ubiquitous occurrence of* C. gibba.

INTRODUCTION

The rich and well-preserved invertebrate Pliocene-Pleistocene fauna exposed along the Stirone River (Parma-Piacenza, Northern Italy) has been the target of numerous studies (Dominici, 2001, 2004; Pervesler et al., 2011; Brunetti & Vecchi, 2015; Cau et al., 2019; Crippa et al., 2019). In particular, this marine succession records the occurrence of Pinnidae in life position in a portion of the stratigraphic section attributed to the Gelasian Stage based on magnetostratigraphic data (Gunderson et al., 2012) and to the Calabrian Stage, based on biostratigraphy (Crippa et al., 2019). Dominici (2001) identified these semi-infaunal bivalves as *Atrina pectinata* (Linnaeus, 1767), whereas Pervesler et al. (2011) attributed these fossils to *Pinna nobilis* Linnaeus, 1758.

Pinnidae of the Stirone River have been described as rare findings in the *Timoclea* palaeocommunity and as dominant in the *Pinna* palaeocommunity by Dominici (2001), the latter interpreted as living on soft bottoms of the inner shelf, at a minimum depth of 20 m and during time of highest clastic input. *Pinna* sp. was identified in the Lithozone 3 of Crippa et al. (2019) which is delimited at its base by a unit of closely packed macrobenthic invertebrate shells, represented by taxa retrieved in offshore transition to inner shore settings, with low hydrodynamic energy and low accumulation rates and dominated by suspension settling (Crippa et al., 2019).

Although already reported (Dominici, 2001; Crippa et al., 2019), and generally interpreted as representative of shallow water environment, no detailed palaeoecological study based upon benthic marine bionomics (Pérès & Picard, 1964) has been conducted on this Pinnidae-rich unit (= biofacies hereafter) so far. Furthermore, this autochthonous assemblage could reveal the past occurrence of phanerogams, whose potential fossil record deserves a special investigation effort.

Marine benthic bionomics is a particularly useful approach in palaeoecology, because: 1) substrate and benthos define biocoenoses, and they are the basic observational data for most palaeoenvironmental interpretations; 2) communities are named after the most abundant component of the assemblage (Gray, 1981), while marine benthic bionomics stresses the ecological meaning of the characteristic species, based on their statistical fidelity to the biotope, regardless of their abundance (Pérès & Picard, 1964). The two different approaches have complementary advantages in various possible applications in the fossil record: the community-based approach is applicable to any kind of present or fossil assemblage (Basso & Corselli, 2002). However, the ubiquitous, largely distributed species are likely to become numerically over-represented by time averaging, and they

become dominant in most modern shell assemblages and fossil associations (Clarke & Green, 1988; Kidwell, 2002; Basso & Brusoni, 2004; Albano & Sabelli, 2011). This bias obscures the structure of the association and the role of the less frequent species, therefore leading to an oversimplified picture of the distribution of communities. For example: the *Timoclea* community = *Venus* community (Guille & Soyer, 1970; Di Geronimo, 1975; Pinedo et al., 2015; Tillin, 2016), is named after a common infaunal suspension feeder, inhabiting several different detritic habitats, and potentially covers a large part of the shelf. On the other hand, the biocoenosis-based approach of marine bionomics requires a knowledge of the characteristic species, but, like in the studied Pleistocene section, it allows for a more articulate classification of habitats and benthic associations, as already demonstrated in other studies on Pleistocene mollusc fossil assemblages (Bracchi et al., 2014, 2016).

The study of the mollusc fossil assemblage recovered in the Pinnidae biofacies (= *Pinna* palaeocommunity in the sense of Dominici, 2001) has been conducted to define the species of Pinnidae of the Stirone River and to reconstruct its palaeoenvironment, including the possible occurrence of a vegetated palaeo-seafloor.

GEOLOGICAL SETTING

The studied deposits crop out in Northern Italy, and in particular in the area near San Nicomede village, 3 km northwest of the town of Salsomaggiore Terme (Fig. 1a). These deposits formally belong to the Castell'Arquato Basin (CAB), developing from the late Miocene (Messinian, 6 Ma) to the Pleistocene, after the NW migration of the Po Plain - Adriatic foredeep (Roveri & Taviani, 2003; Ghielmi et al., 2013). The CAB succession is controlled by tectonics: layers form a monocline dipping

toward the foreland of the Apennines thrust-fold belt (Roveri & Taviani, 2003; Artoni et al., 2010) with no major faults (Monegatti et al., 2001; Cau et al., 2019). The basal part of the CAB infill, when the marine conditions were restored after the Messinian salinity crisis, is composed of deep-sea sediments (Ceregato et al., 2007; Calabrese & Di Dio, 2009). During the Pliocene and Pleistocene, the depositional environment progressively changed to epibathyal and shelf. Starting from the Early Pleistocene, the regressive trend led to the establishment of continental conditions (Cigala Fulgosi, 1976; Pelosio & Raffi, 1977; Ciangherotti et al., 1997; Esu, 2008; Esu & Girotti, 2015). The Stirone River has easily accessible banks, where the Pliocene-Pleistocene section is well exposed (Fig. 1b). The studied biofacies crops out at a river curve, where strata gently dip (less than 10°) allowing the exploration of lateral and vertical biofacies change along a 3-4 m thick and almost 100 long outcrop (Fig. 1b). This biofacies consists of grey sandy sediments with specimens of Pinnidae in life position (Fig. 2a-b), which initially occur sparsely, becoming dominant eastward, along the left bank of the Stirone River. This biofacies corresponds to the *Pinna* palaeocommunity of Dominici (2001, fig. 8), to the upper part of the stratigraphic interval, between 59-63 m of Pervesler et al. (2011, fig. 3) and between 68-74 m of Crippa et al. (2019, fig. 8).

MATERIALS AND METHODS

To account for the lateral variation of fossil content (i.e., patchiness), four bulk samples of at least 2 liters were collected at laterally-adjacent sites along the outcrop, a few meters one from the other (Tab. 1) and at 2 m (sample 1) and 1 m (samples 2, 3 and 4) above the base of the silty unit (Fig. 1). Several specimens of Pinnidae were collected at the same sites (Fig. 2a-b). Bulk sediment
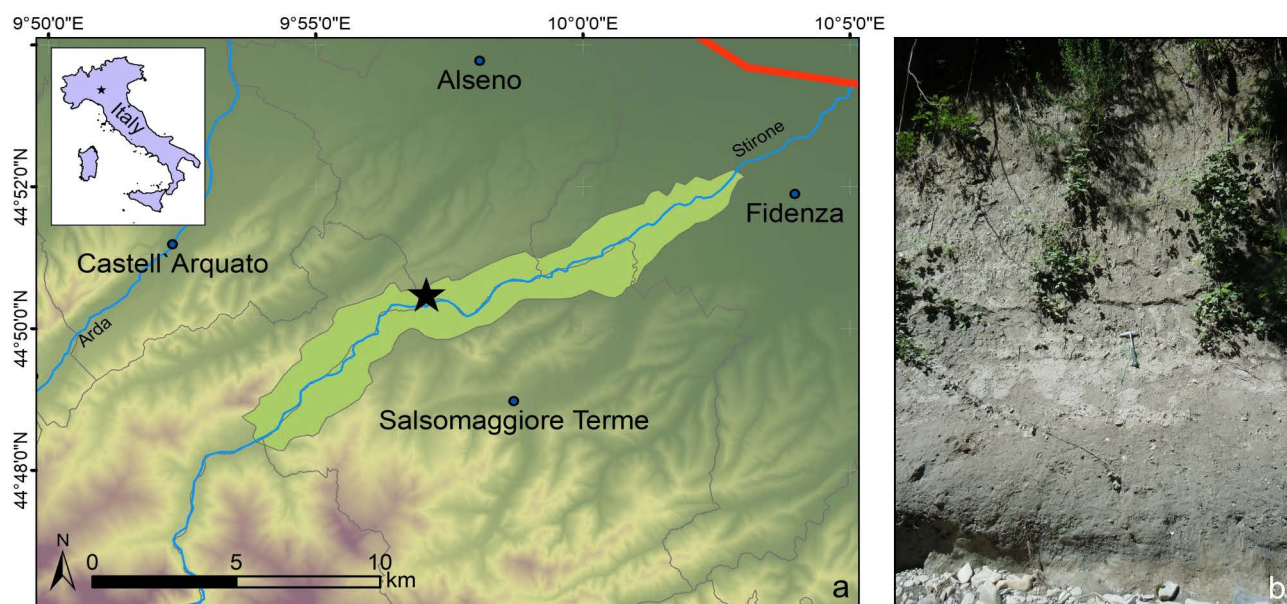

Fig. 1 - (color online) Location of the outcrop. a) Geographic map of the Stirone study site: in green the area of the Parco Regionale dello Stirone e del Piacenziano. The black star indicates the sampling site. b) The left riverbank of the Stirone where samples have been collected (hammer = 22 cm as scale).

Samples	Latitude	Longitude
Sample 1	44°50'39.3"N	9°58'59.9"E
Sample 2	44°50'39.3"N	9°59'00.1"E
Sample 3	44°50'38.9"N	9°59'02.1"E
Sample 4	44°50'38.9"N	9°59'02.6"E

Tab. 1 - List and georeferencing of the four collected samples.

samples have been air-dried and weighted. Wet sieving has been conducted to separate components by grain size, and several statistical parameters (mean, sorting, skewness and kurtosis) were calculated using GRADISTAT (Blott & Pye, 2001). Mean is the average grain size; sorting is the expression of the grain size variation of a sample by encompassing the largest parts of the size distribution as measured from a cumulative curve; skewness measures the degree to which a cumulative curve approaches symmetry; kurtosis is a measure of the peak in a cumulative curve.

Following the criteria summarised in Basso & Corselli (2007), mollusc entire shells and fragments in the fraction > 1 mm have been manually picked under a binocular microscope. To avoid the possible bias of specimens counting toward very distinctive species (the "*Chlamys* effect" of Kowalewski et al., 2003), bivalve fragments have been counted only when they included the hinge. Gastropods were retained only when they consisted of at least 2/3 of the abapical portion of the shell including the aperture, or the apical portion with the apex.

Articulated bivalves counted as one specimen. Left and right disarticulated valves were counted separately. As shell damage occurs much faster after disarticulation, the total number of bivalve specimens was obtained by taking the number of the most abundant valve and adding half the number of the other plus the number of entire specimens. Each gastropod fragment was counted as one specimen. Abundance is the counted number of individuals of each species in each sample. The dominance (or percent abundance) of each species in the fossil assemblage was then calculated as in Hily et al. (2008).

Specimens were identified at the lowest possible taxonomic level. Species richness is the number of species in a given sample, while species diversity has been calculated by the Shannon diversity Index (Spellerberg & Fedor, 2003). Evenness follows Pielou (1966) based on Shannon's index. Preservation and status codes have been attributed to the identified species following Basso & Corselli (2007). Preservation code (ranging 1-4 in the fossil) corresponds to a combined taphonomic grade assigned to the best preserved specimens of each species in a sample (Basso & Corselli, 2007). It is used as a synthetic indicator of possible biostratinomic processes affecting the fossil assemblage, such as post-mortem transport. Status code (J for juvenile, A for adult and P for population) is given to each species in a sample. If total population demographics were represented (shells of juveniles and adults mixed together), status code P was assigned. For exclusively adult shells status code A was applied, and if only juveniles were recovered, the designation was status code J (Basso & Corselli, 2007). In combination with the
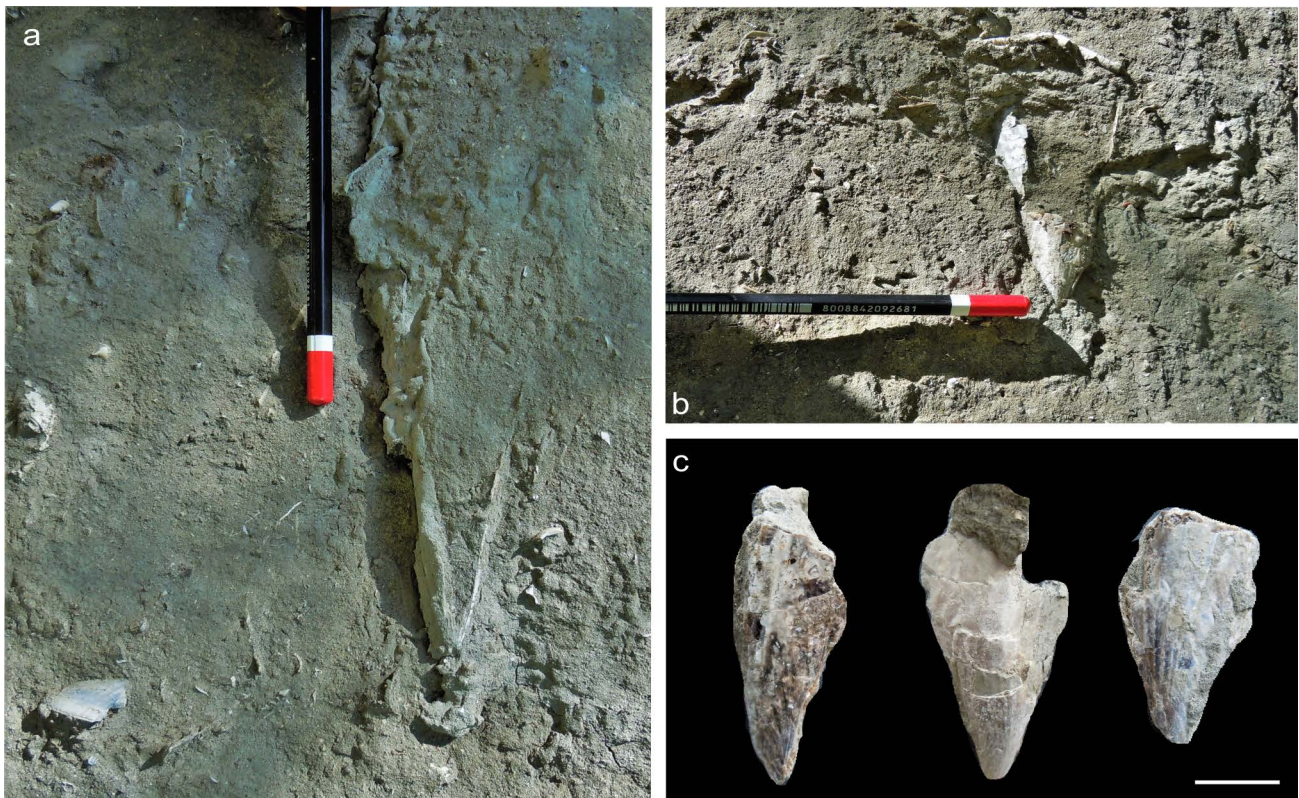

Fig. 2 - (color online) *Pinna* specimens. a-b) Specimens in life position along the outcrop (pencil for scale = 12 cm). c) Examples of collected specimens (scale bar = 1 cm).

preservation code, it is used to establish if a species in the fossil assemblage is autochthonous and was a permanent resident in equilibrium with its environment (P), or not (J or A) (Basso & Corselli, 2007).

Ecological affinity has been attributed to each species basing upon the ecology of the species as reported in literature (among others, Pérès & Picard, 1964; Parenzan, 1974a, b; Tebble, 1976; Poppe & Goto, 1991; Riedl, 1991; Basso & Corselli, 2002).

Each species has been assigned to biocoenosis, following the concept of ecological fidelity at the basis of marine benthic bionomics, as in Pérès & Picard (1964), Pérès (1982), Bellan-Santini et al. (1994) and Basso & Corselli (2002). Exclusive characteristic species (= excl) and, at a lesser degree, preferential characteristic species (= pref) express their fidelity to a given biocoenosis. Used acronyms from benthic bionomics are: SFBC for well sorted fine sand; C for coralligenous; DC for coastal detritic; VP for bathyal mud; SGCF for coarse sand and fine gravel under bottom currents; PE for heterogeneous assemblages; pss for species indicative of small hard substrates; sspr for species without a precise ecological meaning (in the sense of lack of fidelity to biocoenoses or even to a benthic zone); lre for large ecological distribution (Pérès & Picard, 1964; Basso & Corselli, 2002).

RESULTS

Grain size

The color of sampled sediments is grey (10YR 6/1) or light-yellow brown (10YR 7/4) (Munsell Color Chart, 2010). All samples are composed of very fine to fine, generally poorly to moderately sorted sand (Tab. 2; Fig. 3a-b). Two samples show a bimodal distribution (Fig. 3a) with two peaks corresponding to grains measuring 47.5 (mud) and 187.5 (fine sand) μm, and therefore statistical measures of the central tendency are not applicable (Tab. 2). Samples 3 and 4 are unimodal (Fig. 3a): 47.5 μm (mud) for sample 3, and 94 μm (very fine sand) for sample 4 (Tab. 2). Their mean values correspond to very fine sand (3.7 φ). Skewness is negative, whereas kurtosis is always > 0. The coarse fragments are skeletal remains, but also abundant tiny plant frustules.

Mollusc fossil assemblage

A total of 16 specimens of Pinnidae has been collected. Specimens were in life position (Fig. 2a-b), which means that both valves, frequently closed, were oriented vertically, perpendicular to the main stratification. They
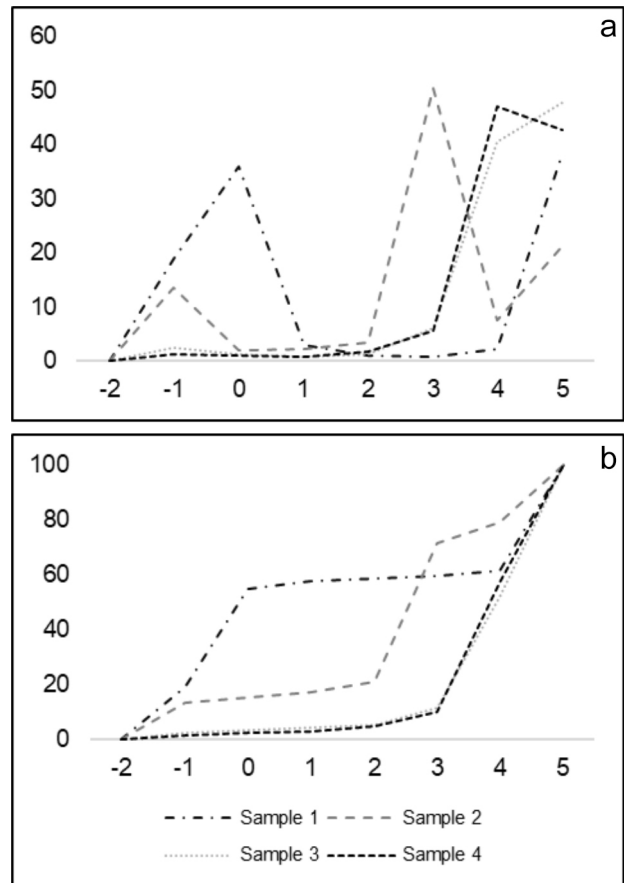

Fig. 3 - Graphical expression of grain size. a) Bimodal (samples 1 and 2) and unimodal (samples 3 and 4) distributions of grain size. b) Cumulative curves.

were preserved exclusively as the anterior umbonal region (about 4-7 cm long) (Fig. 2c), the part resting in the sediments during life. Shells preserve their nacreous structure and show externally very thin longitudinal striae and a very narrow umbonal angle (Fig. 2c). Based on these morphological evidences, the studied specimens have been identified as belonging to *P. nobilis*.

A total of 53 mollusc species have been identified: 31 bivalves, 20 gastropods and two scaphopods (Tabs 3-4; Appendix) for a total of 500 specimens (Tab. 4). Samples have comparable species richness, species diversity and evenness (Tab. 3). Bivalve species are more abundant than gastropods, whereas scaphopods were found only in sample 1 (Appendix). The preservation is generally medium to low, between 3 and 2, but specimens of species fall within the category of population (Appendix).

Samples	Distribution	Mean	Sorting	Skewness	Kurtosis	Definition
Sample 1	Bimodal (47.5; 187.5)	-	-	-	-	Very fine sand poorly sorted
Sample 2	Bimodal (187.5; 47.5)	-	-	-	-	Fine sand poorly sorted
Sample 3	Unimodal (47.5)	3.8	0.8	- 0.2	1.16	Very fine sand moderately sorted
Sample 4	Unimodal (94)	3.8	0.7	- 0.1	1.05	Very fine sand poorly sorted

Tab. 2 - Results of the grain size analyses using GRADISTAT (Blott & Pye, 2001). Results (in logarithmic scale, φ) are reported following Folk & Ward method.

Samples	Abundance	n° species	H	J
Sample 1	161	30	2.81	0.83
Sample 2	104	25	2.81	0.87
Sample 3	130	27	2.71	0.82
Sample 4	105	26	2.90	0.90

Tab. 3 - Abundance and species richness per sample, Shannon Index (H) for species diversity and Pielou's Evenness (J).

The fossil assemblage shows a heterogeneous mixing of species (Tab. 4). Thirteen species out of 53 are reported from all of the samples, with different ecological affinity (Tab. 4). Among them, the most abundant are *Anomia ephippium* Linnaeus, 1758 (infralittoral, vegetated bottoms; 79 specimens; 15.80%) and *Corbula gibba* (Olivi, 1792) (unstable bottoms independent from benthic zonation; 50 specimens; 10%). To follow: *Pododesmus patelliformis* (Linnaeus, 1761) (coarse detritic bottoms; 47 specimens; 9.4%), *Saccella commutata* (Philippi, 1844) (mud-related; 46 specimens; 9.2%), *Incatella cingulata* (G.B. Sowerby I, 1825) (infralittoral; 35 specimens; 7%), *Mimachlamys varia* (Linnaeus, 1758) (infralittoral, vegetated bottoms; 33 specimens; 6.6%), *Heteranomia squamula* (Linnaeus, 1758) (mud-related; 28 specimens; 5.6%), *Aequipecten opercularis* (Linnaeus, 1758) (coarse detritic; 20 specimens; 4%), *Parvicardium scabrum* (Philippi, 1844) (infralittoral, sand-related; 20 specimens; 4%), *P. nobilis* (infralittoral, vegetated bottoms; 16 specimens; 3.2%), *Glycymeris nummaria* (Linnaeus, 1758) (infralittoral, current-loving; 11 specimens; 2.2%), *Timoclea ovata* (Pennant, 1777) (coarse detritic; ten specimens; 2%), and *Nucula sulcata* Bronn, 1831 (coarse detritic; seven specimens; 1.2%). Within this nucleus of common and numerically important species, the suspension feeders are by far more represented than the mud-related detritus feeders (*S. commutata* and *N. sulcata*), with a significant stock of epifaunal/epibiotic species (*A. ephippium, P. patelliformis, M. varia, H. squamula, A. opercularis*).

An important percentage of species is linked to hard and coarse detritic bottoms, collectively up to 26.92% in sample 2, and mud-related settings (up to 26.67% in sample 4) (Tab. 4; Fig. 4) which are usually located in deeper environments with respect to the infralittoral zone.

Considering exclusively those species that are characteristic of one biocoenosis (Tab. 4), we obtain a list of seven species for a total of 68 specimens: *G. nummaria* and *Mangelia attenuata* (Montagu, 1803) (SFBC exclusive), *Limatula subovata* (Monterosato, 1875) (VP exclusive), *Palliolum incomparabile* (Risso, 1826) (C exclusive), *G. glycymeris* (Linnaeus, 1758) (SGCF exclusive) and *Flexopecten flexuosus* (Poli, 1795) (DC preferential). The most significant species among this group is *C. gibba* (PE preferential), occurring across all of the samples, and representing the highest proportion of the characteristic species with values ranging from 55.56% to 95.45% per sample (Fig. 5). Among the infralittoral biocoenoses, the most significant is SFBC with exclusive species up to 27.73% (Fig. 5). The VP exclusive species *L. subovata* occurs only in sample 4 with 10.53% (Fig. 5). Moreover, five species indicative of pss are reported (Tab. 4: column Biocoenosis).

DISCUSSION

The Stirone riverbanks represent an extraordinary outdoor palaeontological laboratory where rich and diverse fossil marine assemblages can be identified. The studied biofacies hosts 53 species and a total of 500 mollusc specimens. The fossil assemblage is quite heterogeneous (Tab. 4; Fig. 4). Most of the species are considered as autochthonous (Appendix), although with different preservation codes. This biofacies is formed by a heterogeneous mixing of species representative of both the infralittoral zone and deeper muddy bottoms (Tab. 4). Several records of species linked to photophilous and vegetated environment (infralittoral, vegetated; Tab. 4) indicate that the studied biofacies belongs to the infralittoral zone (Tab. 4; Fig. 4). The same for species linked to infralittoral sand-related setting (Tab. 4: column ecological affinity) or SFBC biocoenosis, which is represented by two exclusive characteristic species (one juvenile *M. attenuata* and a population of *G. nummaria*). Although belonging to the infralittoral zone, these species are not perfectly concordant with the substrate. In fact, the grain size corresponds to fine sand, but with a large amount of mud (Tab. 2; Fig. 3) with a mean of 3.8 ϕ. Statistic parameters underline the poorly sorted nature of the sediment, where coarse fragments occur, as confirmed by the negative values of skewness (Tab. 2). Most of them are represented by both plant frustules and skeletal remains, in accordance with the occurrence of pss species (Tab. 4). Nevertheless, given the important sandy component of the sediment, the SFBC species can be considered as accidental recruitments in the *Pinna* biofacies.

Mud-related species (Tab. 4; Fig. 4) are concordant with the occurrence of mud as indicated by grain size results. Where an infralittoral setting undergoes pulses, in our case episodic, of fine sediment supply from rivers, local conditions in shallow setting may foster the occurrence of mud-loving deeper species (Basso & Spezzaferri, 2000).

One of the most significant species is *C. gibba*, preferential of PE biocoenosis. This biocoenosis is independent from benthic zonation, because it develops when unstable ecological conditions occur at the seafloor along the shelf (Pérès & Picard, 1964; Picard, 1965; Pérès, 1982), typically hosting a mixing of opportunistic species of heterogeneous affinity. Di Geronimo & Robba (1988) described several phases of the development of PE biocoenosis, as a function of sedimentation and turbidity: our fossil assemblage resembles phase 1, where opportunistic species such as *C. gibba* appear with moderate abundance and accompanied by a heterogeneous assemblage of species. *C. gibba* is a species of high ecological importance due to its opportunistic nature. This species is tolerant to organic supply, mud increase and bottom hypoxia, and is reported to tolerate anthropogenic and natural disturbances, in ecologically unstable environments (Amorosi et al., 2002; Hrs-Brenko, 2006; Moraitis et al., 2018). In our samples, it occurs together with species linked to an infralittoral setting and with the occurrence of other mud-related biocoenoses (species with VP affinity) (Tab. 4). The observed abundance of *C. gibba* is not sufficient to support the presence of a well-defined PE biocoenosis. Nevertheless, this species is the most abundant

Species	Samples						Ecological affinity	Biocoenosis	*P.oceanica*	*C.nodosa*
	1	2	3	4	Ab	D				
Calliostoma granulatum	1				1	0.20	Infralittoral, vegetated			x
Jujubinus striatus		2	1		3	0.60	Infra-circalittoral	sspr	x	x
Xenophora crispa			1		1	0.20	Mud-related		x	
Incatella cingulata	17	3	6	9	35	7.00	Infralittoral			
Capulus ungaricus			5	1	6	1.20	Infralittoral, vegetated	pss	x	
Calyptraea chinensis			3		3	0.60	Coarse detritic	pss	x	x
Notocochlis dillwynii	3		5	4	12	2.40	Infralittoral, vegetated			
Epitonium sp.			1		1	0.20	Infralittoral		x	x
Eulima glabra		1			1	0.20	Infra-circalittoral		x	x
Trophonopsis muricata			1	1	2	0.40	Mud-related	sspr	x	
Coralliophila meyendorffii	1				1	0.20	Infralittoral, vegetated			
Tritia incrassata	1				1	0.20	Infralittoral, vegetated		x	x
Tritia lima	4		2	5	11	2.20	Coarse detritic	pss		x
Tritia ovoidea	3		1	5	9	1.80	Mud-related			
Mitrella sp.	2			1	3	0.60	Infralittoral, vegetated			
Comarmondia gracilis	2				2	0.40	Coarse detritic		x	x
Mangelia attenuata			1		1	0.20	Infralittoral, sand-related	SFBC excl	x	x
Pusia ebenus	1				1	0.20	Infralittoral, vegetated			
Gibberula recondita		1			1	0.20	Infralittoral, vegetated			
Ringicula auriculata		1	2	2	5	1.00	Infralittoral, vegetated			x
Fustiaria rubescens	1				1	0.20	Coarse detritic		x	x
Paradentalium pseudosexagonum	1				1	0.20	Infra-circalittoral			
Nucula sulcata	2	1	1	2	6	1.20	Mud-related		x	
Saccella commutata	11	10	13	12	46	9.20	Mud-related			
Yoldiella lucida			2	1	3	0.60	Mud-related			
Bathyarca pectunculoides	1				1	0.20	Mud-related			
Glycymeris glycymeris		1			1	0.20	Independent, current related	SGCF excl	x	
Glycymeris nummaria	1	5	1	4	11	2.20	Infralittoral, sand-related	SFBC excl	x	x
Pinna nobilis	6	2	1	7	16	3.20	Infralittoral, vegetated		x	x
Aequipecten opercularis	3	11	2	4	20	4.00	Coarse detritic	sspr	x	x
Mimachlamys varia	9	3	14	7	33	6.60	Infralittoral, vegetated	pss	x	x
Delectopecten vitreus			1		1	0.20	Mud-related			
Similipecten similis			1		1	0.20	Coarse detritic	pss		
Flexopecten flexuosus		1			1	0.20	Coarse detritic	DC pref	x	x
Palliolum incomparabile			2		2	0.40	Circalittoral, hard substrate	C excl		
Limatula subovata				2	2	0.40	Mud-related	VP excl		
Anomia ephippium	27	14	29	9	79	15.80	Infralittoral, vegetated	Ire	x	x
Pododesmus patelliformis	16	11	17	3	47	9.40	Coarse detritic	sspr		x
Ostrea edulis	2	3			5	1.00	Infra-circalittoral		x	x
Heteranomia squamula	11	7	7	3	28	5.60	Mud-related		x	x
Pseudochama gryphina	1				1	0.20	Infralittoral, vegetated		x	
Parvicardium scabrum	6	7	2	5	20	4.00	Infralittoral, sand-related			

Tab. 4 - List of the identified species per sample with the indication of abundance (Ab), dominance (D; Hily et al., 2008), the ecological affinity, the fidelity to biocoenosis, the occurrence among *Posidonia oceanica* or *Cymodocea nodosa* meadows based on literature data. For acronyms see Materials and Methods paragraph.

Species	Samples						Ecological affinity	Biocoenosis	*P. oceanica*	*C. nodosa*
	1	2	3	4	Ab	D				
Parvicardium sp.				1	1	0.20	Infralittoral, sand-related			
Cerastoderma edule		2			2	0.40	Infralittoral, sand-related			
Acanthocardia echinata			1		1	0.20	Coarse detritic		x	
Centrocardita aculeata		1			1	0.20	Coarse detritic	sspr		
Lucinella divaricata	1	1			2	0.40	Infralittoral, sand-related		x	x
Gouldia minima	1	2			3	0.60	Coarse detritic		x	
Timoclea ovata	4	2	3	1	10	2.00	Coarse detritic		x	
Callista chione			2		2	0.40	Infralittoral, sand-related		x	
Pharus legumen		1			1	0.20	Infralittoral, sand-related			x
Lutraria lutraria	1				1	0.20	Infralittoral, sand-related			x
Corbula gibba	21	11	5	13	50	10.00	Independent, unstable bottoms	PE pref	x	x

Tab. 4 - Continuation.

among those with biocoenotic fidelity (Fig. 5), probably favored by episodic mud transport, which is coherent with the influence of a fluvial system, as already suggested by Crippa et al. (2019; and references therein).

The biofacies is particularly interesting for the frequent occurrence of Pinnidae in life position (Fig. 2a-b), in a sediment containing a large amount of tiny plant frustules indicating organic content of the ancient seafloor and possibly vegetated bottoms. We identified the Pinnidae as belonging to *P. nobilis*, in agreement with Pervesler et al. (2011). Three taxa are indicated for present-day Mediterranean Sea (WoRMS, 2020): *P. nobilis*, *Pinna rudis* Linnaeus, 1758 and *Atrina fragilis* (Pennant, 1777). *P. rudis* generally presents a larger umbonal angle, resulting in a less slender anterior end of the shell compared to the studied specimens. Moreover, the observed thin longitudinal striae starting from the umbo region (Fig. 2c) are typical of *P. nobilis* whereas absent in *P. rudis*. The name *A. pectinata*, corresponding to an Indo-Pacific species, has long been misapplied to the European species now known as *A. fragilis* (WoRMS, 2020). *A. fragilis*, the other Pinnidae recorded for the Mediterranean Sea, shows similar narrow umbonal angle and slender umbo region, but no striae. *A. fragilis* is distributed from the Mediterranean Sea to the Shetland Islands (Solandt, 2003; Fryganiotis et al., 2013) in detritic bottom communities (Gamulin-Brida, 1974; Tebble, 1976) reaching very deep waters (Poppe & Goto, 1991; Riedl, 1991), with dense Mediterranean populations occurring between 25 and 50 m (Šimunović et al., 2001; Fryganiotis et al., 2013). Therefore, *A. fragilis* is not consistent with the shallow palaeoenvironmental setting reconstructed for the studied segment of the Stirone section. The interpretation of a deeper facies is excluded also because of the geological field observations (no obvious discontinuity among lateral facies) and the stratigraphic context (Crippa et al., 2019). *P. nobilis* is the largest endemic Mediterranean bivalve since the Miocene Epoch (Gómez-Alba, 1988), reaching up to 120 cm in length (Garcia-March et al., 2007). Presently it lives in coastal areas, at a depth between 0 and 32 m (Basso et al., 2015), primarily in soft sediments with seagrass

meadows of *Posidonia oceanica* (Linnaeus) Delile, 1813 or *Cymodocea nodosa* (Ucria) Ascherson, 1870 (Pérès & Picard, 1964; Basso et al., 2015; and references herein). This species is also reported from unvegetated soft bottoms in marine and estuarine areas (Basso et al., 2015), even under hypoxic conditions (Cappello et al., 2019). It is very sensitive to pollution, and listed as endangered species protected under the EU Habitats Directive (1992), Bern Convention and Barcelona Convention Protocol
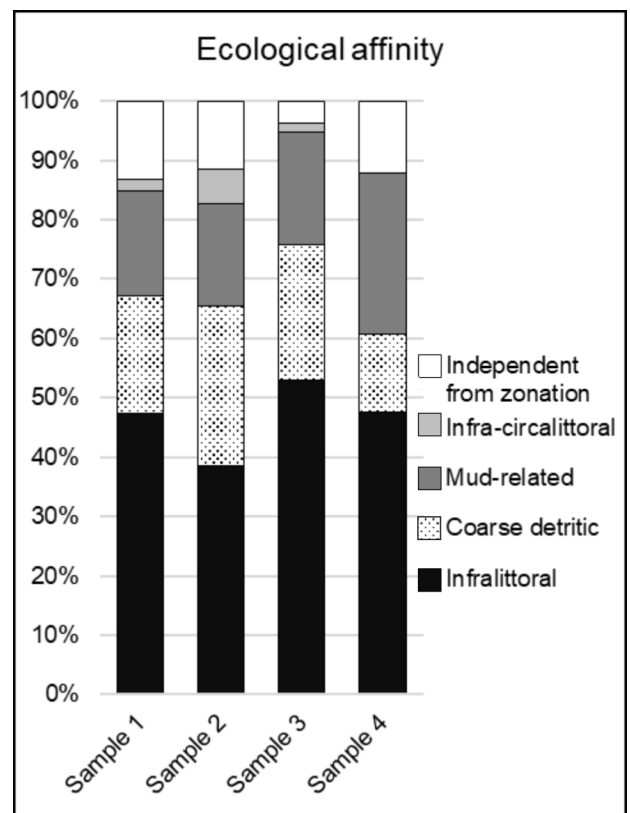

Fig. 4 - Cumulative bar graph of the percentage distribution based on ecological affinity.
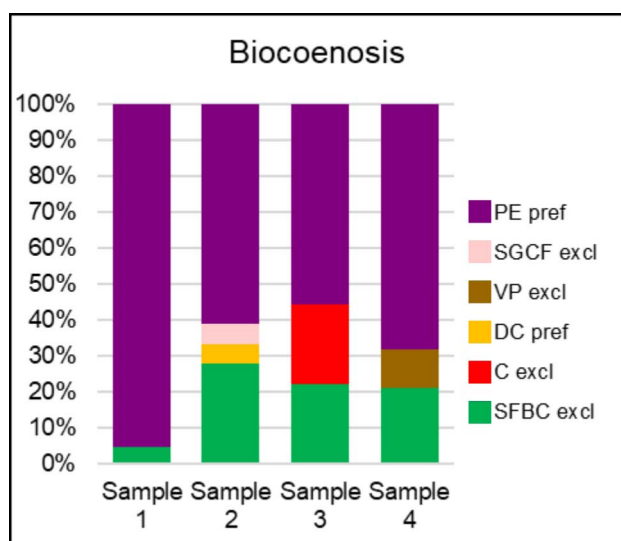
Fig. 5 - (color online) Cumulative bar graph of the percentage distribution based on biocoenosis. For acronyms, see Materials and Methods paragraph. Excl is for exclusive species, pref for preferential species.

(Annex II), and Marine Strategy Framework Directive (MSFD 56/EC, 2008).

Comparing the Stirone assemblage with literature data on present-day mollusc species associated with these two distinct meadows (Tab. 4; Mizzan, 1992; Ruggieri, 1993; Bequiraj et al., 2008; Marina et al., 2012), our material shows a higher number of specimens of those species that are solely linked to *Cymodocea* meadow (six species, 66 specimens) than those listed for the *Posidonia* meadow (ten species, 44 specimens).

Moreover, periodic pulses of sediment supply may be tolerated by *Cymodocea* (Marba & Duarte, 1994), while *Posidonia* shows a much lower tolerance to excess sedimentation (Cabaço et al., 2008). In the presence of a 4 meter-thick *Pinna* sedimentary interval with in-situ macrobenthic invertebrates, testifying to a minimum displacement of the fossil remains, we would expect to find other fossil evidences usually linked to the occurrence of well-developed *Posidonia* meadows, such as: 1) remains of the "matte" (= a semi-consolidated structure of lignified roots and rhizomes admixed with sediment); 2) aegagropilae (= centimeter-sized, nearly spherical fiber aggregates resulting from compaction of the remains of *Posidonia*); 3) rhizomes, as for example in the Pliocene of Rhodes, Greece (Moissette et al., 2007). None of them were observed, despite the abundance of plant frustules. Moreover, the mollusc fossil assemblage recorded few occurrences of molluscs typical of infralittoral vegetated biocoenoses (photophylous algae, *Posidonia* meadows; Pérès & Picard, 1964) (Tab. 4; Fig. 4; Appendix). Finally, no remains have been recorded of the dim-light association typically thriving under the canopy of *Posidonia* leaves, such as coralline algae encrustations or abundant C and DC exclusive or preferential species (Pérès & Picard, 1964). These considerations exclude the existence of a well-developed *Posidonia* meadow, and rather point to a more likely colonisation by *Cymodocea*, although the occurrence of mosaic facies of vegetated bottoms, with

both phanerogams, and unvegetated bottoms cannot be ruled out. We conclude that the ancient sedimentary bottom was strictly infralittoral, probably shallower than 15 m of water depth, with pulses of abundant mud by fluvial transport, supporting the mixing of infralittoral and mud-loving deeper water species, and the ubiquitous occurrence of the opportunistic species *C. gibba*.

CONCLUSIONS

The Early Pleistocene marine succession of the Stirone riverbanks (Northern Italy), already well studied from a stratigraphic point of view, contains well preserved specimens of Pinnidae in life position. The palaeoecological study revealed that such specimens belong to the species *P. nobilis*, possibly signifying the occurrence of a vegetated palaeo-environment. The study of related sediments and mollusc fossil assemblage showed a complex infralittoral palaeo-setting. Sediments are poorly sorted fine to very fine sand with bi-modal distribution (sand with abundant mud) and an important coarse component (skeletal remains and plant frustules). The fossil assemblage is formed by a mixing of infralittoral species, indicating both vegetated and unvegetated or sand-related (SFBC) substrates, together with deep mud-loving species (VP) or coarse detritic dwellers (DC). One of the most significant species is *C. gibba*, reported also as indicative of unstable ecological conditions that in the studied case might be related with episodic riverine sediment supply. No evidence of well-developed *Posidonia* meadows has been identified. In conclusion, the palaeoenvironment of deposition of the Stirone *Pinna* bed was strictly infralittoral, probably less than 15 m depth, either with a mosaic of facies only partially vegetated (possibly *Cymodocea* or both phanerogams), and the overarching control on the development of the mollusc associations that was exerted by episodic pulses of terrigenous sedimentation from fluvial input.

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APPENDIX

The fossil assemblage for each sample, with the indication of abundance (Ab) and dominance (D) (Hily et al., 2008); Preservation code (P: from 1 = low, up to 4 = very good in the fossil record); Status code (S: J for juvenile, A for adult and P for population). For bivalves: L = Left valve abundance, R = Right valve abundance, E = Entire for articulate bivalves; Ab for total abundance calculated as reported in the Material and Methods paragraph.

Sample 1						
Gastropods						
Species			**Ab**	**D (%)**	**P**	**S**
Calliostoma granulatum			1	0.62	3	J
Incatella cingulata			17	10.56	3	P
Notocochlis dillwynii			3	1.86	3	P
Coralliophila meiendorffi			1	0.62	4	A
Tritia incrassata			1	0.62	3	A
Tritia lima			4	2.48	3	P
Tritia ovoidea			3	1.86	2	A
Mitrella sp.			2	1.24	2	P
Comarmondia gracilis			2	1.24	3	P
Pusia ebenus			1	0.62	2	A
Total gastropods			**35**	**22.15**		
Scaphopods						
Fustiaria rubescens			1	0.62	3	A
Dentalium pseudosexagonum			1	0.62	2	A
Total scaphopods			**2**	**1.24**		
Bivalves						
	L	**R**	**E**	**Ab**		
Nucula sulcata	1	1	0	2	1.24	3	A
Saccella commutata	6	7	1	11	6.83	4	P
Bathyarca pectunculoides	1	0	0	1	0.62	3	A
Glycymeris nummaria	0	1	0	1	0.62	3	J
Pinna nobilis	0	0	6	6	3.73	3	A
Aequipecten opercularis	1	3	0	3	1.86	3	P
Mimachlamys varia	4	7	0	9	5.59	3	P
Anomia ephippium	27	0	0	27	16.77	2	P
Pododesmus patelliformis	16	0	0	16	9.94	3	P
Ostrea edulis	1	2	0	2	1.24	3	J
Heteranomia squamula	11	0	0	11	6.83	3	P
Pseudochama gryphina	1	0	0	1	0.62	3	J
Parvicardium scabrum	0	5	1	6	3.73	3	P
Lucinella divaricata	0	1	0	1	0.62	3	J
Gouldia minima	0	1	0	1	0.62	3	A
Timoclea ovata	4	1	0	4	2.48	3	J
Lutraria lutraria	0	1	0	1	0.62	2	J
Corbula gibba	2	20	0	21	13.04	2	P
Total bivalves				**124**	**77.02**		
Total Molluscs	**161**				**100**		

Sample 2						
Gastropods						
Species			**Ab**	**D (%)**	**P**	**S**
Jujubinus striatus			2	1.92	2	J
Incatella cingulata			3	2.88	3	A
Eulima glabra			1	0.96	2	J
Gibberula recondita			1	0.96	2	A
Ringicula auriculata			1	0.96		
Total gastropods			**8**	**7.69**		
Bivalves						
	L	**R**	**E**	**Ab**		
Nucula sulcata	1	0	0	1	0.96	2	A
Saccella commutata	5	5	0	10	9.62	4	P
Glycymeris glycymeris	1	0	0	1	0.96	2	A
Glycymeris nummaria	5	1	0	5	4.81	3	P
Pinna nobilis	0	0	2	2	1.92	3	A
Aequipecten opercularis	8	5	0	11	10.58	3	P
Mimachlamys varia	1	3	0	3	2.88	3	P
Flexopecten flexuosus	1	0	0	1	0.96	3	A
Anomia ephippium	14	0	0	14	13.46	2	P
Pododesmus patelliformis	11	0	0	11	10.58	2	P
Ostrea edulis	0	3	0	3	2.88	3	J
Heteranomia squamula	7	0	0	7	6.73	2	P
Parvicardium scabrum	5	3	0	7	6.73	3	A
Cerastoderma edule	2	0	0	2	1.92	2	J
Centrocardita aculeata	0	1	0	1	0.96	4	J
Lucinella divaricata	1	0	0	1	0.96	4	A
Gouldia minima	0	2	0	2	1.92	3	J
Timoclea ovata	1	2	0	2	1.92	2	A
Pharus legumen	1	0	0	1	0.96	2	J
Corbula gibba	2	10	0	11	10.58	2	P
Total bivalves				**96**	**92.31**		
Total Molluscs	**104**				**100**		

Sample 3				
Gastropods				
Species	**Ab**	**D (%)**	**P**	**S**
Jujubinus striatus	1	0.77	1	A
Incatella cingulata	6	4.62	3	J
Capulus ungaricus	5	3.85	3	A
Calyptraea chinensis	3	2.31	3	A
Notocochlis dillwynii	5	3.85	3	P
Epitonium sp.	1	0.77	2	J
Trophonopsis muricata	1	0.77	3	J
Tritia lima	2	1.54	3	J
Tritia ovoidea	1	0.77	3	A

Species	L	R	E	Ab	D (%)	P	S
Mangelia attenuata				2	0.77	2	A
Ringicula auriculata				2	1.54	4	A
Total gastropods				28	21.54		

Bivalves

Species	L	R	E	Ab	D (%)	P	S
Nucula sulcata	1	0	0	1	0.77	3	A
Saccella commutata	3	11	0	13	10.00	3	A
Yoldiella lucida	2	0	0	2	1.54	2	A
Glycymeris nummaria	0	1	0	1	0.77	3	J
Pinna nobilis	0	0	3	1	0.77	3	A
Aequipecten opercularis	2	0	0	2	1.54	3	J
Mimachlamys varia	3	12	0	14	10.77	3	P
Palliolum incomparabile	1	2	0	2	1.54	3	J
Anomia ephippium	29	0	0	29	22.31	3	P
Pododesmus patelliformis	17	0	0	17	13.08	2	P
Heteranomia squamula	7	0	0	7	5.38	3	J
Parvicardium scabrum	1	2	0	2	1.54	3	J
Acantocardia echinata	1	0	0	1	0.77	3	A
Timoclea ovata	1	3	0	3	2.31	3	P
Callista chione	2	0	0	2	1.54	3	P
Corbula gibba	0	5	0	5	3.85	2	P
Total bivalves				102	78.46		
Total molluscs	130				100		

Sample 4				

Gastropods

Species	Ab	D (%)	P	S
Xenophora crispa	1	0.95	3	A
Incatella cingulata	9	8.57	2	J
Capulus ungaricus	1	0.95	4	A
Notocochlis dillwynii	4	3.81	3	J
Trophonopsis muricata	1	0.95	3	P
Tritia lima	5	4.76	3	J
Tritia ovoidea	5	4.76	3	P
Mitrella sp.	1	0.95	3	A
Ringicula auriculata	2	1.90	4	A
Total gastropods	29	27.62		

Bivalves

Species	L	R	E	Ab	D (%)	P	S
Nucula sulcata	1	1	0	2	1.90	2	J
Saccella commutata	5	9	1	12	11.43	3	P
Yoldiella lucida	0	1	0	1	0.95	2	A
Glycymeris nummaria	0	4	0	4	3.81	4	J
Pinna nobilis	0	0	7	7	6.67	3	A
Aequipecten opercularis	0	4	0	4	3.81	3	P
Mimachlamys varia	4	5	0	7	6.67	4	P
Delectopecten vitreus	0	0	1	1	0.95	2	J

Similipecten similis	1	0	0	1	0.95	2	J
Limatula subovata	2	0	0	2	1.90	1	A
Anomia ephippium	9	0	0	9	8.57	2	P
Pododesmus patelliformis	3	0	0	3	2.86	2	J
Heteranomia squamula	3	0	0	3	2.86	3	J
Parvicardium scabrum	2	4	0	5	4.76	3	J
Parvicardium sp.	1	0	0	1	0.95	2	J
Timoclea ovata	0	1	0	1	0.95	3	A
Corbula gibba	1	13	0	13	12.38	2	P
Totale bivalves				**76**	**72.38**		
Total Molluscs	**105**				**100**		