**Benthic foraminifera as proxy for fossil seagrass from the Lower Pleistocene deposits**

**of the Stirone River (Emilia-Romagna, Italy)**

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## Abstract

This paper analyses and describes the benthic foraminiferal associations within the Pleistocene

deposits of the Stirone River (Emilia-Romagna, Italy), with the purpose of testing foraminifera as

Indirect Palaeo-Seagrass Indicators (IPSIs). Our analyses focused on two different biofacies: a

*Thalassinoides* biofacies, characterised by an oligotypic biotic assemblage and a *Pinna* biofacies

representing an infralittoral soft bottom colonised by marine phanerogams and characterized by

high biodiversity. To strengthen the analyses, we have compared the Stirone foraminiferal

association with the one of Fauglia (Tuscany, Italy), in which a well-preserved, early Pleistocene,

fossil *Posidonia* meadow, is present. The aim of this work is to provide qualitative and quantitative

parameters that can be used to recognize past vegetated environments, where fossil seagrass are no

longer present. Considering the influence of ecological constraints and diagenetic processes on the

foraminiferal assemblages, several indexes such as the $Index_{EP}$, the modified FORAM index (FI'),

the "long vs. short life-span index" ($I_{LS}$), and the $K/R_{EXT}$ (keeled/rounded morphotypes) have been

calculated and a morphotype-based analysis has been provided. Among the tested indexes, the latter

26    proved to be the most reliable IPSI, in association with the presence of morphotype A*,

27    permanently attached, encrusting foraminifera and the abundance of Rosalinidae.

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## 1. Introduction

33    The ecological significance and environmental importance of seagrass-related habitats is widely

34    known. Seagrass meadows generally present a higher biodiversity than the surrounding unvegetated

35    marine areas (e.g., Brasier, 1975; Hirst & Attrill, 2008; Barnes & Barnes, 2012). They provide

36    indisputable ecosystem benefits and services (Sanchez-Vidal et al., 2021), including water quality

37    improvement (de los Santos et al., 2020), carbon dioxide sequestration (Deyanova et al., 2017),

38    stabilization of the seafloor, coastal protection and sediment production (Gacia et al., 2003;

39    Ondiviela et al., 2014), and climate change mitigation (Duarte et al., 2013). With the term "seagrass

40    meadows", we identify large stretches of shelf environment (up to 100s $m^2$) dominated by marine

41    angiosperms (e.g., *Posidonia* spp*., Cymodocea* spp.) (Reich et al., 2015b). Patchy seagrass

42    meadows are also common. They are widespread worldwide in shallow coastal waters, at all

43    latitudes, from Greenland to New Zealand (Cullen-Unsworth et al., 2013; Reich et al., 2015b).

44        Nowadays the effects of climate change highlighted the importance of the relationship

45    between environmental dynamics, such as sea-level fluctuations and temperature variations, and

46    marine biodiversity. This is especially relevant in sensitive environments such as seagrass meadows

47    (Alvarez Zarikian et al., 2000; Mateu-Vicens et al., 2014; Unsworth et al., 2014; Arias-Ortiz et al.,

48    2018). In this respect, the recognition of seagrass-related palaeoenvironments in the fossil record

could help us in investigating habitat dynamics in response to environmental changes (Reich et al., 2015b).

Although several studies of modern seagrass habitats and associated communities have been carried out (e.g., Heck et al., 1989; Langer, 1993; Boström & Bonsdorff, 1997; Barnes & Barnes, 2012; Mateu-Vicens et al., 2014; Benedetti & Frezza, 2016; Sanchez-Vidal et al., 2021), only few detailed studies on fossil seagrass meadows and related palaeocommunities exist (e.g., Brasier, 1975; Eva, 1980; Dominici, 2001; Domning, 2001; Vélez-Juarbe, 2014; Baceta & Mateu-Vicens, 2021; Bosio et al., 2021; Pavia et al., 2022).

The most significant reason for this numerical disparity is that seagrass roots, leaves and pollens decompose easily. Thus, even if finding well-preserved fossil seagrasses is not impossible, these occurrences are rare (e.g., Brasier, 1975; Ivany et al., 1990; Hesse et al., 1999; Moissette et al., 2007; Bosio et al., 2021). Furthermore, the recognition of patchy seagrass meadow environments in the fossil record is even more limited (Zuschin and Hohenegger, 1998; Kusworo et al., 2015). The most ancient examples of well-preserved fossil marine plants are reported from the Upper Cretaceous of the Netherlands (Debey, 1848, 1851; Pomel, 1849; Voigt & Domke, 1955; Voigt, 1981), Japan (Koriba & Miki, 1931; Oishi, 1931), Germany (Hosius & Von der Marck, 1880), and USA (Dilcher, 2016). Few other examples are reported from the Cenozoic (e.g., Ivany et al., 1990, Van der Ham et al., 2007; Van der Ham et al., 2017). The most recent fossil seagrasses are reported from the Pleistocene of 1) the Kritika Member of the Rhodes Formation in Greece (Moissette et al., 2007), 2) the Arda River outcrops of Emilia-Romagna (Italy; Brunetti & Vecchi, 2005, 2012), 3) the Fauglia sand quarry of Tuscany (Italy; Bosio et al., 2021) and 4) the Stirone River outcrops near Parma and Piacenza (Italy; Raffi & Serpagli, 2003), which is the study site described in this paper.

Due to their scarce preservation potential, the recognition of paleo-seagrass meadows commonly relies on indirect evidence (Brasier, 1975; Eva, 1980; Langer, 1993; Domning, 2001; Beavington-Penney et al., 2004; Leonard-Pingel, 2005; Reuter et al., 2010; Vélez-Juarbe, 2014;

75  Reich, 2014; Reich et al., 2015b; Forsey, 2016; Mariani et al., 2022). Generally, these proxies are

76  either based on the presence and morphology of fossil organisms that are usually associated with

77  seagrasses (Brasier, 1975; Eva, 1980; Reuter et al., 2010) or on taphonomic and sedimentological

78  indicators considered as typical of seagrass-dominated environments. Reich et al. (2015b) defined

79  all these indicators as IPSIs (Indirect Palaeo-Seagrass Indicators) and critically reviewed them,

80  exploring their usefulness in detecting fossil seagrass-related environments, where plant remains are

81  no longer present. These IPSIs have been summarized in different categories, based on the different

82  criteria used to infer the presence of a palaeo-seagrass meadow: i) taxonomic groups, including

83  benthic foraminiferal assemblages (e.g., Betzler et al., 2000; Puga-Bernabéu et al., 2007; Mariani et

84  al., 2022), coralline red algae (e.g., Beavigton-Penney et al., 2004), hydroids (e.g., Hughes et al.,

85  1991), corals (e.g., Budd et al., 1996), bryozoans (e.g., Di Martino & Taylor, 2014), molluscs

86  (bivalve taxa such as Pinnidae and chemosymbiotic species, gastropods; e.g., Pérès & Picard, 1964;

87  Reich, 2014; Basso et al., 2015; Koskeridou et al., 2019; Bracchi et al., 2014, 2016, 2020; Pavia et

88  al., 2022), ostracods (e.g., Forsey, 2016), echinoderms (Ivany et al., 1990), fish otoliths (Green,

89  2002), dugongid remains (e.g., Vélez-Juarbe, 2014); ii) sedimentological features, such as grain size

90  and sorting, since in modern seagrass meadows sediments are poorly sorted and display an

91  abundant fine fraction (Fornos & Ahr, 1997), the presence of fining-upward sequences (Wanless,

92  1981), and the abundance of "constructive" micrite envelops (Perry, 1999); iii) taphonomic

93  features, including the taphonomic signature of skeletal remains (Leonard-Pingel, 2005; Reich et

94  al., 2014), the presence of root casts (Cramer & Hawkins, 2009) and root etchings on shells

95  (Parsons & Brett, 1991); iv) geochemical features, such as the carbon isotopic signal of mollusc

96  shells (Reich et al., 2015a), and molecular seagrass biomarkers (e.g., De Leeuw et al., 1995).

97      Regarding the IPSIs based on taxonomic groups, many of them are related to epiphytic

98  carbonate producers, i.e., those organisms that present a mineralized skeleton and grow on a phytal

99  substrate (Mazzella et al., 1989; Langer, 1993; De Falco et al., 2008; Mateu-Vicens et al., 2014;

100 Brandano et al., 2016). The main carbonate-producing biota associated with seagrass meadows are

foraminifera and calcareous algae, thus allowing to name "GA-Foralgal" or "RA-Foralgal"

(depending on the abundance of green or red calcareous algae) the typical seagrass-related

carbonate factories, also including other skeletal components such as molluscs and bryozoans

(Brandano et al., 2019).

Foraminiferal abundance within seagrass meadows has been widely studied by different

authors (e.g., Den Hartog, 1979; Langer, 1993; Mateu-Vicens et al., 2014). Foraminifera have the

advantage of being globally distributed and are usually abundant also in small samples (e.g.,

Murray, 2006). Furthermore, foraminifera have short reproductive cycles (Murray, 1991) making

them useful to track environmental changes over short periods of time (Hallock et al., 2003;

Pergent-Martini et al., 2005). Although foraminifera represent only a part of the trophic niches and

guilds of an environment (Barras et al., 2013), their ecological diversification is large enough to

obtain reliable reconstructions (e.g., Murray, 2006; Jorissen et al., 2007). Thus, benthic foraminifera

present an extraordinary potential as (palaeo)ecological proxies (e.g., Murray, 2006; Benedetti &

Frezza, 2016).

According to Langer (1993) and Mateu-Vicens et al. (2014), the analysis of epiphytic

benthic foraminifera for palaeoecological purposes can be based on ecomorphological

characteristics, overcoming problems related to the taxonomic identification at species level.

Epiphytic foraminifera have been divided into five different groups based on: i) type of motility; ii)

life span; iii) feeding mode; and iv) test morphology and structure. More recently, following the

classification provided by Langer (1993), Mateu-Vicens et al. (2014) established five

ecomorphological groups (morphotypes) to analyse epiphytic benthic foraminifera (Fig. 1): A*)

long-lived (> 10 months) sessile species, permanently attached to the substrate (e.g., *Planorbulina*

*mediterranensis*, *Nubecularia lucifuga*); SB) symbiont-bearing long-lived (> 10 months) taxa (e.g.,

*Amphistegina, Peneroplis, Sorites*); B) short-lived (3-5 months), generally motile, taxa that

temporarily attach their tests to the substrate using organic materials (e.g., *Ammonia*, Cibicididae,

Rosalinidae); C) motile, short-lived, suspension-feeding foraminifera (e.g., keeled elphidiids,

127 *Astrononion*, *Cribroelphidium*); D*) short-lived (< 4 months), permanently motile, grazing

128 foraminifera, such as opportunistic species with porcelaneous or agglutinated test that live within

129 rhizomes and sediment particles (e.g., small miliolids, textulariids). Based on this, several authors

130 used foraminiferal associations as indirect indicators of palaeo-seagrass meadows in the geological

131 record (e.g., Colom, 1942; Blanc-Vernet, 1969; Mateu, 1970; Brasier, 1975; Blanc-Vernet et al.,

132 1979; Langer, 1993; Ribes et al., 2000; Beavington-Penney at al., 2004; Mateu-Vicens et al., 2010,

133 2012, 2014; Frezza et al., 2011; Tommasetti et al., 2016; Coletti et al., 2021; Baceta et al., 2021;

134 Mariani et al., 2022).

135       This paper analyses the benthic foraminiferal associations of a Pleistocene succession

136 exposed along the Stirone River, in the province of Parma (Northern Italy). As reported in literature,

137 these deposits host rare but well-preserved seagrass rhizomes (Raffi & Serpagli, 2003) and common

138 seagrass remains (Bracchi et al., 2020). Furthermore, the occurrence of several specimens of the

139 bivalve *Pinna nobilis* in life position further supports the presence of a palaeo-seagrass meadow, or

140 at least of a vegetated substrate (Bracchi et al., 2020). The aim of this paper is thus to describe

141 quantitatively and qualitatively the foraminiferal assemblages of these deposits and to test them as

142 valuable IPSI, with indices that can be applied in settings where seagrass remains are no longer

143 preserved.

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## 2. Geological setting

146 The studied outcrop is located along the Stirone River, near the village of San Nicomede, between

147 the provinces of Piacenza and Parma (44°50'38.53"N, 9°59'2.52"E) (Fig. 2). The Stirone River

148 carves its way through a continuous upper Miocene (Messinian) to Pleistocene succession (Papani

149 & Pelosio, 1962; Pelosio & Raffi, 1974; Mary et al., 1993; Channell et al., 1994; Pervesler et al.,

150 2011; Gunderson et al., 2012). In the studied locality, easily accessible and well-exposed deposits

151 crop out for about 100 m along the riverbanks. These deposits belong to the Castell'Arquato Basin

152 (CAB),a small wedge-top basin developed since the upper Miocene (Messinian) above the Northern

Appennines orogenic wedge (Roveri & Taviani, 2003; Pervesler et al., 2011; Ghielmi, 2013; Cau et al., 2015). After the Messinian salinity crisis, the newly restored marine conditions resulted in the deposition of deep marine sediments in the CAB (Ceregato et al., 2007; Calabrese & Di Dio, 2009). These deposits constitute the basal part of the succession. During the Pliocene and the Pleistocene, the depositional environment experienced a general regressive trend, from epibathyal to shelfal conditions (Gunderson et al., 2012; Coletti et al., 2018). Before the end of the early Pleistocene, this shallowing upward trend culminated in the deposition of continental deposits (Cigala Fulgosi, 1976; Pelosio & Raffi, 1977; Ciangherotti et al., 1997; Esu, 2008; Esu & Girotti, 2015). Several authors interpreted the general late Cenozoic depositional environment of the Stirone River as a fluviodeltaic system within a tectonically active basin, dominated by fluvial floods and related hyperpycnal flows (Mutti et al., 1996, 2003; Martini et al., 2002), as it is typical for structurally confined basins characterised by phases of advancement and retreats of fan-delta systems (Einsele, 2000).

The deposits analysed in this paper belong to two of the lithozones identified by Crippa et al. (2019) along the Stirone River succession (Fig. 2, 3): i) the upper part of Lithozone 2, which consists of silty sands organized in metre-thick beds and heavily bioturbated sand-infilled and cemented *Thalassinoides* burrows, and ii) Lithozone 3, which consists of grey sandy to muddy sediments with Pinnidae specimens in life position (Dominici, 2001), corresponding to the *Pinna* biofacies described by Bracchi et al. (2020). More precisely, the section investigated in this paper corresponds to the 56-77 m interval of Crippa et al. (2019). This interval has been dated to the Calabrian (Early Pleistocene) (Crippa et al., 2019), based on nannofossils (zone CNPL7; Backman et al. 2012), foraminifera (*Globigerina cariacoensis* zone; Cita et al., 2012 and references therein), and magnetostratigraphy (Gunderson et al., 2012; Monesi et al., 2016).

## 3. Materials and methods

## 3.1 Field work

The Stirone deposits were investigated by describing lithology, macrofossils distribution, and sedimentary structures. A stratigraphic section was measured at centimetre-scale with a Jacob's staff, characterizing bed thickness, dip and dip-direction (Fig. 4). A total of 12 samples were collected at different stratigraphic heights along the two Lithozones (Figs. 2, 3, 4), together with the samples collected for the analysis of molluscs carried out by Bracchi et al. (2020). Samples R1 and R2 were collected within the upper section of Lithozone 2 in the sediments surrounding *Thalassinoides* ichnofossils. Samples S1, S2, S3, S5, S6, S7, S8, S9, S10 and S12 were collected in Lithozone 3 in correspondence of Pinnidae specimens in life position (S3, S5, S6, S9, S12), alongside Pinnidae specimens not in life position (S2) and randomly within the sediments of the Pinnidae biofacies (S1, S7, S8, S10). All samples were obtained by collecting at least 20 g of sediment, after slightly digging inside the deposits to remove the weathered material on the surface.

## 3.2 Sediments and foraminiferal analysis

### 3.2.1 Granulometry and foraminiferal assemblages

Grain-size analyses were performed on each sample with a Malvern Mastersizer 2000E$^{\text{TM}}$ Laser granulometer at the Università degli Studi di Milano-Bicocca. Grain-size distribution and sedimentological parameters were analysed through the software GRADISTAT Version 4.0 (Blott & Pye, 2001) (Table 1). For micropaleontological analyses, a small amount of each sample (Table 2) was weighted and treated with 30 % hydrogen peroxide to remove organic matter (Dimiza et al., 2016). Each sample was then wet-sieved through a 125-μm-sized mesh, in order to separate the fraction for the picking of benthic foraminifera. We decided to identify benthic foraminifera in the > 125 μm fraction to avoid counting juvenile forms, which are often abundant and difficult to identify (Malek et al., 2014). Before proceeding with the picking, the sieved fractions were oven-

202 dried at 40°, weighted and divided into equal fractions using a microsplitter, to obtain sub-samples

203 containing at least 300 specimens (Buzas, 1990; Murray, 1991; Murray, 2006; Lòpez-Belzunce,

204 2014). Handpicking was performed under a ZEISS Olympus SZ61 stereo microscope equipped with

205 a high-resolution camera. We relied on Foraminiferi Padani (Agip S.p.A., 1982), Loeblich and

206 Tappan (1988), Cimerman and Langer (1991), Langer and Schmidt-Sinns (2006), Milker and

207 Schmiedl (2012), the Foraminifera.eu-Project (Hesemann, 2020), and the World Register of Marine

208 Species (WoRMS Editorial Board, 2021) for the taxonomic identification of foraminifera. SEM

209 imaging of epiphytic foraminifera was performed using a FEG (SEM-FEG) Gemini 500 Zeiss

210 scanning electron microscope at the Università degli Studi di Milano-Bicocca. For each sample, all

211 foraminifera identified and relative counts are provided in the supplementary materials (Appendix

212 1), and the following parameters were calculated: i) the standardized abundance of benthic

213 foraminifera (n/100 g of sediment), ii) the relative abundance (%) of each species, and iii) the ratio

214 between broken and total number of tests.

215        A Q-mode cluster analysis of species abundances across the samples, based on the Bray-

216 Curtis similarity index, was performed with the software Primer v.6. No data transformation was

217 applied.

218        **3.2.2 Environmental indices**

219 Epiphytic foraminiferal species were assigned to the different morphotypes (A* to D*) proposed by

220 Langer (1993) and Mateu-Vicens et al. (2014). The abundance of each morphotype was calculated

221 for each sample through the Index$_{EP}$ i.e., the ratio between the number of epiphytic and total benthic

222 foraminifera (Mateu-Vicens et al., 2014).

223        Two indices, created for the analysis of modern environments, were tested on the

224 foraminiferal fossil assemblage:

225        i) the modified FORAM Index (FI') developed by Mateu-Vicens et al. (2014) based on

226 Hallock et al. (2003) FORAM Index. FI' is expressed as:

227 $$FI' = 10 \times (P_{A^*} + P_{SB}) \times P_{D^*} + 2 \times (P_B + P_C),$$

228    where $P_{A*}$, $P_{SB}$, $P_B$, $P_C$, and $P_{D*}$ indicate the relative abundance of the foraminifera morphotypes.

229    Values of FI' >4 indicate optimal environmental conditions, whereas values of FI' <2 are indicative

230    of stressed conditions (Mateu-Vicens et al., 2014);

231         ii) the "long vs. short life-span" index ($I_{LS}$) developed by Mateu-Vicens et al. (2014). $I_{LS}$,

232    which consists of the ratio between longer-living and short-living forms, was built to highlight the

233    differences between well-preserved and stressed *Posidonia oceanica* meadows (Mateu-Vicens et

234    al., 2014) and is expressed as:

235    $$I_{LS} = (3.5 \times (P_{A*} + P_{SB}) + 0.01)/(P_{D*}+0.01)$$

236    $I_{LS}$ values range between 0 and 36. If D* is the dominant morphotype, the index is close to 0; if the

237    dominant morphotypes are A* and SB, the index points towards 36.

238         The K/$R_{EXT}$ index from Mariani et al. (2022) was also calculated in each sample. It consists

239    of the ratio between keeled *Elphidium* and the sum of rounded elphidiids (e.g., *Cribroelphidium*,

240    *Porosononion*), and other related genera that display a rounded periphery (i.e., *Astrononion*,

241    *Haynesina, Melonis, Nonion, Nonionella, Pullenia, Valvulineria*). Values of K/$R_{EXT}$ > 0.4 point to

242    the presence of vegetated substrate nearby. In this work, to facilitate the definition of this index, we

243    introduce two new morphotypes, namely K and R, useful for the K/R analysis (Fig. 1). Morphotype

244    K is constituted by epiphytic keeled *Elphidium*, whereas morphotype R includes the group of

245    generally infaunal foraminifera that display a rounded periphery. This classification does not

246    overlap with the epiphytic morphotypes from Langer (1993) and Mateu-Vicens et al. (2014). Thus,

247    specimens belonging to morphotype C can be either placed into morphotype K or R.

248         Statistical analyses were performed with the software RStudio (RStudio Team, 2020). In

249    particular, a bivariate statistical analysis was performed considering the relationship between

250    K/$R_{EXT}$ and morphotype A* abundance, taking into account all the samples from Stirone and the

251    samples from the Fauglia site, described by Mariani et al. (2022). The correlation between the two

252    variables has been tested and a correlation coefficient was calculated. Only one sample from the

253    latter site (P11) was excluded from the analysis, as an outlier.

254

## 4. Results

### 4.1 Field observation and stratigraphic section

The measured stratigraphic section consists of a 20-m-thick mixed carbonate-siliciclastic succession (Fig. 4). The base of the succession consists of 2 meters of slightly NE dipping (with an average attitude of 042/18), fine sandy to coarse silty deposits. These deposits, which belong to Lithozone 2 of Crippa et al. (2019), can be divided into a 1.5-m-thick poorly consolidated layer, followed upward by a 0.5-m-thick cemented layer. The different cementation of the two layers is deeply enhanced by erosion (Fig. 4). Both layers are intensely bioturbated by *Thalassinoides*. Within this lithozone, macrofossils are scarce and consist solely of shells of the mollusc *Aequipecten opercularis*. In the present work, we will refer to these deposits as the *Thalassinoides* biofacies. Upwards, the stratigraphic section continues with a 19-m-thick, slightly N to NNE dipping (with an average attitude of 005/20), massive to laminated, very fine sandy to coarse silty deposits. These layers, which belong to the Lithozone 3 of Crippa et al. (2019), are mostly characterized by poorly cemented sediments, except for a 1-m-thick interval located at about 7.5 m from the base of this facies (approximately 9.5 m from the base of the entire section), which consists of two well cemented layers separated by a very thin and poorly cemented interval. The different cementation of the strata is once again enhanced by the erosion. Within Lithozone 3 macrofossils are common, easily recognizable, and mainly consist of molluscs (Dominici, 2001; Bracchi et al., 2020), solitary scleractinians, bryozoans, echinoids and fragments of red calcareous algae. *Pinna nobilis* specimens in life position were recorded (Fig. 3, 4; *Pinna* biofacies). The measured section ends with a well-cemented biocalcarenite layer.

### 4.2 Foraminiferal analysis and skeletal assemblage

The associate sediments display noticeable differences between the samples from the two facies. In the *Thalassinoides* biofacies, the bioclastic fraction is scarce, mainly constituted by planktic

foraminifera, while terrigenous grains (e.g., quartz) dominate the deposit. In the *Pinna* biofacies the

bioclastic fraction (mainly consisting of benthic foraminifera, molluscs, ostracods and echinoderms

associated with rare erect bryozoans fragments and planktic foraminifera) is more relevant. Plant

remains are also common in this biofacies.

In the analysed samples, we identified i) 83 species of hyaline benthic foraminifera, ii) 4

genera of agglutinated foraminifera and iii) 7 genera of miliolids (Figs. 5, 6). Hyaline benthic

foraminifera were identified at species level and selected species were clustered in different  groups

to perform statistical analyses (Table 3, 4). Agglutinated foraminifera (*Bannerella gibbosa*, *Sahulia*

spp., *Spiroplectinella* spp., *Textularia* spp.) were counted as a single group. Miliolids (*Adelosina*

spp., *Cycloforina* spp., *Miliolinella* spp., *Quinqueloculina* spp., *Siphonaperta* spp., *Spiroloculina*

spp., *Triloculina* spp.) were also clustered as a single group. All other species identified are reported

in the supplementary material (Appendix 1).

The standardised abundance of benthic foraminifera presents the lowest values within the

*Thalassinoides* biofacies (samples R1 and R2) with an average value of 16.858 specimens/100 g of

sediment, whereas in the *Pinna* biofacies the values are one order of magnitude higher, with an

average value of 134.466 specimens per 100 g of sediment. The abundance of broken tests shows

no significant difference among the samples.

The average abundances of the species (Table 3) in the *Thalassinoides* and *Pinna* biofacies

were used to calculate the similarity matrix and to plot the corresponding dendrogram (Fig. 7). Two

main sample groups are separated at 55% similarity. The first group corresponds to

the *Thalassinoides* biofacies, and includes *A. beccarii*, *A. parkinsoniana*, *B.*

*spathulata*, *Buccella* aff. *frigida*, *C. carinata*, *C. refulgens*, *C. pachyderma*, *E. translucens*, *G.*

*subglobosa*, *N. boueanum* and *N. terquemi* as the most common taxa.

The second group of samples corresponds to the *Pinna* biofacies, and is characterized by

the presence of *Planorbulina mediterranensis*, *C. carinata*, *C. refulgens*, *N. terquemi* (with a much

higher abundance than in the *Thalassinoides* facies), and miliolids (except for samples S2, S3 and

S7). Further subdivisions (Fig. 7) are based on the abundance of certain species in particular samples. For instance, S5, S6 and S8 contain frequent *Asterigerinata mamilla*; S1 and S12 are characterized by *L. lobatula*; S2 and S3 form a group with locally frequent *A. beccarii* and *B. spathulata*, *B. elongata*, *C. pachyderma*, *G. subglobosa*, *N. boueanum*, and scarce small miliolids.

Within the *Thalassinoides* biofacies, the ammoniid group and the Bolivinidae are present with higher abundances (8.7%). Buliminidae display low values in both *Thalassinoides* and *Pinna* biofacies, whereas Cassidulinidae are abundant in both the biofacies (around 8%). Cibicididae constitute nearly 20% of the assemblage in both biofacies and are slightly more abundant within the *Thalassinoides* biofacies. Within Cibicididae, *L. lobatula* is slightly more abundant in the *Pinna* biofacies. The group of keeled *Elphidium* (morphotype K) is abundant in both facies, presenting a slightly higher value in the *Pinna* biofacies (7.4%) compared to the *Thalassinoides* biofacies (5.9%). Rosalinidae are much more abundant in the *Pinna* biofacies (18.6%). The rounded periphery group (morphotype R) is highly common within the *Thalassinoides* biofacies (22.1%). Uvigerinidae are rare in both levels. Agglutinated foraminifera are mostly not abundant but are slightly more common in the *Pinna* (3.7%) than in the *Thalassinoides* biofacies (2.5%). Miliolids are abundant in the *Pinna* biofacies (9.1%) and scarce in the *Thalassinoides* biofacies (0.8%).

Epiphytic foraminifera were assigned to different morphotypes of Mateu-Vicens et al. (2010, 2014) (Table 4). Morphotype A* only contains *P. mediterranensis* and consequently its abundance is equal to the abundance of this species, which is absent in the *Thalassinoides* biofacies and present in every sample of the *Pinna* biofacies (but its abundance is low: 1.1%). No specimens belonging to morphotype SB have been observed. Morphotype B (*Ammonia* group, *A. mamilla*, *Aubignyna perlucida*, *B.* aff. *frigida*, Cibicididae, *Discorbinella bertheloti*, *Eponides repandus*, *Hanzawaia boueana*, Rosalinidae) are equally common in both biofacies, with values around 44%. Morphotype C (*A. stelligerum*, *Cribroelphidium* sp., keeled *Elphidium* group) is slightly more abundant in the *Pinna* biofacies (7.7%) compared to the *Thalassinoides* biofacies (5.9%). Morphotype D* (agglutinated foraminifera and miliolids) is much more abundant in the *Pinna*

biofacies (12.8%), and rather scarce in the *Thalassinoides* one (3.4%). $Index_{EP}$ is higher for the *Pinna* biofacies, with an average value of 0.66, compared to the 0.53 of the *Thalassinoides* biofacies.

FI' display the lowest values in sample R1 and R2 (*Thalassinoides* biofacies), with an average of 1.02, whereas the average value for the *Pinna* biofacies is slightly higher (1.27). $I_{LS}$ index shows very low values in all samples, without clear trends.

$K/R_{EXT}$ presents higher values in the samples from the *Pinna* biofacies (average of 0.91), and distinctly lower values in the *Thalassinoides* biofacies (average of 0.27).

The bivariate statistical model, considering the relationship between $K/R_{EXT}$ and morphotype A* abundance, display a mild-strength linear correlation. Pearson and Spearman correlations are 0.54 and 0.53, respectively. $R^2$ display a statistically significant value of 0.29.

## 5. Discussion

### 5.1 Foraminiferal assemblages in a seagrass-related palaeoenvironment

The preservation of seagrass remains within the fossil record is extremely rare and mainly related to processes such as silicification or rapid burial by fine-grained sediments (e.g., Ivany et al., 1990; Moisette et al., 2007; Van der Ham et al., 2007; Reich et al., 2015; Dilcher, 2016; Van der Ham et al., 2017; Bosio et al., 2021). On the other hand, seagrass related carbonate producing-organisms have a much higher fossilization potential. In the Stirone area, the presence of a palaeo-meadow is indicated by both direct (seagrass rhizomes reported by Raffi & Serpagli, 2003) and indirect observations (*Pinna nobilis* in life position reported by Bracchi et al., 2020). *P. nobilis* is a large endemic bivalve of the Mediterranean, occurring between 0 and 60 m of water depth and commonly associated with *Posidonia oceanica* and *Cymodocea nodosa* meadows (Pérès & Picard, 1964; Gòmez-Alba, 1988; Lemer et al., 2014; Basso et al., 2015). Although due to its fragile shell this mollusc displays a relatively low preservation potential compared to other bivalves (Beesley et al., 1998), its occurrence in life position has been used as an IPSI (Reuter & Piller, 2011; Reuter et al.,

358     2012; Reich et al., 2015b; Tomassetti et al., 2022). The *Pinna* biofacies of the Stirone River

359     displays many *P. nobilis* specimens in life position and includes large amounts of tiny plant

360     frustules. Based on these features and the molluscan assemblage of the facies, Bracchi et al. (2020)

361     suggest the presence of a vegetated substrate, possibly *Cymodocea* meadow (although the

362     occurrence of a patchy meadow with both plants cannot be excluded). Overall, the

363     palaeoenvironmental reconstruction of the *Pinna* biofacies of the Stirone River suggests a shallow

364     (less than 15 m) infralittoral seafloor, colonised by marine phanerogams, and characterised by

365     periods of high terrigenous influx (Bracchi et al., 2020). Sedimentological evidence, especially

366     grain size, suggest that the *Thalassinoides* biofacies also represents an infralittoral environment,

367     even if bioturbation has obliterated most sedimentary structures (Crippa et al., 2019).

368     *Thalassinoides* is a system of horizontal, unlined, cylindrical burrows possibly joined by vertical or

369     oblique shafts (Pervesler et al., 2011), generally produced by crustaceans in shallow water settings

370     (Curran & Frey, 1977; Belt et al., 1983; Ekdale et al., 1984; Frey et al., 1984; Kamola, 1984; Miller

371     & Knox, 1985; Myrow, 1995; Pervesler & Uchman, 2009; De Araújo et al., 2021). Although not

372     limited to shallow water settings (e.g., Crimes, 1977; Link & Bottjer, 1982; Ekdale & Bromley,

373     1984), *Thalassinoides* burrows are commonly reported in intertidal-subtidal deposits characterised

374     by fine-grained sediments like those of the Stirone River (Table 1; Fig. 3), thus supporting the

375     shallow-water interpretation of this biofacies. The benthic foraminiferal associations of the two

376     studied facies is consistent with the interpretation based on molluscs (Bracchi et al., 2020) and

377     ichnofacies (Pervesler et al., 2011), thus confirming that the analysed Stirone section displays a

378     slightly deepening-upward sequence (Crippa et al., 2019). High abundances of the foraminifera of

379     the *Ammonia* group and associated taxa (e.g., *Buccella*) support this interpretation for the

380     *Thalassinoides* biofacies, while the higher biodiversity associated to *Pinna* biofacies is consistent

381     with a seagrass-related environment.

382         Q-mode cluster analysis (Fig. 7) allows to recognise two groups corresponding to the two

383     biofacies (*Thalassinoides* and *Pinna*) and to the lithozones described by Crippa et al. (2019).

*Thalassinoides* biofacies is dominated by foraminiferal taxa grouped in low-oxygen foraminiferal

assemblages (LOFA; Bernhard & Sen Gupta, 1999), which is consistent with high riverine

terrigenous and nutrient input. The assemblage of the *Pinna* biofacies is instead representative of a

seagrass environment, based on the presence of *P. mediterranensis* and the abundance of small

epiphytic foraminifera (*Planorbulinatum mediterranensae* sensu Colom, 1942). Moreover, several

sub-biofacies can be distinguished based on differences in the foraminiferal assemblages, mostly

referring to the small miliolids and LOFA taxa. In particular, very abundant LOFA and scarce

miliolids (samples S2 and S3) might indicate punctual episodes of high riverine influence or,

alternatively, they may represent transitional settings between the terrigenous-dominated and the

well-developed seagrass environments.

Index$_{EP}$ displays higher average values within the *Pinna* biofacies as compared to the

*Thalassinoides* biofacies (average value of 0.66 for the former and 0.53 for the latter; Table 2). This

means that almost 70% of the species within the *Pinna* biofacies might have lived on a phytal

substrate, compared to the 50% of potential epiphytes of the *Thalassinoides* facies. If *Ammonia* spp.

(and related genera such as *Aubignyna* and *Buccella*) are excluded from the epiphytic association,

since they are not exclusive of seagrass meadows, the difference is enhanced (0.39 of the

*Thalassinoides* biofacies vs. 0.62 of the *Pinna* biofacies). Although *Ammonia* is often reported to be

present within vegetated seafloors, especially in those characterised by a high content of organic

matter (Frezza et al., 2011; Mateu-Vicens et al., 2014), this genus can populate a wide range of

coastal, shallow-water environments (Murray, 2006). Nonetheless, here we have considered

*Ammonia* group as part of the epiphytic taxa, following different authors (e.g., Mateu-Vicens et al.,

2014; Mariani et al., 2022), in order to facilitate comparisons with other sites.

In modern environments, epiphytic photosymbiotic foraminifera (morphotype SB, e.g.,

*Amphistegina*, *Peneroplis*, *Sorites*) are indicative of shallow, well-illuminated environments and are

usually, but not always, associated to flat, long-lasting, vegetated substrates (Langer, 1993; Murray,

2006; Mateu-Vicens et al., 2014; Reich et al., 2015). *Peneroplis* can be found on seagrass rhizomes

and leaves (Hohenegger, 1994; Renema, 2006), but also on algal and sandy substrates (Hohenegger, 1994). Similarly, *Amphistegina* can be very abundant within seagrass meadows (Riordan et al., 2012), but its distribution is not exclusively related to the presence of a vegetated substrate. Both peneroplids and soritids are limited by the 14°C (or even colder) isotherm (Langer & Hottinger, 2000; Beavington-Penney & Racey, 2004; Murray, 2006), while *Amphistegina* is limited by the 14°C winter isotherm (Langer et al., 2012; El Kateb et al., 2018). Therefore, although the presence of morphotype SB foraminifera in the fossil record may be indicative for vegetated habitats (e.g., *Orbitolites* in the Eocene; Beavingotn-Penney et al., 2006; Tomassetti et al., 2016; Coletti et al., 2021), their absence is not necessarily evidence for the lack of phytal substrates. For the Stirone *Pinna* biofacies, the lack of this group is definitively more likely related to the cold climate of the early Pleistocene (Prista et al., 2015).

Morphotyope A*, represented here by *P. mediterranensis* only, is one of the most reliable IPSIs (Mariani et al., 2022) and a useful indicator to distinguish between palaeo-seagrass meadows and other phytal substrates (e.g., macroalgae; Mateu-Vicens et al., 2010). Indeed, *P. mediterranensis* is present in every samples from the *Pinna* biofacies, whereas in the *Thalassinoides* biofaces it is absent (Table 3, 5; Fig. 8). Morphotype B* dominates in both biofacies, constituting about 45% of the entire epiphytic assemblage (Fig. 8; Table 5). According to Murray (2006) and Benedetti and Frezza (2016), morphotype B* usually constitutes 25-85% of vegetated seafloor assemblages (both seagrass and algae), suggesting its dependence on the presence of a vegetated substrate. However, its large frequency within the *Thalassinoides* biofacies indicates that its abundance cannot be solely related to the presence of seagrasses. Some species that belong to morphotype B are not directly related to a phytal substrate but can colonize a large variety of environments (e.g., *Ammonia*, *Buccella*), whereas other species, such as *Lobatula lobatula,* are generally more linked to marine vegetation (Jorissen et al., 1995), even if nowadays it is commonly found in almost vegetation-free environments in colder climates (e.g., Hald & Korsun, 1997). Also, Rosalinidae (e.g., *Rosalina* spp., *Neoconorbina terquemi*) and Asterigerinidae (*Asterigerinata*

*mamilla*), are generally linked to vegetated sea-bottoms (Langer, 1988; Panieri et al., 2005; Frezza & Carboni, 2009). In our case, both Rosalinidae and *A. mamilla* are much more abundant within the *Pinna* biofacies (Table 3, 5). Morphotype C is slightly more abundant in the *Pinna* biofacies, but it also includes motile suspension feeders that are not strictly epiphytic taxa (Fig. 8; Table 4, 5). Murray (1991) suggested that elphidiids can range from epifaunal to infaunal, with elphidiids with an acute periphery, such as *Elphidium crispum* or *Elphidium aculeatum*, generally linked to phytal substrates (e.g., Langer, 1993; Mateu-Vicens et al., 2014), as this test shape seems to facilitate their motility on algae and plants. On the other hand, elphidiids with rounded periphery and other genera such as *Astrononion* or *Cribroelphidium* are not solely epiphytes but can conduct an infaunal mode of life. Morphotype D* is constituted by stress-tolerant taxa with a short life-span, such as small miliolids and agglutinated foraminifera (Langer, 1993). These species could be adapted to nutrient-rich environments, such as seagrass rhizomes (Mateu-Vicens et al., 2014). In the Stirone River, samples from the *Pinna* biofacies display a larger abundance of morphotype D* specimens, especially miliolids (Fig. 8; Table 5). Miliolids are in general very abundant in shallow water seagrass meadows (Frezza et al., 2011), but not exclusively. Moreover, their abundance must be carefully considered because, they are strongly affected by diagenetic processes due to their high-Mg-calcite tests (Budd & Hiatt, 1993).

The FI' index is based on the abundance of epiphytic foraminifera and has been successfully implemented in the modern Mediterranean Sea as a proxy of water quality (e.g., El Kateb et al., 2020; Khokhlova et al., 2022). This index presents low values in both biofacies and display only a minor difference between the samples of the *Thalassinoides* and *Pinna* biofacies (Table 2). As suggested by Mariani et al. (2022), the application of FI' to fossil context might be hindered by diagenesis (e.g., the preferential dissolution of miliolids). Similarly, $I_{LS}$ (which is used to assess the ecological status of modern seagrass meadows) displays no significant differences between the samples of the two biofacies. Overall, the use of FI' and $I_{LS}$ alone is not recommended as an IPSI but can be helpful for the palaeoenvironmental reconstruction of the seagrass-related deposits.

Actually, their low values in the Stirone River deposits might suggest that the local palaeo-seagrass were growing under stressed conditions. The presence of mud-loving, deeper water, opportunistic foraminifera (e.g., *Bolivina*, *Bulimina*, Cassidulinidae), could be related to episodic pulses of fluvial discharge which are considered an important factor in the evolution of the Stirone environment by both Crippa et al. (2019) and Bracchi et al. (2020). Although some of these foraminiferal taxa are very common in cold climates (and thus their abundance could be related to the cold climate of the Calabrian), the overall distribution of *Ammonia* group and infaunal taxa (e.g., Bolivinidae, Buliminidae, Cassidulinidae, morphotype R foraminifera) within the Stirone River sediments could be also connected to river-related organic-matter input and not solely to seagrass distribution.

K/R$_{EXT}$ index confirms to be one of the most significant tools to perform this kind of palaeoenvironmental reconstructions, and its use as IPSI can be considered very important (Mariani et al., 2022). Indeed, in the seagrass-related palaeoenvironment (*Pinna* biofacies), K/R$_{EXT}$ displays remarkably higher values than in the *Thalassinoides* biofacies (Table 2).


**5.2 Comparison with a similar study site: the case of Fauglia**

To enhance the observations collected within the Stirone river deposits and strengthen the application of benthic foraminifera as IPSIs, in this section we compare the results from this case study with the fossil *P. oceanica* meadow of Fauglia (Tuscany, Italy). Both the successions belong to the Calabrian (lower Pleistocene) and are located at relatively close latitude, thus excluding large differences in climate. The Fauglia succession formed in a shallow, low- to moderate-energy, marine environment, as indicated by the presence of in situ *P. oceanica* rhizomes*, a *Cladocora caespitosa* bank, an oyster reef and abundant foraminifera of the *Ammonia* group (Bosio et al., 2021; Mariani et al., 2022). As for the Stirone River deposits, Fauglia benthic foraminiferal associations were analysed inside different deposits: within *Posidonia*-bearing layers and in a *C. caespitosa* bank.

487      Based on the morphotypes analysis, morphotype B is the most abundant group in both sites.

488    In particular, Cibicididae and Rosalinidae are the most abundant families in both the palaeo-

489    meadows deposits. In Fauglia, Cibicididae display a higher frequency in the seagrass-related

490    intervals, whereas in the *Cladocora* bank their abundance is much lower. On the other hand, in the

491    Stirone outcrop, Cibicididae are similarly distributed between vegetated and non-vegetated settings.

492    In both sites, Rosalinidae displays higher abundance in the seagrass-related deposits, indicating

493    Rosalinidae as one of the most clearly seagrass-related family. In both successions, morphotype A*

494    foraminifera only occur in seagrass-related deposits, thus indicating the presence of morphotype A*

495    foraminifera as a highly reliable IPSI. Also, the presence of foraminifera with a curved basal

496    surface, such as Cibicididae and *P. mediterranensis* specimens, indicates that possibly they lived

497    attached onto a firm substrate, which most likely consisted of seagrass leaves and rhizomes (Langer

498    et al., 1993). Anyway, this feature is not undoubtedly diagnostic of a phytal substrate, as small

499    benthic foraminifera could develop a curved attachment surface even in correspondence of non-

500    phytal substrate (Mariani et al., 2022). Morphotype C abundance is similar in both the study sites.

501    In both sites morphotype K taxa are more common in seagrass related deposits, while morphotype

502    R foraminifera are much more common in the layers that are not associated with seagrasses. This

503    clearly testifies in favour of the usefulness of the $K/R_{EXT}$ index as indirect indicator of the presence

504    of a palaeo-seagrass meadow. Although other tests based on recent foraminiferal assemblages

505    would be necessary, considering the data collected in this paper and in the study of the

506    exceptionally well-preserved Pleistocene seagrass meadow of Fauglia (Bosio et al., 2021; Mariani

507    et al., 2022), values of $K/R_{EXT}$ higher than 0.4 could be used as an indirect indicator of a seagrass-

508    related palaeoenvironment (Table 2; Fig. 8). Indeed, in every samples collected within the seagrass-

509    related layers the value of this index is higher than 0.4, whereas in the other samples is always

510    lower than this threshold.

511     The preferential dissolution of miliolids observed in Fauglia (Mariani et al., 2022) further

512    suggests evaluating Morphotype D* with caution. Indeed, miliolids and agglutinated foraminifera

are more influenced by diagenesis than foraminifera with hyaline, pure calcite tests. However, this is not the case of the Stirone deposits, in which morphotype D* are well-preserved in all the samples and evidence of dissolution processes are not shown.

If we do not consider miliolids, the morphotype abundances are similar in both study sites (Fig. 8), testifying that excluding the taxa that are mostly affected by diagenesis could be useful to identify fossil seagrass meadows.

Finally, the higher abundance of foraminifera of the *Ammonia* group suggests that the Fauglia *Posidonia* meadow probably developed closer to the coastline than the Stirone River palaeo-seagrass meadow.


**5.3 The usefulness of K/R$_{EXT}$ index: insights and perspectives**

Based on the evidence from known paleo-seagrass settings, such as those documented at the Fauglia and Stirone outcrops, the K/R$_{EXT}$ index and the abundance of Morphotype A* foraminifera appear as the most promising indicators of such palaeo-environment. Both indices are based on morphological characters, more than species identifications. This means that they could be easily calculated even in more ancient successions than Stirone or Fauglia, where lowest-level taxonomical identification can be difficult to perform. Most likely, they could be calculated also in thin sections. This approach would also allow for the comparison of widely different sites, because even if the taxa are different, morphotypes can be recognized and the morphotype analysis could still be carried out.

A bivariate statistical analysis was performed considering the relationship between K/R$_{EXT}$ and the abundance of morphotype A* among all of the samples from the Stirone river deposits and the Fauglia successions (Fig. 9), with the exception of sample P11 from Fauglia, which was excluded from the analysis due to the very pervasive diagenetic processes. This analysis shows that the values from the two sites are comparable and that there is a weak positive correlation between the value of K/R$_{EXT}$ and the abundance of permanently attached foraminifera (Fig. 9). However, the

occurrence of morphotype A* taxa is always indicative of fossil seagrass meadows, independently

from its abundance. This model will be integrated in future with new data that will be collected

from different fossil and modern foraminiferal associations, both in seagrass-related environments

and in environments with no phytal substrate.


## 6. Conclusion

Benthic foraminifera were analysed from two different shallow water paleo-settings outcropping

along the Stirone River. In particular, our results on the foraminifera confirm the occurrence of a

vegetated marine palaeoenvironment in correspondence of the *Pinna* biofacies accordingly to

Bracchi et al. (2020). On the other hand, the *Thalassinoides* facies represents a palaeoenvironment

devoid of seagrass.

The morphotype analysis of benthic foraminifera confirmed their effective application as

Indirect Palaeo-Seagrass Indicators (IPSIs), as demonstrated from a similar vegetated palaeo-setting

at Fauglia (Mariani et al., 2022). In particular:

i) when we exclude the taxa that are mostly affected by diagenesis (e.g., miliolids), it is

possible to reproduce comparable signals in different fossil seagrass meadows.

ii) the lack of photosymbiotic foraminifera (e.g., *Amphistegina, Sorites, Peneroplis*), was

most likely related to the low early Pleistocene temperatures in this area, which did not allow the

development of these species.

iii) the presence of permanently attached, encrusting foraminifera, confirmed as one of the

most reliable IPSI, as well as the abundance of Rosalinidae.

iv) among the tested indexes, the $K/R_{EXT}$ proved to be the most reliable in this kind of

analysis, displaying values higher than 0.4 when calculated within seagrass-related environments.

Further analyses are required in order to improve the $K/R_{EXT}$ index, making it comparable

between different successions in terms of spatial and time distribution.

**Author contributions**

**Luca Mariani:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – Original Draft, Visualization, Supervision, Project administration. **Giovanni Coletti:** Conceptualization, Resources, Writing – Review & Editing. **Giulia Bosio:** Formal analysis, Investigation, Data Curation. **Claudia Tentorio:** Investigation. **Guillem Mateu Vicens:** Formal analysis, Supervision, Writing – Review & Editing. **Valentina Alice Bracchi:** Writing – Review & Editing. **Daniela Basso:** Writing – Review & Editing. **Elisa Malinverno:** Resources, Writing – Review & Editing, Project administration, Funding acquisition.

**Data availability**

Datasets related to this article can be found at https://board.unimib.it/datasets/hrgfj7xfgs, an open-source online data repository hosted at Mendeley Data (Mariani et al., 2022).

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Figures**

**Fig. 1** Epiphytic benthic foraminifera morphotype categories, modified from Langer et al. (1993)
and Mateu-Vicens et al. (2014). Morphotype categories for the K/R analysis (Mariani et al., 2022)
are also present.

**Fig. 2** A. Simplified geologic map of the analysed area. It is possible to appreciate the Stirone River
section. Modified from Crippa et al. (2019). B. Satellite image of the analysed Stirone River section
(Google Earth), with the location of the sampling sites.

**Fig. 3** Field views and photos of the lower Pleistocene deposits cropping out at the Stirone River section, with location of some collected samples. A. Overview of the two analysed biofacies. The white arrow indicates a *Thalassinoides* burrow specimen. B. *Thalassinoides* biofacies. The white arrows indicate *Thalassinoides* specimens. C. *Pinna* biofacies. The arrow indicates a *Pinna nobilis* specimens in life position. D. *Pinna nobilis* specimens within the *Pinna* biofacies. E. *Pinna* biofacies outcropping on the southern side of the Stirone River. F. Stratigraphic contact between the upper level of the *Pinna* biofacies and the overlying biocalcarenites.

**Fig. 4** Stratigraphic log of the analysed section of the Stirone River. Is it possible to appreciate the contact between the *Thalassinoides* biofacies (in purple), the *Pinna* biofacies (in green) and the upper biocalcarenites (in yellow). The curve of the $K/R_{EXT}$ values is also reported, showing the differences between the two biofacies.

**Fig. 5** LM images of selected foraminifera species. A. *Sahulia conica*; B. *Cycloforina* sp.; C. *Spiroloculina* sp.; D. *Bolivina elongata*; E. *Bolivina alata*; F. *Bolivina spathulate*; G. *Cassidulina carinata*; H. *Ammonia beccarii*, spiral side; I. *A. beccarii*, umbilical side; J. *Reussella spinulosa*; K. *Planorbulina mediterranensis*, spiral side; L. *P. mediterranensis*, umbilical side; M. *Rosalina bradyi*, spiral side; N. *R. bradyi*, umbilical side; O. *Neoconorbina terquemi*, spiral side; P. *Cibicides refulgens*, spiral side; Q. *C. refulgens*, umbilical side; R. *Lobatula lobatula*, spiral side; S. *L. lobatula*, umbilical side; T. *N. terquemi*, spiral side. Specimen with two proloculus; U. *Melonis affinis*; V. *Nonion boueanum*; W. *Haynesina germanica*; X. *Valvulineria bradyana*; Y. *Hanzawaia boueana*; Z. *Uvigerina mediterranea*; AA. *Elphidium translucens*; AB. *Elphidium aculeatum*; AC. *Elphidium fichtelianum*; AD. *Elphidium crispum*. The white bars correspond to 100 μm.

**Fig. 6** SEM images of selected foraminifera species and seagrass remains. A. *Planorbulina mediterranensis*, umbilical side; B. *P. mediterranensis*, spiral side; C. *Asterigerinata mamilla*, spiral side; D. *Cassidulina carinata*; E. *Neoconorbina terquemi*, spiral side; F. *N. terquemi*, umbilical side; G. *Cibicides refulgens*, umbilical side; H. *C. refulgens*, spiral side; I. *Lobatula lobatula*, spiral side; J. *L. lobatula*, umbilical side; K. *Nonion boueanum*; L. *Elphidium translucens*; M. *Elphidium crispum*; N. *Elphidium macellum*; O. *Elphidium fichtelianum*; P. *Elphidium advenum*; Q. *Elphidium aculeatum*; R. *E. aculeatum*.

**Fig. 7** Q-mode cluster analysis.

**Fig. 8** Pieplots resulting from the morphotype analysis for each studied sample. Average plots for the *Pinna* biofacies (S) and *Thalassinoides* biofacies (R), are present. Average plots for the two

biofacies without considering miliolids are also present. Average pieplots from the Fauglia

foraminiferal associations are also present (see Mariani et al., 2022).

**Fig. 9** Bivariate analysis and linear regression model.


**Tables**

**Table 1** Grain-size analysis of the collected sample. The analysis and the results were obtained with

software GRADISTAT version 4.0 (Blott and Pye, 2001).

**Table 2** Foraminifera data and parameters calculated from all the samples. Total weight: total

weight of sediment before sieving; Tot. BF: Total number of benthic foraminifera counted and

considered for the analysis for each sample, after the splitting; BF/100g: standardized number of

benthic foraminifera within 100 g of sediment; $Index_{BR}$: proportion of broken tests (BR) within a

sample, BR/(Tot. BF + BR); $Index_{EP}$: number of epiphytic specimens/total foraminifera; $Index_{EP\text{-}Ammonia}$: $Index_{EP}$ without considering *Ammonia* (and related genera such as *Aubignyna* and *Buccella*)

as epiphytic specimens; FI': modified foraminifera index (Mateu-Vicens et al., 2014); $I_{LS}$: long vs.

short life-span index (Mateu-Vicens et al., 2014); $K/R_{EXT}$: ratio between morphotype K (keeled

*Elphidium*) and morphotype R foraminifera (e.g., rounded elphidiids, *Astrononion*, *Haynesina*,

*Nonion*, *Pullenia*, *Valvulineria*) (Mariani et al., 2022).

**Table 3** Relative percentage frequency of the analysed foraminiferal groups and of the common taxa (i.e.,

those with an abundance higher than 5%.

**Table 4** Morphotype classification and foraminifera groups used in this study. Species were assigned to a

specific morphotype as in literature (Langer, 1993; Mateu-Vicens et al., 2010; Mateu-Vicens et al., 2014;

Mariani et al., 2022).

**Table 5** Morphotypes abundances within each sample and average abundance of each morphotype within the

two lithozones of the Stirone river deposits.