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1 Quantitative paleoecology in shallow-marine settings: the value of ostracods and

2 foraminifers from the Holocene North Adriatic record

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12 Keywords

13 Sequence stratigraphy; Po Delta; prodelta; micropaleontology

14 Abstract

- 15 Benthic ostracods and foraminifers are commonly applied as paleoenvironmental indicators in shallow
- 16 marine successions, ignoring that individual meiofaunal groups could provide distinct information. We aim to
- 17 shed light on the distinct paleoecological record of benthic ostracods and foraminifers by analyzing the shallow
- 18 marine Holocene succession of the Po Delta (Italy) in a sequence stratigraphic fashion. Multivariate
- 19 elaborations connecting the modern North Adriatic reference set to fossil data allowed to investigate
- 20 community dynamics, obtain quantitative estimates of (paleo-)environmental drivers and assess the

21 meiofaunal response to coastal and delta dynamics through time and space under the influence of allogenic 22 and autogenic factors. Benthic ostracods and foraminifers easily discern transgressive (TST) and highstand 23 (HST) systems tract, and also discriminate between locations at different distance from paleo-river mouths 24 under highstand conditions. Specifically, community changes reflecting shifts in delta regimes at distal locations 25 suggest that lobe-fringe deposits are more indicated for paleoenvironmental purposes. We emphasize that a 26 deep knowledge of the analyzed datasets should drive the interpretation of multivariate outputs, as 27 reconstructed values from significantly similar deposits could be inappropriate, and the lack of true modern 28 analogs could reflect authentic differences in community composition, or either pitfalls in the modern 29 reference set. Our results show that ostracods evidence depositional regimes determined by the interplay of 30 sediment supply and hydrodynamic energy in relationship with the position from main river outlets; on the other hand, foraminifers highlight changes in riverine inputs in terms of organic matter. Our findings 31 32 demonstrate that shallow marine benthic ostracods and foraminifers provide distinct but complementary paleoecological information, and their integration allows to achieve high-resolution reconstructions. 33

34 1. Introduction

Ostracods and foraminifers represent a main component of the marine benthos (Murray, 2006; Horne et al., 2012; Yasuhara et al., 2017). Characterized by similar size ranges (from a few microns to millimeters), short life cycles and mostly possessing calcareous hard shells that ensure high preservation potential in the sedimentary record, they form abundant communities on the seafloor (Gooday, 2001; Schellenberg, 2007).

Nevertheless, the taxonomic positions of benthic ostracods (multicellular crustaceans) and foraminifers
(unicellular protistans) highlight remarkable biological and paleoecological differences. Benthic ostracods swim
relatively fast (a few cm·s⁻¹), whereas foraminifers move very slowly (a few µm·s⁻¹) or can even be sessile
(Murray, 2001; Sutherland et al., 2011). Although benthic ostracods can be subject to long-distance transport
due to natural events or anthropogenic activities (Faasse, 2013; Tanaka et al., 2018), the lack of a nauplius
larval stage determines a low dispersal potential (Rodriguez-Lazaro and Ruiz-Muñoz, 2012). Conversely, the

global distribution of propagules banks was hypothesized to explain the greater dispersion of benthic
foraminifers even in coastal settings (Weinmann and Goldstein, 2017). Concerning the growing mechanism,
ostracods perform several moults and discarded valves are preserved in the sediment, whereas benthic
foraminifers mainly add successive chambers on single tests (Mesquita-Joanes et al., 2012; Hohenegger, 2018).
Other biological differences, such as reproduction mechanisms and feeding strategies, could account for
distinct structure and composition of assemblages (Yasuhara et al., 2012).

51 Comparing the (paleo-)ecological response of benthic ostracods and foraminifers may shed new light on the 52 interaction among species, community patterns and environmental parameters, especially in shallow-marine 53 areas, where the interplay of many environmental factors may lead to high temporal and spatial heterogeneity. 54 Since the application of the meiofauna as paleoecological indicator is rooted in the principle of taxonomic 55 uniformitarianism, the micropaleontological investigation of past shelves dynamics should ideally start from 56 modern reference datasets. Unfortunately, heterogeneity in measured parameters and taxonomic resolution 57 has commonly prevented the development of integrated meiofaunal distribution models. Studies performed 58 on Mediterranean shelves mostly deal with single groups (e.g., Goineau et al., 2015; Sciuto et al., 2015; Benito 59 et al., 2016) and the few works performed on both benthic ostracods and foraminifers aimed to identify 60 ecological patterns in response to anthropogenic pressure (e.g., Triantaphyllou et al., 2005; Pascual et al., 2008; 61 Salvi et al., 2015). As a consequence, even though benthic ostracods and foraminifers have been extensively 62 employed in late Quaternary paleoenvironmental reconstructions (e.g., Carboni et al., 2002; Flaux et al., 2013; 63 Cacciari et al., 2019), paleoecological information has been extracted from separate modern datasets (e.g., 64 Breman, 1975; Jorissen, 1988; Mendes et al., 2004; Frezza and Carboni, 2009; Frezza and Di Bella, 2015) and 65 reviews (e.g., Athersuch et al., 1989; Murray, 2006; Horne et al., 2012). An integrated analysis of present-day 66 benthic ostracods and foraminifers performed on the North Adriatic river-influenced shelf (Barbieri et al., 2019) 67 revealed that these two groups have distinct distribution patterns driven by specific environmental factors (i.e., 68 bathymetry, substrate grain-size and organic-matter fluxes). The distribution model could serve as a basis to

69 investigate and quantify the response of shallow-marine benthic communities to allogenic (sea-level 70 oscillations) or autogenic (e.g., delta lobe switching) factors acting on river-influenced shelves. The well-71 constrained chronostratigraphic framework of its inland counterpart (Ciabatti, 1967; Stefani and Vincenzi, 72 2005; Amorosi et al., 2017; Campo et al., 2017; Giacomelli et al., 2018; Amorosi et al., 2019) makes the Po 73 Delta-North Adriatic system an excellent venue where to analyze and weight up the response of benthic 74 ostracod and foraminifer communities to deposition dynamics across the Holocene. Although some 75 paleoenvironmental studies integrated marine benthic ostracods and foraminifers from upper Quaternary 76 shallow-marine successions of the Mediterranean area (Amorosi et al., 2008; Fanget et al., 2013, 2016; Angue 77 Minto'o et al., 2016), a critical comparison of these groups has never been performed. 78 In the present work, we describe and compare the vertical distribution patterns of benthic ostracods and 79 foraminifers throughout the shallow-marine deposits of three cores from the Po Delta area along a N-S 80 oriented transect, crossing two adjacent ancient delta lobes (Fig. 1). Specifically, we frame meiofauna 81 quantitative data within two well-recognized sediment units: (i) the transgressive systems tract (TST), formed 82 during the Holocene transgression, and (ii) the highstand systems tract (HST), deposited in response to deltaic 83 progradation of two delta lobes (Volano and Goro) that were governed by distinct sediment dynamics under 84 overall high progradation rates (Amorosi et al., 2020). We investigate the analogies with the modern North 85 Adriatic benthic ostracod and foraminifer biofacies and quantitatively estimate trends in selected 86 environmental parameters through the application of multivariate elaborations. Finally, we extract specific 87 paleoecological indications from the two benthic groups, with the objective of comparing their resolution 88 potential in fossil shelves subject to defined coastal and delta dynamics through time and space.

89 **2.** Stratigraphic and geomorphological framework

The Holocene sedimentary succession of the Po delta plain, developed on top of upper Pleistocene
continental deposits, was formed in response to relative sea-level rise (Amorosi et al., 2017). The lower TST
(9.5-8.5 cal kyr B.P.) consists of back-barrier deposits that mark the landward migration of a wave-dominated

93 estuarine system (Bruno et al., 2017). Above a wave ravinement surface, the upper TST (8.5-7.0 cal kyr B.P.) 94 includes a deepening-upward succession of transgressive barrier sands and offshore muds that represent the 95 deepest conditions within the entire Holocene succession (Amorosi et al., 2008). The boundary between 96 offshore and overlying prodelta facies (maximum flooding surface, MFS) records the turnaround from back-97 stepping (TST) to prograding (HST) depositional systems, which took place in response to relative sea-level 98 stabilization (Amorosi et al., 2019), around 8-7 kyr B.P. (Vacchi et al., 2016). Stratigraphic condensation at the 99 MFS (Scarponi et al., 2017) was associated to persistently low accumulation rates, as clastic input was trapped 100 at the head of the estuary (Amorosi et al., 2019). Due to its poor lithological expression, the MFS has been 101 defined by the maximum value of the ratio between open-marine and fluvial-influenced benthic foraminifers, 102 and by ostracods shifts towards assemblages with predominant taxa tolerant to salinity oscillations (e.g., 103 Amorosi and Colalongo, 2005; Amorosi et al., 2008).

104 Thick prodelta clays (up to ca. 20 m) capped by delta front sands record a complex pattern of coastal 105 progradation under highstand conditions (Amorosi et al., 2020). Steps in delta progradation were controlled by 106 distributary-channel avulsions and by the interplay with longshore currents. Geomorphological (i.e., preserved 107 sand ridges; Fig. 1), historical and archeological data indicate that one of the oldest wave-influenced (arcuate) 108 deltas in the northern coastal plain was fed by the Po di Ariano (the present-day Po di Goro) in the Early Roman 109 Age (Ciabatti, 1967; Fig. 1). Towards the south, the Volano lobe mostly prograded from the Roman to the Early 110 Medieval Age (Ciabatti, 1967; Correggiari et al., 2005a). In the second half of the 12th century (800-750 cal yr 111 B.P.), the Ficarolo river avulsion shifted the Po in a northern position. The increased activity of the Goro branch 112 caused the rapid outbuilding of a cuspate Po delta lobe, up to the XVI century, whereas the Volano river mouth 113 remained relatively stable (Ciabatti, 1967). Later, the Fornaci branch (the modern Po di Levante, Fig. 1) became 114 the main outlet and formed the first lobate delta of the Po River, marking the onset of the Modern-Age delta 115 characterized by several supply-dominated lobes prograding at rates even >100 m yr⁻¹ (Correggiari et al.,

116 2005a).

- 117 Modern prodelta lobes show comparable size to their inland buried counterparts, with thickness up to ca.
- 118 15 m and lateral extension of 10-20 km. Their stratigraphic relations reflect activity of individual river branches
- during the last centuries (Correggiari et al., 2005a, 2005b).

120 **3. Materials and methods**

121 3.1 Experimental design and data collection

122 Micropaleontological analyses were performed on Holocene shallow-marine deposits from three cores (Fig. 123 1) drilled by wire-line perforation in the southern portion of the modern Po Delta plain. Cores 187S4 (44°57'49" N, 12°15'09" E), EM13 (44°51'50" N, 12°17'05" E) and 205S9 (44°46'71" N, 12°15'05" E) are 35-54 m long and 124 125 were specifically selected with approximately north-south orientation, in order to capture along-strike 126 paleoecological variations across two adjacent lobes (i.e., Volano and Goro) with documented activity in 127 historical times. Specifically, cores 187S4 and 205S9 were recovered in proximity to distributary channels, 128 whereas core EM13 is located far from river mouths (Fig. 1). Sedimentological features and concise 129 paleontological characteristics have been illustrated by Amorosi et al. (2003, 2017) and Campo et al. (2017), 130 whereas the benthic foraminifer distribution of core 205S9 is reported in Dasgupta et al. (2020). In this work, we present quantitative benthic ostracod and foraminifer data from cores 187S4 and EM13, along with the 131 132 quantitative ostracod distribution from core 205S9, and provide novel multivariate elaborations. The 133 stratigraphic model by Amorosi et al. (2020) and surficial geological map by Ciabatti (1967) were used as a 134 geological framework to compare the record of benthic foraminifers and ostracods from distinct, locally 135 outcropping, Holocene beach-ridge sediment bodies.

Micropaleontological assemblages were recovered from (i) TST barrier sands and offshore clays, and from (ii) the stratigraphically expanded HST of the Volano and Goro delta lobes. The chronologic framework relies on 14 published radiocarbon dates integrated with one sample from core 187S4 (Table 1), dated at the Korea Institute of Geoscience and Mineral Resources (KIGAM, Republic of Korea). Calibration of conventional ¹⁴C ages was performed with Oxcal 4.2 (Bronk Ramsey, 2009) using the IntCal13 and Marine13 curves (Reimer et al.,
2013) and a ΔR value of 139 ± 28 yr (Langone et al., 1996).

142 A total of 258 sediment samples of approximately 100-150 g of dry weight (151 from core EM13, 58 from 143 core 205S9 and 49 from core 187S4) were selected for micropaleontological analyses and treated following the 144 standard procedure adopted in other reference works from the study area (e.g., Rossi and Vaiani, 2008). 145 Samples were dried at 60 °C, soaked overnight in 10% H₂O₂, water-screened with a 63 μ m sieve and dried again 146 for > 8 hours. Samples including abundant, well preserved microfossils were dry-sieved at 125 μm and divided 147 using a microsplitter. At least 300 benthic foraminifers and 100 ostracod valves (with carapaces considered as 148 two valves) were counted from the >125 μ m fraction, otherwise, all the tests or valves were considered. Both 149 adult and juvenile ostracod valves with morphological characters sufficiently developed to perform an 150 identification at species level were counted. Literature adopted for taxonomic identification and structure of 151 meiofaunal matrices are reported in Text S1 and Table S1.

152 *3.2 Data matrices*

153 Microfossil data matrices were treated prior to the application of multivariate analyses, following specific 154 criteria in order to keep the data comparable to the modern reference set based on total assemblages (Barbieri 155 et al., 2019). Clearly transported freshwater and brackish water taxa were removed from the ostracod dataset 156 and only samples including >20 valves were retained, in accordance with other works from marine settings 157 (Azzarone et al., 2020; Barbieri et al., 2019; Bassetti et al., 2010; Cronin et al., 1999). Samples including <300 158 individuals were removed from the benthic foraminifer matrix. The contribution of the fragile agglutinated 159 taxon Eggerella scabra was discarded. Selected taxa with similar ecological characteristics were gathered up to 160 the genus level in order to reduce the dataset dispersion and taxa with relative abundance >5% in at least one 161 sample were retained. We harmonized variables and taxonomic nomenclature in modern and fossil datasets, 162 as reported in Table S2.

Fossil data were subject to the Hellinger transformation, i.e. the square root of the relative abundance was computed (Legendre and Gallagher, 2001). Then, multivariate analyses were separately performed on benthic ostracod and foraminifer matrices using the Euclidean distance in order to obtain the Hellinger distance, a measure recommended to detect community changes in short environmental gradients that gives low weights to rare species (Legendre and Gallagher, 2001; Legendre and De Cáceres, 2013).

169 The contribution of taxa to the composition of sample groups was assessed by means of a Euclidean-based 170 similarity percentage analysis (SIMPER – Clarke, 1993) carried out on Hellinger-transformed data, whereas 171 average values were derived from relative abundance data in order to produce more straightforward outputs.

172 Paleoecological conditions were assessed through the application of the analogue matching technique (AM; 173 (Simpson, 2007). AM identifies the k-closest modern sites to each fossil assemblage, and the degree of analogy 174 is estimated through the computation of dissimilarity values between each fossil and modern sample. Fossil 175 assemblages were compared to the modern North Adriatic ostracod and foraminifer biofacies determined 176 through quantitative thresholds of environmental parameters presented in Barbieri et al. (2019), synthetized in 177 Table 2 (geographic distribution in Fig. 2). This comparison also allowed the interpretation of the 178 paleoecological record in relation to the amount of riverine input and relative distance from the main feeding 179 channel. A threshold value to determine whether fossil samples have an adequate counterpart in the modern reference set should be applied considering selected percentiles (up to 20th) of the distribution of modern 180 dissimilarities (Simpson, 2007). We chose the 20th percentile as a critical threshold to discriminate analog from 181 182 non-analog samples. Although this is considered an adequate value (Jackson and Williams, 2004), it is a bit 183 higher than those traditionally employed in other studies (Overpeck et al., 1985; Anderson et al., 1989). This 184 threshold was selected due to intrinsic properties of the distance measure and heterogeneity of the ostracod 185 datasets. Specifically, the Hellinger distance allows to manipulate percentage data (as expressed in the modern 186 datasets) and produces optimal results when samples share variables with intermediate frequencies (Legendre

and Gallagher, 2001). Nevertheless, it locally emphasized taxonomic discrepancies (e.g., taxa not recorded in
the modern dataset, Table S2), increasing the dissimilarity between fossil and modern datasets and leading us
to choose the 20th percentile as the threshold value for ostracods (Hellinger distance = 0.616). This value was
also applied to benthic foraminifers (Hellinger distance = 0.520) to keep the data comparable. Where several
modern analogs were found for a fossil assemblage, we retained the four modern samples with the lowest
dissimilarity values.

193 The distance between cores and modern assemblages was visualized through a weighted Principal

194 Coordinates Analysis (wPCoA), where core samples were passively plotted as trajectories in stratigraphic order

195 onto the ordination space defined by modern assemblages. To further refine the paleoecological

196 characterization, predicted values of environmental drivers on the distribution of modern North Adriatic

197 assemblages (Barbieri et al., 2019) and the associated standard error were extracted from microfossil

assemblages and plotted against core stratigraphy using a generalized additive model, as it is used

automatically in the wPCoA computation (Goring et al., 2009; Oksanen et al., 2019).

All the statistical elaborations were carried out in the R environment (version 3.6.1; R Core Team, 2019)

using the packages "vegan" (Oksanen et al., 2019), "analogue" (Simpson and Oksanen, 2020), "mgcv" (Wood,

202 2011), and "ggplot2" (Wickham, 2016) for graphical outputs, whereas the SIMPER analysis was performed with

203 PAST (PAleontological STatistics; Hammer et al., 2001).

204 **4. Results**

4.1.1 Composition of fossil ostracod assemblages and analogies with modern North Adriatic sites

206 Relatively high dissimilarity values were recorded between fossil and modern ostracod datasets, mostly due 207 to peak frequencies (>70%) of dominant taxa in fossil assemblages, in contrast to the relatively homogeneous 208 modern North Adriatic communities (maximum relative abundances <55%; Barbieri et al., 2019). Moreover, fossil ostracod assemblages displayed relatively high abundances of species not recorded in the modern fauna
(Table S2).

The SIMPER routine performed on ostracods revealed an overall average dissimilarity of 0.64 (Table 3). *Leptocythere ramosa, Pontocythere turbida, Semicytherura incongruens, Loxoconcha* ex gr. *rhomboidea, Palmoconcha turbida* and other *Semicytherura* account for most of the differences (cumulative contribution
>55%).

215 Abundant statistically significant analogs were found for ostracod assemblages of transgressive deposits. 216 These are mostly represented by samples of the shallow, sediment-starved northern Adriatic shelf (biofacies 217 O5, Table 2), updrift of the main sediment input from the Po River (Figs. 2–4, Table S3). Scattered modern 218 analogs are represented by samples located at either lower (biofacies O4) or higher (biofacies O6) depths, in 219 areas with low-moderate river input. The lowest Hellinger distance values of the entire database indicate high 220 similarity between transgressive ostracod assemblages from the three cores (Fig. 5A, Table S4). Transgressive 221 ostracod assemblages are composed of similar frequencies of S. incongruens, Pontocythere turbida, other 222 Semicytherura and Loxoconcha ex gr. rhomboidea (Table 3), locally associated to Sagmatocythere napoliana 223 and Cytheretta spp.

224 A relatively low number of significant modern analogs was detected for the Volano ostracod assemblages 225 (Table 4). Specifically, the few significant modern analogs found in core 205S9 belong to biofacies O4, located 226 along the northernmost or central Adriatic coasts, where low to moderate river input is recorded. A single 227 sample (13 m core depth) was considered similar to a modern sample from deep-water relict sands (biofacies 228 O6; Fig. 2). A larger number of fossil assemblages is represented by significant modern analogs in core EM13 229 (Table 4, Fig. 3). In the lower portion of core EM13, one sample at 23.69 m depth was significantly similar to a 230 modern site of the sediment-starved shelf (biofacies O5). The upper part of the lobe includes relatively high 231 amounts of significant modern analogs, represented by shallow-water, mid-Adriatic sites with moderate river 232 input on either sandy (biofacies O4) or muddy bottoms (biofacies O2). A moderate dissimilarity (0.48, Table S4) was recorded between the Volano ostracod assemblages of cores 205S9 and EM13, with *Pontocythere turbida*, *S. incongruens* and *Palmoconcha turbida* representing the most abundant species (Fig. 5A, Table 3).

235 Ostracod assemblages from the Goro lobe in core 187S4 are represented by abundant modern analogs 236 along the shallow Adriatic coast, under moderate sediment supply (biofacies O4, subordinately biofacies O2; 237 Fig. 4). Concerning the Goro lobe ostracods from core EM13 (Fig. 3), one sample at 12.27 m core depth was 238 considered significantly similar to a modern site immediately south of the Po Delta, at shallow water depth on 239 fine-grained sediment enriched in organic matter under high sediment supply (biofacies O1). Non-analog sites (i.e., the most similar sites, but exceeding the threshold value defined by the 20th percentile of modern 240 241 dissimilarities) for this interval were attributed to samples from the same area (biofacies O1) or, occasionally, 242 from a southern position on muddy substrates (biofacies O2). Ostracod assemblages from the Goro deposits 243 were characterized by high dissimilarity (1.1, Fig. 5A), due to the dominance of *L. ramosa* in core EM13 (68.4% on average). On the other hand, the Goro sediments from core 187S4 show an ostracod composition with 244 245 common Pontocythere turbida, S. incongruens, Palmoconcha turbida, associated with moderate frequencies of 246 *Xestoleberis* spp. and *Loxoconcha* ex gr. *rhomboidea* (Table 3).

247 4.1.2 Composition of fossil benthic foraminifer assemblages and analogies with modern North Adriatic sites

Fossil and modern foraminifer datasets are taxonomically homogeneous, with a single taxon showing
frequencies >5% in fossil samples, but not in modern ones (*Haynesina* spp.; Table S2).

250 The overall dissimilarity between sediment units from each core is 0.42, as revealed by the SIMPER analysis

251 (Table 5). Most of the differences among sediment units from the three cores (>55%) were determined by

252 Ammonia parkinsoniana – Ammonia tepida, Aubignyna perlucida, Quinqueloculina group, Porosononion ex gr.

253 granosum and Triloculina ex gr. trigonula, representing the most abundant taxa.

254 Benthic foraminifer assemblages from transgressive deposits showed statistically significant analogs in the 255 modern North Adriatic (Figs. 2-4, Table 4). Specifically, transgressive assemblages from cores 187S4 and 205S9 256 are significantly similar to modern sites along the Adriatic coast, north of the Po Delta, under negligible organic 257 matter inputs and strong longshore currents (biofacies F3; Table 2). On the other hand, many significant 258 modern analogs of EM13 transgressive benthic foraminifer assemblages occur on the Adriatic shelf at high 259 water depth (biofacies F5). Relatively low dissimilarity values were recorded between transgressive benthic 260 foraminifer assemblages (Fig. 5B, Table S4), due to similar frequencies of the most common taxa, namely the 261 Quinqueloculina group (Table S2), Porosononion ex gr. granosum, Adelosina spp. and Textularia agglutinans. 262 The higher dissimilarity of transgressive assemblages from core EM13 was determined by the higher 263 contribution of Buccella granulata, Neoconorbina terguemi, Rosalina bradyi and Asterigerinata mamilla (Table 264 5).

265 Benthic foraminifer assemblages from the Volano lobe show abundant significant modern analogs in core 266 205S9, whereas a lower number of significantly similar modern sites was detected from core EM13 (Figs. 2, 3). 267 In core 205S9, between 25.25 and 23.50 m core depths, significantly similar modern sites are mostly located on 268 the shallow northern Adriatic coast with low organic matter levels (biofacies F3) and subordinately south of the 269 Po Delta on substrates with moderate organic matter (biofacies F2). Upwards, significant modern analogs are 270 positioned along the mid-Adriatic coast (biofacies F2) or in proximity of the Po and Adige delta outlets 271 (biofacies F1) under moderate to high organic matter inputs, respectively. In core EM13, up to 21.06 m core 272 depth, the Volano lobe shows a low number of significant modern analog sites along the northern and middle 273 Adriatic coasts (biofacies F3, F2). In the upper portion of the lobe, benthic foraminifers show high similarity to 274 modern sites in proximity or south of the Po and Adige delta mouths (biofacies F1, F2). The Volano benthic 275 foraminifer assemblages show a moderate dissimilarity between locations (0.39, Fig. 5B, Table S4), mostly 276 driven by the lower frequency of A. parkinsoniana -A. tepida in core EM13, associated to relatively high 277 concentrations of A. perlucida, Porosononion ex gr. granosum and Quinqueloculina group (Table 5).

A large number of significant analogs was found for benthic foraminifer assemblages from the Goro lobe
(Figs. 3, 4). Significantly similar modern analog sites for core 187S4 were identified along the shallow mid-

Adriatic coast (biofacies F2) or near the Po and Adige river mouths (biofacies F1) under moderate to high organic matter fluxes, with alternating trends along the prodelta succession. Oscillations in modern analogs were also detected for assemblages of core EM13, but with a dominance of significantly similar sites from the central Adriatic coast (biofacies F2). A very low dissimilarity (0.24; Fig. 5B, Table S4) was recorded between benthic foraminifer assemblages from the Goro lobe, due to similar frequencies of *A. parkinsoniana – A. tepida* (Table 5).

286 4.2 Quantitative paleoecological data from the fossil record

The distance between modern and core samples in terms of species composition was visualized through the wPCoA, which also allowed to estimate paleoecological changes in relation to environmental drivers in the modern North Adriatic ostracod and foraminifer biofacies (Figs.6-8).

In core 205S9, the trajectory of ostracod assemblages crosses the multivariate space of sites from biofacies O5-O4-O2, and then turns back (Fig. 6B). This reflects a decrease in paleobathymetry from transgressive to highstand assemblages (ca. 25–15 ± 1 m water depth), with a scattered higher water depth value at the delta front transition (ca. 21 ± 1 m), paralleled by a similar trend in sand concentration (from ca. 62 ± 3% to 26 ± 4%, up to >50% in the delta front transition; Fig. 6A; Table 6). The trajectory of transgressive benthic foraminifers from core 205S9 crosses the area of biofacies F3, F2 and F1, mirroring a progressive decrease in water depth (from ca. 19 ± 1 m to 11 ± 2 m) and a parallel increase in organic matter (ca. 0.8 ± 0.3–2.7 ± 0.6%).

297 The trajectory of fossil ostracod assemblages in core EM13 extends through the upper multivariate space,

approximately parallel to the first axis of ordination, crossing biofacies O5-O4-O2-O1 (Fig. 7B). The

reconstructed bathymetry and sand evenly decrease throughout the core, from transgressive (27 ± 1 m water

depth, 75 ± 4 % sand) to highstand (13 ± 1 m water depth, 4 ± 4 % sand) deposits. Benthic foraminifers show a

301 zig-zag trajectory distributed through biofacies F5-F3-F2-F1, reflecting an overall decrease in paleo-water depth

302 (ca. from 27 ± 1 m in TST to 11 ± 2 m in HST) and increase in organic matter (ca. from 0.6 ± 0.3% in TST to 2.5 ±
303 0.6% in HST), with localized oscillations throughout the succession (Fig. 7A).

304 The trajectory of ostracods from core 187S4 resembles that of core 205S9, with a back and forth trend that 305 crosses sites from biofacies O5-O4 and comes back towards biofacies O5 (Fig. 8B). In terms of 306 paleobathymetry, it reflects decrease in water depth from transgressive (ca. 24 ± 1 m) to highstand (ca. 11 ± 1 307 m) assemblages, with a few oscillations within the Goro lobe. Estimated sand concentration decreases from 308 transgressive barrier (ca. $71 \pm 4\%$) to lower prodelta (ca. $30 \pm 4\%$) deposits and increases in the upper portion 309 of the Goro lobe (>50%). The relatively short core trajectory of benthic foraminifers that crosses biofacies F3, 310 F2 and F1 reflects higher paleobathymetry in TST (ca. 18 ± 1 m) and almost stable, lower water depths 311 throughout highstand prodelta deposits (ca. 12 ± 1 m). Accordingly, organic matter increases from TST to HST, 312 with relatively constant values across the Goro lobe $(0.8 \pm 0.3 - 2.6 \pm 0.6\%)$, Fig. 8A). 313 Differences between study cores and systems tracts can be visualized in a main effects plot (Fig. 9), where

the centroids of each sediment unit are distributed in a multivariate space. Ostracod and foraminifer plots display the maximum distance on a systems tract-scale, with the centroids of transgressive assemblages being clearly separated from the highstand (delta lobe) ones. Concerning the study cores, centroids of 187S4 and 205S9 plot relatively close to each other showing negative PCoA axes scores for ostracods and positive values for foraminifers. Core EM13 is distinctly separated in both plots, with positive values of both axes in the ostracod plot and negative scores in the foraminifer PCoA.

320 **5. Discussion**

321 5.1 Know your setting: assessing the resolution of shallow-marine benthic ostracod and foraminifer records

The high contrast between centroids of systems tract in the main effects plot indicates that both ostracods and foraminifers efficiently discriminate transgressive from highstand deltaic deposits (Fig. 9). Abundant opportunistic taxa in deltaic sediments (i.e., *L. ramosa, Palmoconcha turbida, Pontocythere turbida* and *A.* 325 parkinsoniana – A. tepida; Lachenal and Bodergat, 1988, 1990; Jorissen et al., 2018) drive the high dissimilarity 326 with transgressive assemblages. Ostracods and foraminifers also highlight differences between cores, 327 discriminating core EM13, which geographically lies between two delta lobes, from the markedly similar cores 328 187S4 and 205S9 located near paleo-river mouths (Figs. 1, 9). The unique character of core EM13 is ascribed to 329 transgressive assemblages with abundant epiphytic foraminifers, i.e., B. granulata, N. terquemi, R. bradyi and 330 A. mamilla (Langer, 1993; Sgarrella and Moncharmont Zei, 1993; Table 5), influencing the centroid position 331 towards negative values of axis 1 (Fig. 7). Ostracods show marked dissimilarities in progradational deltaic 332 deposits of core EM13, due to the dominance of the mud-lover *L. ramosa* (Barbieri et al., 2019) in the Goro 333 lobe that determine a shift towards positive axis 1 values characteristic of highstand delta lobes. Core EM13 334 also shows the highest faunal turnover (Figs. 6B-8B), suggesting that paleoecological variations are better 335 recorded at distal locations.

336 The comparison between modern and fossil assemblages with the AM technique allowed to obtain further 337 insights in the paleoenvironmental record provided by each faunal group. In transgressive assemblages, the 338 significant similarity with sites on the shallow North Adriatic relict sand barriers (biofacies O5, Figs. 2-5) is 339 based on sand-related ostracods, such as Semicytherura spp. (including S. incongruens), Pontocythere turbida, 340 Loxoconcha ex gr. rhomboidea, S. napoliana and Cytheretta spp. (Bonaduce et al., 1975; Frezza and Di Bella, 341 2015). Ostracods track the same deposit in the Po Delta subsurface and in the northern Adriatic shelf, as 342 biofacies O5 is developed on sediment-starved sand ridges shaped from the reworking of relict transgressive 343 sands (Trincardi et al., 1994; Correggiari et al., 1996). Therefore, reconstructed values of water depth reflect 344 the geographic position of the deposit on the shelf instead of representing a true modern analog (Figs. 6A-8A). 345 Concerning benthic foraminifers, the similarity to modern sites depleted in organic matter (biofacies F3, F5) is 346 mostly driven by organic matter-sensitive taxa (Triloculina ex gr. trigonula, Adelosina spp., Cycloforina spp., 347 Siphonaperta aspera, B. granulata, N. terquemi, R. bradyi and A. mamilla; Jorissen, 2018), widespread in the 348 modern, shallow North Adriatic shelf (Barbieri et al., 2019).

In prograding delta lobes, the similarity with modern assemblages is driven by abundances of opportunistic
 taxa, particularly *Palmoconcha turbida, Pontocythere turbida, S. incongruens* and *A. parkinsoniana – A. tepida.* The presence of non-analog samples (Figs. 2-5) is ascribed to differences in assemblage composition or to
 under-representative modern dataset.

353 The paucity of significant modern analogs in the Volano lobe is determined by the marked compositional 354 differences with modern assemblages. Ostracod and foraminifer taxa abundant in the Volano assemblages 355 show contrasting ecological characteristics. Specifically, sand-related ostracods (Pontocythere turbida, 356 Loxoconcha ex gr. rhomboidea, S. napoliana, Semicytherura spp.) are associated to taxa preferring fine-grained 357 (Palmoconcha turbida, S. versicolor) or mixed (Callistocythere spp.) substrates (Bonaduce et al., 1975; Arbulla 358 et al., 2004; Frezza and Di Bella, 2015). Similarly, benthic foraminifer assemblages from the lower Volano lobe 359 of core EM13 include moderate frequencies of species tolerant (A. parkinsoniana – A. tepida, A. perlucida, 360 Cribroelphidium ex gr. granosum) and sensitive (Triloculina ex gr. trigonula) to organic matter (Jorissen et al., 361 2018). Such microfossil assemblages chronologically overlap the development of wave-influenced cuspate and 362 arcuate deltas characterized by a marked longshore transport component (Ciabatti, 1967; Amorosi et al., 363 2019). In wave-dominated deltas, fine-grained sediments supplied by rivers can be reworked, integrated within 364 the delta or transported alongshore by wave-induced longshore currents. Even under high fluvial discharge 365 regimes, waves can strongly affect delta dynamics in case of episodic high-energy events (Anthony, 2015). In 366 the microtidal Mediterranean Sea, an example is represented by the Ombrone delta, where muddy sediments 367 brought by episodic floods are transported alongshore by wave-induced currents on the long term (Tortora, 368 1999). As a result, benthic ostracod and foraminifer assemblages from the shallow Ombrone prodelta are 369 composed of species with divergent ecological preferences (Frezza and Carboni, 2009; Frezza and Di Bella, 370 2015). Therefore, the absence of significant analogs in the Volano lobe still provides significant information, 371 specifically, the absence of similar processes currently acting in the modern reference set. In fact, the high 372 amount of riverine sediment and organic matter supplied by the lobate Po Delta represents the main forcing

on the meiofaunal zonation in the present-day North Adriatic system, whereas along-shore transport mostly
operates in the southern Adriatic, where low fluvial inputs are recorded (Frignani et al., 2005; Barbieri et al.,
2019).

376 A particular case is represented by the paucity of significant modern analogs for the Goro ostracod 377 assemblages in core EM13, determined by the higher abundance of *L. ramosa* in fossil assemblages (ca. 70% vs. 378 ca. 50% in modern communities). *Leptocythere ramosa* is one of the most opportunistic marine ostracods: 379 abundant in transitional settings subject to mixed marine-freshwater contribution, it is strongly positively 380 correlated with organic matter and prefers fine-grained bottoms at shallow depth (Uffenorde, 1972; 381 Montenegro and Pugliese, 1996; Barbieri et al., 2019). To our knowledge, very high concentrations (>60%) are 382 not reported from present-day environments. In sedimentary successions, L. ramosa is abundant at the 383 transition from lagoonal to deltaic deposits or in proximal prodelta intervals (Carboni et al., 2002; Rossi, 2009). 384 Studies on mollusks have shown that higher concentrations of opportunistic taxa in marine fossil assemblages 385 are connected to rapid multiple invasions that are hardly preserved individually in the stratigraphic record 386 (Levinton, 1970; Pearson and Rosenberg, 1978). Considering the paleoecological affinity of mollusks and 387 ostracods (Amorosi et al., 2014; Rossi et al., 2018), we cannot rule out that L. ramosa-dominated assemblages 388 in core EM13 were determined by comparable processes. In such nearshore river-influenced settings severely 389 impacted by organic enrichments, the estimated paleoecological information is not necessarily incorrect as 390 opportunistic population dynamics could greatly affect the dissimilarity with modern assemblages.

Finally, the lack of sites in the modern dataset could lead to biased assignments, as for the topmost prodelta ostracod assemblages of core 205S9. The similarity with a modern site on relict sands at ca. 30-40 m water depth (biofacies O6) is documented by the high abundance of *Pontocythere turbida*. However, this taxon is reported as dominant in the shallow prodelta, delta front, and shoreface zones of the Western Adriatic coast (Ruggieri, 1952; Colalongo, 1969), which were not sampled in the dataset used in the present work (>8 m water depth; (Breman, 1975).

397 5.2 Meiofauna-based paleoecological reconstructions: transgressive deposits

398 Bathymetric estimates from transgressive benthic ostracods and foraminifers show some discrepancies 399 (Figs.6A-8A). Based on analogies with modern Adriatic sites (see section 5.1), we consider more reliable the 400 values provided by benthic foraminifers, which indicate an average water depth of ca. 18 ± 1 m at cores 18754 401 and 205S9, and of 26 ± 1 m for EM13 (Table 6), in accordance with its distal position (Fig. 1). Significant modern 402 analogs for transgressive ostracod assemblages indicate the onset of sediment-starved conditions in the whole 403 study area during the last phases of transgression (ca. 8.5-7.0 cal kyr B.P.; Bruno et al., 2017), as also supported 404 by low organic matter concentrations indicated by foraminifers (Figs. 6A-8A). Comparable foraminifer 405 assemblages are reported from shallow-water, coarse-grained bottoms with low concentrations of refractory 406 organic matter, such as relict deltaic deposits subject to high-energy conditions and sediment reworking 407 (Goineau et al., 2015).

Paleoecological insights retrieved from transgressive microfossil assemblages are consistent with the early Holocene paleogeography, when a backstepping wave-dominated estuary occupied the modern Po coastal plain (Bruno et al., 2017). At the estuary mouth, transgressive barriers were affected by high-energy wave action and offshore deposits developed under a reduced sediment influx due to sediment trapping in the estuarine system (Bruno et al., 2017; Amorosi et al., 2019).

413 5.3 Meiofauna-based paleoecological reconstructions: highstand delta lobe deposits

In prodelta successions, ostracods and benthic foraminifers provide similar water depth estimates, tracking a major decrease in paleobathymetry from bottom to top (Figs. 6A-8A). Overall, benthic foraminifers show more regular trends and suggest slightly shallower water depths than ostracods (13 ± 1 m and 15 ± 1 m on average, respectively), but these differences fall within the range of the standard error, with a few exceptions mostly connected to the lack of significant modern analogs (Figs. 2-4, 6-8). No significant paleobathymetric differences are recorded at proximal (core 205S9, 187S4) and distal (core EM13) locations. The different driving 420 factors that govern benthic ostracod and foraminifer distribution in the marine realm may account for local 421 discrepancies in water depth and meiofaunal zonation (see section 5.1) (Yasuhara et al., 2012; Barbieri et al., 422 2019). Under highstand conditions, approaching river outlets due to delta progradation are consistent with a 423 decrease in water depth, as observed in modern deltaic systems (Lavoie et al., 2014; Bomer et al., 2019), 424 including the Po Delta (Correggiari et al., 2005b; Bosman et al., 2020). The relatively stable paleobathymetry 425 recorded in ca. 10 m-thick upper prodelta deposits is ascribed to the rapid accumulation of riverine material 426 that resulted in the deposition of expanded prodelta successions, with abundant opportunistic benthic 427 ostracods and foraminifers that benefitted from continental organic matter inputs (Goineau et al., 2012; Frezza 428 and Di Bella, 2015). High organic matter concentrations estimated from benthic foraminifers $(2.1 \pm 0.4 \text{ on})$ 429 average; Figs. 6A-8A) mostly linked to degraded, continental organic material are in accordance with data from 430 the major deltaic systems of the Mediterranean (Goineau et al., 2011).

431 *5.3.1 Volano lobe*

432 Organic matter levels reconstructed from benthic foraminifers reflect the development of delta lobes. The 433 good chronological resolution at core locations 205S9 and EM13 documents an increase in organic matter after 434 the demise of the Roman Empire, when the countryside was abandoned and channel regulation ended, causing 435 widespread inland flooding (Stefani and Vincenzi, 2005). Unstable river regime and high discharge are 436 confirmed by relatively high organic matter concentrations (Figs. 4A, 5A), likely of continental origin that is 437 typically associated to proximal prodelta settings with dominant A. tepida – A. parkinsoniana (Goineau et al., 438 2015). Nevertheless, abundant riverine organic inputs hardly reached updrift, distal locations at that time, as 439 confirmed by the lower concentrations in core EM13 ($1.5 \pm 0.4 \%$ vs. $2.1 \pm 0.4 \%$ in 205S9; Table 6).

High sand concentrations (Figs. 6-7A; Table 6) support considerable influence by longshore currents at both study sites, in accordance with the arcuate morphology of the Volano lobe (Fig. 1). In updrift position (EM13), a first phase of low sediment supply far from river outlets is suggested by analogy with ostracod assemblages on relict sands. After ca. 1.6-1.5 kyr B.P., ostracods track the approaching Volano lobe, with persistent longshore currents and low to moderate sediment supply at shallow water depth (Figs. 3, 7). The increase of ostracodderived sand concentration in the upper prodelta and within delta front transition deposits at proximal
locations (core 205S9) is consistent with higher hydrodynamic conditions at the transition to the delta front in
microtidal Mediterranean deltas (Lavoie et al., 2014; Ciampalini et al., 2015).

High sand concentration estimated from ostracods that highlight strong hydrodynamic conditions, along
with increasing organic matter levels traced by benthic foraminifers, efficiently document the development of
the Volano lobe. The cuspate morphology provides evidences for wave influence, nevertheless, abundant
sediment supply from the Po River is recorded by sediment geochemistry and high sedimentation rates
(Amorosi et al., 2020).

453 5.3.2 Goro lobe

454 Strong sediment and organic matter inputs of continental origin in proximity to a river mouth are consistent 455 with benthic foraminifers throughout prodelta deposits, both at the proximal location of core 187S4 and at the 456 distal EM13 site (Table 6, Figs. 7-8A).

In core 187S4, similarities with modern ostracod communities and high estimated sand concentrations
suggest an important longshore drift component, whereas an abundance of fine-grained sediments and
possible oxygen deficiency are recorded at the downdrift location (Figs. 3-4, 7-8).

The "Ficarolo avulsion" in the XII century AD caused a major switch from the Volano to Goro delta lobes. This event is recorded by localized low organic matter levels from benthic foraminifers, without significant associated paleobathymetric variations (Fig. 7A). The onset of the Goro lobe occurred at low water depth (<15 m), possibly due to decreasing accommodation after the progradation of the downdrift Volano lobe (Correggiari et al., 2005a). Afterwards, the increased fluvial discharge in response to the late Middle Ages climatic instability (including the Little Ice Age) and anthropogenic activity that led to the major Po delta lobe outbuilding (Veggiani, 1990; Stefani and Vincenzi, 2005) is documented as changes in sediment dynamics by

467 ostracods (biofacies O1), which suggest increased riverborne sediment supply. Structure and composition of 468 ostracod communities suggest unstable environmental conditions in a mud-dominated, shallow-marine 469 environment subject to enrichment in continental organic matter, in accordance with the accumulation of 470 thick flood layers that promoted the rapid progradation of the Goro lobe (Correggiari et al., 2005b). At seaward 471 locations, extremely high sediment and organic-matter supplies are recorded by mud-belt microfossil assemblages (Rossi and Vaiani, 2008; Rossi, 2009; Barbieri et al., 2017) responding to both refractory and labile 472 473 organic matter of continental and marine origin, respectively (Diz et al., 2006; Mojtahid et al., 2009; Goineau et 474 al., 2012).

475 **6. Conclusions**

Integrated analyses of benthic ostracods and foraminifers from the marine Holocene succession of the Po
Delta provide the opportunity to assess the paleoecological information recorded by individual microfossil
groups in past river-influenced shelves. The comparison with the modern North Adriatic reference set through
multivariate analyses revealed to be a powerful tool for investigating meiofaunal dynamics in relation to
coastal and deltaic evolution. Specifically, we reconstructed and connected three environmentally significant
parameters (water depth, sand and organic matter concentrations) that allow to characterize delta dynamics in
shallow-marine, river-influenced settings.

We demonstrated that benthic ostracods and foraminifers discriminate transgressive from highstand
 units. Furthermore, microfossils allow to identify locations at different distance from paleo-river mouths.
 Particularly, lobe-fringe deposits seem to be more suitable for paleoecological studies, as the highest faunal
 turnover in response to major changes in delta regimes is recorded distally.

We stress that an extensive knowledge of the modern reference set should drive a critical
 interpretation of (non-)analogies with fossil assemblages. Significant modern analogs could mirror non-true
 environmental conditions (e.g., estimated water depth from transgressive relict ostracod samples). On the

490	other hand, the lack of significant modern analogs can be important, as in our study reflects wave-
491	influenced deltaic conditions not recorded in the modern dataset. However, other factors, such as
492	population dynamics and limitations in the modern reference set may also influence the detected
493	paleoecological information.
494	• We show the complementarity of marine benthic ostracods and foraminifers as proxies for high-
495	resolution paleoecological reconstructions in river-influenced successions. Ostracods provide insights into
496	depositional regimes, furnishing an overview of bottom-water conditions in terms of sediment supply,
497	hydrodynamic energy and, locally, oxygen conditions. Transgressive ostracod assemblages indicate
498	sediment starvation, whereas highstand ostracods reflect position of the study site in relationship with the
499	river mouth in the three-dimensional space (along-dip and along-strike) and delta regimes. Benthic
500	foraminifers discriminate localized transgressive paleoenvironmental conditions and provide information
501	about highstand changes in riverine input in terms of organic matter, in relationship with the position from
502	river mouths.

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790 Tables

Core	Sample depth (m)	Dated material	Convention al 14C age (yr B.P.)	Calibrated age 2σ range (yr B.P.)	Calibrated age mean (yr B.P.)	σ	Laboratory	References
187 S4	25.45	Peat	8020 ± 70	9035-8635	8875	115	Beta analytic (FL, USA)	Sheet 187, Geological Map of Italy at 1:50,000 scale
187 S4	20.70	Shell fragments	1590 ± 24	1310-1185	1270	25	KIGAM (Korea)	This study
EM13	10.90	Shell	840 ± 40	650–510	580	40	KIGAM (Korea)	Amorosi et al., 2017
EM13	17.50	Wood	1060 ± 30	1055–925	975	35	KIGAM (Korea)	Amorosi et al., 2017
EM13	22.65	Shell	1900 ± 40	1700–1420	1570	50	KIGAM (Korea)	Amorosi et al., 2017
EM13	26.75	Wood	8040 ±50	9090-8715	8900	100	KIGAM (Korea)	Amorosi et al., 2017
EM13	29.00	Peat	8500 ± 50	9545–9440	9500	30	KIGAM (Korea)	Amorosi et al., 2017
EM13	32.00	Wood	9080 ± 50	10385–10175	10250	50	KIGAM (Korea)	Amorosi et al., 2017
205 S9	8.40	Organic clay	2013 ± 57	1560–1285	1425	70	ENEA (Italy)	Amorosi et al., 2003
205 S9	22.40	Shell	2000 ± 40	1800–1570	1680	60	KIGAM (Korea)	Campo et al., 2017
205 S9	25.30	Shell	6440 ± 50	7225–6950	7080	70	KIGAM (Korea)	Campo et al., 2017
205 S9	26.95	Shells / Lentidium	7975 ± 30	8382–8192	8298	50	Keck-CCAMS (CA., USA)	Scarponi et al., 2013
205 S9	26.95	Shells / Varicorbula	8075 ± 30	8501–8316	8398	45	Keck-CCAMS (CA. <i>,</i> USA)	Scarponi et al., 2013
205 S9	31.20	Plant fragments	9500 ± 80	11,110– 10,570	10,840	160	ETH (Switzerland)	Amorosi et al., 2003
205 S9	35.30	Wood	18,830 ± 140	23,035– 22.410	22,710	165	ETH (Switzerland)	Amorosi et al., 2003

Table 1 – List of radiometric ages.

p cies				Abiot	ic parar val	neters' r ues	nean		
Benthic grou	Modern biofac	Color	Key taxa	Depth (m)	Sand (%)	Organic matter (%)	CaCO ₃ (%)	Geographic distribution	Environmental features
	01		Palmoconcha turbida, L. ramosa, other Leptocythere	11.7	6.3	3.9	21.8	A few km south of the Po Delta	High sediment and organic matter supply determining recurrent oxygen deficiency at shallow depth
	02		S. incongruens, Palmoconcha turbida	17.0	4.9	1.1	32.1	Adige river mouth; South of the Po Delta	Moderate sediment supply at intermediate water depth
	03		C. neapolitana, L. ramosa, S. versicolor	27.5	2.2	1.4	28.1	Mud belt	High sediment and organic matter supply south of the feeding mouths at moderate water depth
acods	04		S. incongruens, Pontocythere turbida, Palmoconcha turbida, Xestoleberis spp.	12.3	51.9	0.5	50.4	Along the coast, North and South of the Po Delta	Low to moderate sediment supply, sandy substrates with high CaCO₃ subject to strong longshore currents at shallow depth, outside of the main feeding mouths influence
Ostra	05		S. incongruens, L. tumida, Cytheretta spp., Aurila spp., Semicytherura spp., L. napoliana	24.2	75.8	0.5	49.6	Shallower relict sands	Sediment starvation, very sandy substrate with high CaCO₃ at moderate water depth
	90		Pontocythere turbida, Semicytherura spp., Aurila spp.	35.0	66.4	0.7	30.6	Deeper relict sands	Sediment starvation, sandy substrate at high water depth
	07		C. neapolitana, Semicytherura spp., Callistocythere spp., Pterigocythereis spp., C. edwarsii, Cytheropteron spp., Bosquetina spp.	34.4	32.7	0.7	32.5	Fine-grained shelf	Low sediment supply on mixed substrates at high water depth
	F1		A. parkinsoniana - A. tepida, N. turgida	14.3	4.2	3.3	26.5	In proximity to the Po and Adige river mouths	High organic matter supply near the main feeding mouths
S	F2		A. parkinsoniana - A. tepida, A. perlucida, Cribroelphidium ex gr. granosum, Cribroelphidium ex gr. poeyanum	16.0	13.5	0.8	29.5	Along the coast, South of the Po Delta	Moderate organic matter supply at shallow water depth
Foraminifer	F3		Q. seminula, Adelosina spp., T. trigonula, other Quinqueloculina, Cribroelphidium ex gr. granosum, Cribroelphidium ex gr. poeyanum	14.5	49.7	0.6	62.0	Along the coast, North of the Po Delta	Low organic matter supply, strong longshore currents, high CaCO₃ at shallow depth updrift of the main feeding sources
	F4		N. turgida, V. bradyana	30.7	2.9	1.5	28.6	Mud belt	High organic matter supply south of the feeding mouths at moderate water depth
	F5		B. granulata, A. beccarii, A. mamilla, C. lobatulus, N. terquemi, R. bradyi	31.6	59.7	0.6	36.8	Shelf	Low organic matter supply at high water depth

Table 2 - List of the modern North Adriatic biofacies defined in Barbieri et al. (2019) through thresholds of
 environmental variables. Modern biofacies are used in this work as reference for the comparison with fossil
 assemblages.

798

	Aver			Mean abundance							
Taxon	age	Contrib	Cumulat		TST		HST - Vol	ano lobe	HST - Goro lobe		
	dissi m.	ution %	ive %	187 S4	205 S9	EM13	205 S9	EM13	187 S4	EM13	
Leptocythere ramosa	0.12	18.19	18.19	2.24	0.86	0.43	2.59	6.52	3.89	68.37	
Pontocythere turbida	0.07	10.75	28.95	18.99	18.05	19.71	27.32	22.43	34.72	3.86	
Semicytherura incongruens	0.06	10.09	39.04	20.44	30.59	24.95	15.18	16.68	15.08	2.73	
Loxoconcha ex gr. rhomboidea	0.05	7.55	46.59	14.52	10.67	17.86	1.65	3.22	5.44	0.00	
Palmoconcha turbida	0.04	6.81	53.39	1.92	1.62	1.48	10.91	9.98	9.27	11.71	
Other Semicytherura	0.04	5.50	58.89	13.85	14.76	15.06	7.23	7.05	5.37	0.24	
Sagmatocythere versicolor	0.03	5.25	64.14	2.24	2.59	1.07	3.41	7.46	2.46	0.00	
Sagmatocythere napoliana	0.03	4.34	68.48	2.24	3.63	9.94	0.31	1.83	0.00	0.00	
Xestoleberis spp.	0.03	4.04	72.52	1.76	1.44	0.41	3.38	3.96	6.33	2.15	
Hiltermannicythere turbida	0.02	3.60	76.11	1.76	5.71	1.00	0.31	0.32	0.54	7.51	
Hiltermannicythere sphaerulolineata	0.02	3.49	79.60	2.40	0.81	1.09	5.33	3.82	3.93	0.86	
Neocytherideis subulata	0.02	3.10	82.70	0.00	0.52	0.36	3.87	2.52	2.66	1.25	
Carinocythereis whitei	0.02	2.88	85.58	0.79	1.33	0.34	3.53	0.87	1.02	0.45	
Leptocythere bacescoi	0.02	2.69	88.27	0.48	2.01	0.00	2.31	2.27	1.97	0.00	
Loxoconcha rubritincta	0.01	2.25	90.53	0.96	1.04	0.00	1.86	0.00	1.41	0.00	
Loxoconcha aff. L. bonaducei	0.01	2.01	92.54	0.48	0.00	1.43	0.97	1.78	0.08	0.00	
Callistocythere spp.	0.01	1.84	94.37	1.59	1.62	0.70	0.76	0.35	1.94	0.00	
Cytheretta spp.	0.01	1.71	96.08	7.94	0.00	0.20	0.44	0.00	0.00	0.00	
Hemicytherura spp.	0.01	1.30	97.38	0.00	0.29	0.00	0.96	0.83	0.33	0.00	
Other Leptocythere	0.01	0.80	98.19	0.00	0.00	0.24	0.31	0.87	0.00	0.00	
Pontocypris spp.	0.00	0.71	98.90	0.00	0.00	0.14	0.00	1.08	0.00	0.00	
Paracytheridea spp.	0.00	0.62	99.52	2.07	0.00	0.20	0.00	0.29	0.16	0.00	
Aurila spp.	0.00	0.30	99.82	0.00	0.57	0.14	0.13	0.00	0.11	0.00	
Bosquetina group	0.00	0.13	99.95	0.00	0.00	0.22	0.00	0.11	0.00	0.00	
Cytheridea neapolitana	0.00	0.05	100.00	0.00	0.29	0.00	0.00	0.00	0.00	0.00	

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Table 3 - Results of the SIMPER analyses performed on sediment units within each core, on Hellinger transformed ostracod data, with mean abundances expressed in percentage form. Grey cells evidence
 characteristic mean frequencies of taxa with a marked paleoecological significance for each study interval.
 Overall average dissimilarity: 0.64.

		Core	Ostracods	Foraminifers
		205\$9	100.0%	100.0%
тѕт		EM13	81.3%	100.0%
		187S4	100.0%	100.0%
	ano oe	205S9	25.0%	90.6%
цст	Vola Iot	EM13	38.9%	55.7%
пэт	ro Je	187S4	69.0%	93.8%
	Go Tot	EM13	6.0%	100.0%

806 Table 4 - Relative abundance of significant modern analogs per unit based on the four most similar modern807 sites.

		• • •	Cumulat	Mean abundance							
Taxon	Average	Contrib			TST		HST - Vol	ano lobe	HST - Go	oro lobe	
	aissim.		ive %	187 S4	205 S9	EM13	205 S9	EM13	187 S4	EM13	
Ammonia parkinsoniana - A. tepida	0.11	25.85	25.85	15.61	11.42	3.94	57.49	36.50	63.67	62.73	
Aubignyna perlucida	0.03	8.07	33.92	2.82	1.28	0.00	6.59	11.09	5.98	17.21	
Quinqueloculina group	0.03	7.62	41.54	14.11	15.82	17.34	4.91	8.05	4.61	1.03	
Porosononion ex gr. granosum	0.03	7.41	48.95	10.68	13.76	12.54	3.56	10.49	3.49	9.22	
Triloculina ex gr. trigonula	0.03	6.73	55.68	5.56	8.44	14.20	1.00	3.95	1.71	0.16	
Nonionella turgida	0.02	5.50	61.17	0.90	1.59	0.40	1.99	4.55	1.10	0.17	
Ammonia beccarii	0.02	4.90	66.07	1.51	3.81	2.32	3.78	0.44	1.04	1.00	
Textularia agglutinans	0.02	4.76	70.83	8.03	4.54	4.75	1.06	1.88	0.77	0.00	
Haynesina spp.	0.02	4.76	75.60	2.37	3.03	0.47	6.37	3.44	6.16	1.29	
Adelosina spp.	0.02	4.00	79.60	9.79	7.26	6.74	1.89	3.33	1.89	1.15	
Cribroelphidium ex gr. poeyanum	0.01	3.29	82.89	7.29	5.08	2.81	3.91	2.04	4.06	3.31	
Elphidium advenum	0.01	2.86	85.75	4.59	5.81	2.50	1.31	1.07	0.66	0.09	
Asterigerinata mamilla	0.01	2.66	88.40	0.00	0.00	3.66	0.00	1.52	0.00	0.00	
Rosalina bradyi	0.01	2.53	90.93	2.55	0.29	5.29	0.20	1.04	0.10	0.00	
Neoconorbina terquemi	0.01	2.27	93.20	0.00	0.00	5.44	0.00	0.74	0.00	0.00	
Buccella granulata	0.01	2.23	95.43	1.94	2.13	6.09	0.37	0.38	0.21	0.09	
Quinqueloculina seminula	0.01	1.88	97.31	0.74	3.29	2.68	1.39	1.58	1.24	2.04	
Elphidium crispum	0.01	1.37	98.68	1.79	1.50	1.24	0.41	0.23	0.19	0.00	
Reussella spinulosa	0.00	0.60	99.28	0.30	0.00	0.16	0.03	0.42	0.03	0.00	
Cassidulina carinata	0.00	0.32	99.60	0.15	0.00	0.00	0.15	0.01	0.11	0.05	
Bulimina marginata	0.00	0.20	99.81	0.00	0.00	0.00	0.00	0.01	0.13	0.14	
Cibicidoides lobatulus	0.00	0.19	100.00	0.00	0.00	0.38	0.02	0.04	0.03	0.00	
Valvulineria bradyana	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

Table 5 - Results of the SIMPER analyses performed on sediment units within each core, on Hellingertransformed benthic foraminiferal data, with mean abundances expressed in percentage form. Grey cells
evidence characteristic mean frequencies of taxa with a marked paleoecological significance for each study
interval. Overall average dissimilarity: 0.42.

				Ostr	acods	Benthic foraminifers				
			Water depth (m)		Sand concentr (%)	Sand concentration (%)		h (m)	Organic matter (%)	
			Estimated value	S.E.	Estimated value	S.E.	Estimated value	S.E.	Estimated value	S.E.
		TST	23.3	1.1	58.3	3.5	18.4	1.3	0.8	0.3
205S9	ТЗН	Volano prodelta	15.3	1.3	35.1	3.8	13.1	1.5	2.0	0.4
		Volano delta front	14.8	1.2	42.0	3.8	12.2	1.5	2.2	0.4
		TST	22.3	1.2	67.9	4.1	26.0	1.3	0.6	0.4
EM13	ST	Volano prodelta	15.0	1.2	31.7	3.9	14.7	1.3	1.5	0.4
	Η	Goro prodelta	14.0	1.3	3.6	4.3	12.2	1.5	2.3	0.4
18754	TST		20.2	1.0	62.7	3.8	17.6	1.3	0.9	0.3
	HST	Goro prodelta	15.0	1.2	42.8	3.9	12.4	1.4	2.1	0.4

Table 6 – Average values of estimated parameters *per* study unit within each core and associated standard

819 error (S.E.), considering only samples represented by significant modern analogs.



Figure 1 – Location of the three study cores and extension of Po Delta lobes based on preserved onshore
sand ridges (from Ciabatti, 1967). Maximum shoreline ingression from Bruno et al. (2017), seaward extent of
the modern prodelta from Correggiari et al. (2005a).



Figure 2 – Stratigraphy and modern analogs for benthic ostracods and foraminifers of core 205S9. On the right of the stratigraphic log, ages are reported as calibrated years B.P. Samples included in multivariate ordinations on the right of the sample column; on the left, samples inspected for quantitative analyses, but including a poor fauna. Significant modern analogs are reported in bold colors, whereas non-significant analogs, up to the fourth most similar sample, are reported in shaded tones. Colors are in accordance with modern biofacies defined in Barbieri et al. (2019), whose distribution is reported on the bottom of the figure.



Figure 3 - Stratigraphy and modern analogs for benthic ostracods and foraminifers of core EM13. On the right of the stratigraphic log, ages are reported as calibrated years B.P. For additional information, including the distribution of the modern biofacies, the reader is invited to refer to Fig. 2.



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Figure 4 - Stratigraphy and modern analogs for benthic ostracods and foraminifers of core 18754. On the
right of the stratigraphic log, ages are reported as calibrated years B.P. For additional information, including the
distribution of the modern biofacies, the reader is invited to refer to Fig. 2.



Figure 5 – Graphic display of benthic ostracod (a) and foraminifer (b) dissimilarity matrices for transgressive
and highstand units of the Volano and Goro lobe in each core.



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Figure 6 – (a) Estimated values of environmental drivers on the modern benthic ostracods and foraminifers (from Barbieri et al., 2019) extracted from the wPCoA of core 205S9. Estimated abiotic values that do not reflect true modern environmental conditions are marked by asterisks. Dashed lines indicate estimated values from samples with no significant modern analogs. On the right of the stratigraphic log, ages are reported as calibrated years B.P. (b) In the wPCoA, the core trajectory is indicated by a black line starting from a point and partitioned into study units. The core trajectory is superimposed over the distribution of modern sites on the multivariate space, grouped in accordance to modern biofacies.



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Figure 7 – (a) Estimated values of environmental drivers on the modern benthic ostracods and foraminifers
(from Barbieri et al., 2019) extracted from the wPCoA of core EM13. On the right of the stratigraphic log, ages
are reported as calibrated years B.P. (b) wPCoA of the core trajectory superimposed over the distribution of
modern sites on the multivariate space, grouped in accordance to modern biofacies. For further explanations,
refer to Figure 6.



Figure 8 – (a) Estimated values of environmental drivers on the modern benthic ostracods and foraminifers
(from Barbieri et al., 2019) extracted from the wPCoA of core 187S4. On the right of the stratigraphic log, ages
are reported as calibrated years B.P. (b) wPCoA of the core trajectory superimposed over the distribution of
modern sites on the multivariate space, grouped in accordance to modern biofacies. For further explanations,
refer to Figure 6.





Figure 9 – PCoA ordination of distances among the centroids for individual levels of the two main effects in
the benthic ostracod (a) and foraminifer (b) dataset, namely cores (205S9, EM13, 187S4) and systems tracts

868 (transgressive and highstand Volano and Goro delta lobe deposits).