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Correlation of foraminifera content and granulometric properties of sediment in different transitional environments along a karstic coast, eastern Adriatic, Croatia

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Abstract

Purpose The aim of this study was to describe the distribution and composition of foraminiferal assemblages and granulometric properties of sediment in transitional environments along the eastern Adriatic coast. Another objective was to compare the results and establish correlations (similarities and differences) between these sensitive environments.

Materials and methods Sediments from transitional environments were collected in December 2019 at three geographically separate sites: the Mirna salt marsh, the Soline mud plain, and the Nin intertidal plain. A total of 18 sediment samples (top 2 cm) were collected along the land-sea transect. Micropaleontological and granulometric analyses were performed. Identification of foraminiferal genera and species, absolute and relative abundance, and ecological (biodiversity) indices were determined on standardized samples. Particle size distribution was determined, which allowed classification of the sediment. Carbonate content and organic content anaylses were performed as well.

Results At the northernmost site, at the Mirna salt marsh, muddy sediments with low species diversity predominate. The Soline mud plain was characterized by greater species diversity and a uniform proportion of sandy and silty components in sediment. At the Nin intertidal plain, sediment was primarily sand with the greatest foraminiferal species diversity compared to the other two sites. The genus *Ammonia* dominated in all foraminiferal assemblages.

Conclusions A different distribution pattern of benthic foraminifera in each environment was associated with variations in the grain size of sediment and was also influenced by the supply of freshwater from the river and karstic springs. Considering the lack of research on the transitional environments of the eastern Adriatic coast, this work provides more detailed data and emphasizes the importance of these environments and their biota.

Keywords Salt marsh · Mud plain · Intertidal plain · Benthic foraminifera · Eastern adriatic coast

1 Introduction

Transitional environments (TEs), areas between terrestrial and marine environments, are under the combined influence of marine and freshwater (McLusky and Elliott 2007). They are most impacted by climate change, sea level rise, and increasing human activities and thus are considered very sensitive environments. The high instability of physico-chemical parameters (e.g., salinity, temperature, oxygen; Cognetti and Maltagliati 2000; Elliott and Quintino 2007), a range of diverse ecosystems that contribute to coastal primary production and different geomorphological types (river mouths, lagoons, salt marshes, tidal plains), characterizes TEs.

Along the eastern Adriatic coast (EAC), TEs include lagoons, salt marshes, tidal plains, estuaries, and deltas. The Adriatic Sea, a semi-enclosed sea, is considered a low-energy water body with a microtidal regime (low tidal range) and low wave heights. The eastern Adriatic coast is karstic, steep, and rocky (Pikelj and Juračić 2013, and references therein) and thus considered resilient to erosion. Sediment supply by karstic rivers is limited due to the lithology and geological structure of the coast, and consequently, these rivers formed karstic estuaries at their

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mouth during the Holocene transgression. However, some of these karstic estuaries formed intraestuarine deltas during the Holocene highstand as a consequence of a lower rate of sea-level rise and higher sediment delivery (Felja et al. 2015; Felja 2017). Other TEs were also developed during the Holocene highstand.

Benthic foraminifera are commonly used to describe transitional and marine environments because they are abundant (Murray 2006; Schönfeld et al. 2012) and are sometimes the only tool for describing an environmental signal from featureless muds. Their distributional pattern, species diversity, and density depend on geographic position, sedimentological properties, and the regularity and degree of marine influence (Jorissen et al. 2007; Schönfeld et al. 2012). In stressful environments such as marshes and estuaries, agglutinated foraminifera dominate at higher latitudes (Schafer and Cole 1986) whereas calcareous forms predominate at lower latitudes (Sen Gupta and Schafer 1973). Studies from the Mediterranean (Ionian Sea, Venice lagoon, Scott et al. 1979; Petrucci et al. 1983) showed that calcareous taxa predominate at the lowermost elevation in relation to sea-level that agglutinated, and calcareous taxa are common in the intertidal zone and that the greatest proportion of agglutinated taxa is found in the high marshes. A few studies on foraminiferal composition from marine ponds along the eastern Adriatic coast (island of Cres, the delta of the rivers Mirna and Neretva) emphasize the importance of the reconstruction of the sea level in the past (Felja et al. 2015; Felja 2017; Brunović et al. 2019; Capotondi et al. 2022).

The purpose of this research was to examine the composition of foraminiferal assemblages and granulometric properties of sediment in selected transitional environments located at the northern part of the eastern Adriatic coast, to determine how sediments impact the foraminiferal diversity and the distribution pattern of different life-strategy groups. The research combines the results of analyses of benthic foraminiferal assemblages of surface samples from three TEs: the salt marsh at the mouth of the Mirna River (Istrian Peninsula), the Soline mud plain (Krk Island), and the Nin intertidal plain. In contrast to the abundance of data for the northwestern and western Adriatic coast (Petrucci et al. 1983; Albani et al. 1984; Hohenegger et al. 1989, 1993; Donnici et al. 1997; Serandrei Barbero et al. 2004), there are few studies on salt marshes and transitional environments of the eastern Adriatic coast (Ćosović et al. 2011; Shaw et al. 2016; Felja 2017). This research provides new data on the characteristics of transitional environments in the mainly karstic environments in the northernmost area of the Mediterranean Sea. The study focuses on the interaction between sediment characteristics (grain size, carbonate content) and associated foraminiferal assemblages in three TE biotopes, one under the influence of the river and the others influenced by tides. These results will have application in environmental protection and preservation of these sensitive and vulnerable environments, as well as for reconstruction of the past sea-level changes during the Pleistocene and Holocene (sediment and foraminiferal content in TEs, especially salt marshes, are one of the best markers of the sea-level in the past).

2 Material and methods

2.1 Study area and geological background

The Mirna River is the longest surface watercourse in Istria that flows through carbonate deposits (Cretaceous and Eocene limestones) and Eocene calciclastic deposits (flysch, Polšak and Šikić 1963; Pleničar et al. 1965) and discharges into the Adriatic Sea near the town of Novigrad. Downstream, the river valley widens into a floodplain that is about 1 km wide in some places. The Mirna River delta plain is the largest in the eastern part of the northern Adriatic and was developed during the Holocene highstand as an intraestuarine delta in the karstic estuary (Felja et al. 2015; Felja 2017). In a salt marsh, developed at the mouth of the Mirna River, seven samples were collected from the different parts of the salt marsh (Fig. 1). The Mirna salt marsh is placed at about sea level (except for several mud mounds which are slightly higher) and is mostly covered with marsh vegetation. Most of the marsh is periodically flooded by the tide. Sample M1 was collected most distally from the bay, in the upper part of the salt marsh where the marine influence was weak, and sediment was drier. Samples M2–M5 were collected in the middle part of the marsh that is under marine influence and flooded during high tide. Sample M6 and M7 were collected in the lower marsh, proximal to the sea, with strong marine influence.

In the Soline mud plain on the Krk Island, five samples were taken for analyses (K1–K5). Soline Bay is a large, shallow (an average depth of 3 to 4 m) bay, protected from the open sea. The intertidal mud plain and salt marsh (Čižići) were developed with several streams of freshwater from the land. The mud plain area is large, located on the edges of the salt marsh, large surface covered by water at high tide (sand ripple), and exposed at low tide. Vegetation cover is scarce, mostly developed on mud mounds. This area is heavily impacted by human activities, especially in the summer season (the wet sediments are known for their healing properties). The catchment area of the bay consists of Eocene flysch (Babić 2003), with a calcite content of up to 36% (Horvat et al. 2023, in press). Along the low-lying area, sample K1 was taken in the upper part of the mud plain/salt marsh, in an area minimally influenced by the sea, samples K2 and K3 in the middle part, inundated during high tide, and samples K4 and K5 in the lower part, from the area that is completely flooded by the sea (Fig. 1).

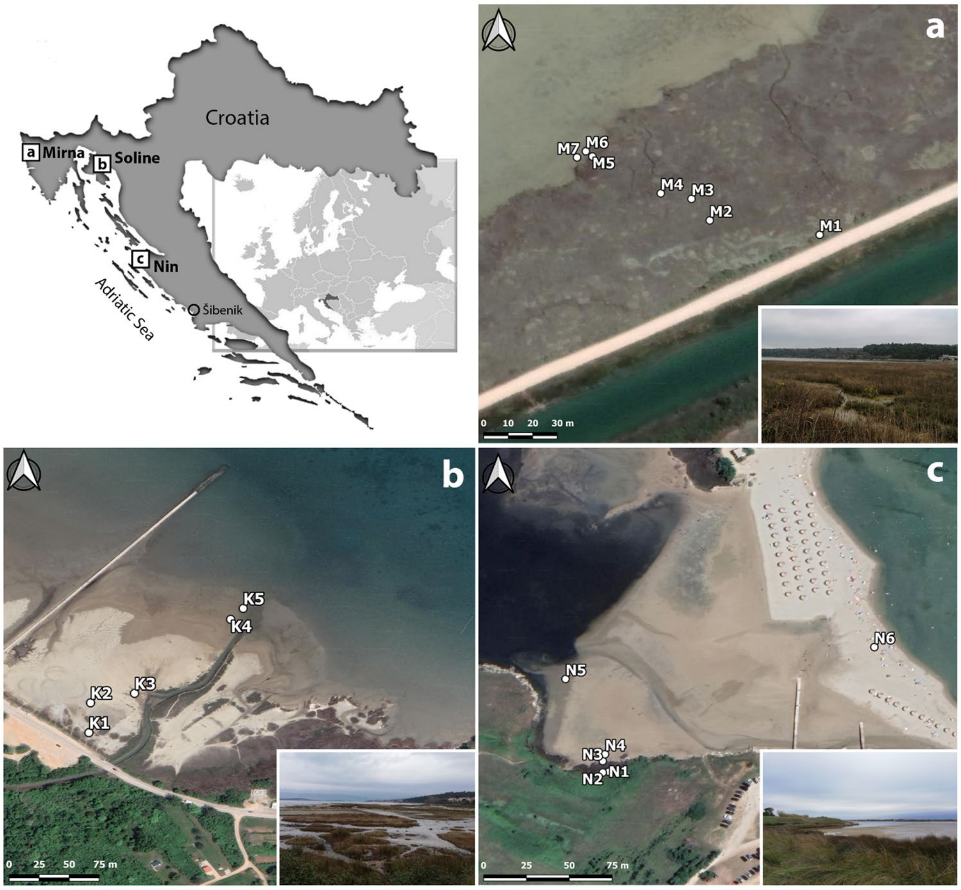

Fig. 1 Location and aerial photographs of the studied sites, with location of sampling stations and related photographs of the environment: a the salt marsh at the mouth of the Mirna River (Istrian Peninsula; 45°19′10″N; 13°36′01″E); b the Soline mud plain (Krk Island; 45°09′03″N; 14°35′57″E); c the Nin intertidal plain (44°14′51″N; 15°10′35″E) (map pictures taken and modified in Google Earth)

The Nin intertidal plain consists of several sub-environments. The study area included the following: salt marsh (small area, covered with vegetation at higher elevations), intertidal plain (with well-developed sand ripples, numerous shells of gastropods and bivalves occur), lagoon, and the shallow sea bottom at the Queen's beach (under strong human influence during summer season). The shores are subjected to abrasion and erosion because of waves and tide. In low-lying areas, samples were taken in the salt marsh (N1 and N2), intertidal plain (limited marine influence N3, N4), and shallow lagoon (sample N5). Only sample N6 was collected at the proximal part of the sea, on a sandy beach that was flooded completely by the sea during high tide (Fig. 1).

2.2 Sampling and sample preparation

Field sampling in all areas was carried out in December 2019. A total of 18 short sediment cores (inner diameter 3 cm, length 10 cm) were collected, stored in the refrigerator, and sliced and preserved the next day in the laboratory of the Department of Geology, Faculty of Science, University of Zagreb. The uppermost 2 cm of the sediment was used for the foraminiferal, granulometric, carbonate content and organic content analyses.

2.3 Micropaleontological methods

Samples for foraminiferal analysis were treated with Rose Bengal solution to distinguish living from dead specimens (Schönfeld et al. 2012). Although samples were kept in 70% (ethanol/2 g l^{-1}) Rose Bengal (l) solution for more than 2 weeks, the small number of tests were stained, and therefore, the total foraminiferal assemblage was analyzed. Total assemblage is a reliable indicator of assemblages because all of the seasonal variations are included in it, and no seasonal variations of living species will be overemphasized (Scott and Medioli 1980a). Each sample was washed over a 63-µm sieve and dried at room temperature. The residue $^{>}$ 63 µm was split (for Mirna and Krk samples between 0 and 3 times and for Nin samples between 0 and 4 times) to aliquots of approximately 300 specimens per sample, and the generic and species identification was performed according to the criteria Loeblich and Tappan (1987) using Cimerman and Langer (1991), Alfirević (1998), and Meriç et al. (2014). Species and genera names follow the Word Register of Marine Species (WoRMS Editorial Board 2020). In this study, ammonias recognized as *A. tepida* from Cimerman and Langer (1991) were referred to as *A.* ex gr. *tepida*, following the Hayward et al. (2021) comprehensive study and their worldwide distribution. Absolute and relative numbers of foraminifera were determined in all samples, as well as the composition of the foraminiferal assemblage. Considering the relative abundance of individual species, dominant (> 10%), common (4–10%), accessory (1–4%), and rare or accidental (< 1%) species were determined according to Murray (1991). A functional grouping was made with regard to the living strategy (epifaunal, infaunal, and epi-infaunal foraminifera) following Langer (1993), Jorissen (1999), and Murray (2006) definition. Some species live at or near the water/sediment interface and show the ability to migrate to microhabitats with more favorable ecological conditions (in terms of stability or concentrations of oxygen and food), thus exhibiting an epifaunal or shallow infaunal habitat's strategy. Reworked individuals (planktonic and benthic) were found in some samples, which were recognized as extinct species, so they were omitted from the statistical analyses. Ecological indices were calculated using Past software (Hammer et al. 2001): Species richness, Simpson index ($1-D$), Shannon (H) index, and Fisher (α) index. Q-mode cluster analysis (HCA) was performed using an unweighted pair-group algorithm (UPGMA) and Euclidean distance. Only foraminifera with abundance greater than 2.5% in at least one sample (from any site) were considered (Table 1). Scattered and infrequently occurring taxa (< 2.5% relative abundance) were omitted because they had an insignificant effect on the formation of the major groups. For cluster analysis only, genera with several species that are rarely represented were merged into a major generic group (*Quinqueloculina* spp. and *Elphidium* spp.). Consequently, the number of benthic foraminifera taxa was reduced to 18.

2.4 Granulometric methods

The determination of the granulometric properties of the sediment was done by a combined method of wet sieving and the use of a sedigraph, which provides a continuous range of particle sizes. Wet sieving is suitable for particles larger than 63 µm, while a sedigraph is used for all smaller particles (silt and clay). Each weighed sample was sieved through seven Retsch®ASTM standard sieves. The diameter of the sieve openings ranged from fine gravel to very fine sand, according to the classification of Wentworth (1922). The remaining mud suspension was analyzed on a sedigraph (SediGraph 5100) using the SediGraphWin 5100 computer program (Micromeritics 2002). Sediments were classified according to Folk's (1954) diagrams based on the ratio of sand (63–2000 µm), silt (2–63 µm), and clay (< 2 µm). Statistical analysis was performed with the Microsoft® Office Excel computer program using the GRADISTAT Ver. 6.0 program (Blott and Pye 2001). The obtained percentages of sand, silt, and clay were plotted in the ternary diagram (Fig. 3).

The abundance of biogenic and lithogenic components in the studied samples was estimated by visual (stereomicroscopic) observation. Therefore, it was only possible to give a definition such as more or less common.

2.5 Carbonate content analyses

The carbonate content of the bulk sediment was determined volumetrically by the Scheibler procedure. The procedure includes the volumetric measurement of released CO_2 after digestion in diluted hydrochloric acid (1:1), at controlled temperature and pressure, using a Scheibler calcimeter (Önorm 1084 1989). Two measurements were made for each sample, so that the final result (Table 4) represents the arithmetic mean with an analytical precision of ± 2%.

2.6 Loss on ignition (LOI) method

This method estimates organic matter in sediments based on the change in weight associated with the oxygenation of organic matter at high temperatures. The modified method of Zhang and Wang (2014) was used. Loss on ignition (LOI) was determined by dry ashing in a muffle furnace at 375 °C for 24 h. Organic matter was calculated as weight loss between 105 and 375 °C. To improve accuracy, analyses were performed in duplicate per sample so that the result (Table 4) represents the arithmetic mean. Values considered to be indicating high levels of sediment organic carbon have ranged from *1.1 to 5%* (Nelson 2020).

3 Results

3.1 Micropaleontological analyses

3.1.1 Distribution and diversity of benthic foraminifera

The distribution of foraminifera in the studied assemblages showed variation between the sampled sites. The relative proportion of species presented in each sample and living strategy are shown in Table S1 (Electronic Supplementary Material). Three species were found only in the sediments from the Mirna salt marsh, 17 species were unique for the Soline mud plain, and 24 for the Nin intertidal plain.

In the Mirna salt marsh, representatives of *A.* ex gr. *tepida* dominated (reaching up to max. of 80.04% of the assemblage in some samples), followed by *Trochammina inflata* (including *Trochammina* sp.; max. 29.40%), *Porosononion granosum* (max. 26.4%), and *Haynesina depressula* (including *Haynesina* sp.; max. 19.35%; Table S1, Table 1). Diversity indices were low, Fisher (α) index ranged from 1.67 to 2.26, Shannon (H) index from 0.83 to 1.84, and Simpson's index (1-D) from 0.33 to 0.81 (Table 2). Foraminifera living as epi-infauna and shallow infauna were the most abundant and make up to 96.33% of the assemblages (Table 3).

In the Soline mud plain, the genus *Ammonia*, represented by *Ammonia beccarii* and *Ammonia parkinsoniana*, and *A.* ex gr. *tepida*, was dominant in almost all samples, followed by representatives of the genus *Haynesina* and the species *T. inflata* (Table S1, Table 1). Reworked tests of the Eocene planktonic foraminifera and *Nummulites* were present and abundant at sites K5 and K2. Values for the Simpson index ($1-D$) ranged from 0.62 to 0.85, the Shannon (H) index from 1.53 to 2.34, and the Fisher (α) index from 4.17 to 8.04 (Table 2). Epi-infaunal specimens dominated with a proportion of up to 79.49% (*A.* ex gr. *tepida*, *T. inflata*), followed by infaunal specimens representing 25.40% of this assemblage (Table 3).

The genus *Ammonia* predominated in all samples at the Nin intertidal plain (Table S1, Table 1). Reworked Eocene planktonic foraminifera were found in all samples, and reworked specimens of the genus *Nummulites* in two samples. The values of the Shannon (H) and Fisher (α) indices were high (2.21–2.71 and 6.44–10.85, respectively), whereas those of Simpson index were uniform (between 0.81 and 0.90; Table 2). Epi-infauna prevailed (up to 64.83%), with *A. beccarii* being the most abundant in the assemblage, followed by epifaunal specimens (22.07%; Table 3).

3.1.2 Cluster analysis

The cluster analysis on foraminifera enabled the distinction of two major groups (Fig. 2) of sampling sites (A and B). Both can be subdivided into AI, *Ammonia* ex gr. *tepida–Porosononion granosum*; AII, *Ammonia* ex gr. *tepida*, BI, *Trochammina inflata–Ammonia* ex gr. *tepida*; and BII, *Ammonia* assemblage.

Cluster AI included six stations, M6 and M7 (lower Mirna marsh) and K1, K3, K4, and K5 (upper and lower part of the Soline mud plain; Fig. 1). This group was characterized by the dominance of *A.* ex gr. *tepida* (30.8–53.9%). The proportion of *P. granosum* (3.6–26.4%) and *H. depressula* (1.4–16.8%) was significant. There was a significant occurrence of *A. parkinsoniana* (3.6–10.5%) and *A. beccarii* (2.8–6.1%) in the samples from the Soline site (Fig. 2).

Cluster AII included three stations (M2, M3, M4) in the middle part of the Mirna salt marsh (Fig. 1). This cluster was characterized by a greater proportion of *A.* ex gr. *tepida* (64.7–80.1%), a lower proportion of *P. granosum* (1.1–19.3%), and a low abundance of *Haynesina* (Fig. 2). The biodiversity was lowest in these samples (Table 2).

Cluster BI included three stations (M1, M5, K2). Stations M1 and M5 were located at opposite ends (distal and proximal part) of the transect in the Mirna salt marsh, and K2 was sampled in the middle of the Soline mud plain (Fig. 1). The foraminiferal assemblages were represented by high proportions of *T. inflata* (16.3–29.4%), *Trochammina* sp. (1.1–14.4%), and lower proportion of *A.* ex gr. *tepida* (12.1–25.8%). The abundance of *H. depressula* was high in the samples from the Mirna River (11.3–19.4), while it was absent in the sample from the Soline site (Table S1, Table 1).

Cluster BII included six stations (N1, N2, N3, N4, N5, N6), all located along the Nin intertidal plain (Fig. 1). The foraminiferal assemblages were mainly represented by large and ornamented individuals of *A. beccarii* (31.3–32.6%), along with a significant occurrence of *A. parkinsoniana* (4.4–10.7%). This group was characterized by the scattered occurrence of *A.* ex gr. *tepida* (0–20.8%), *Q. seminulum* (0–12.7%), and *P. pertusus* (0.9–5.0%). The biodiversity was highest in these samples (Table 2).

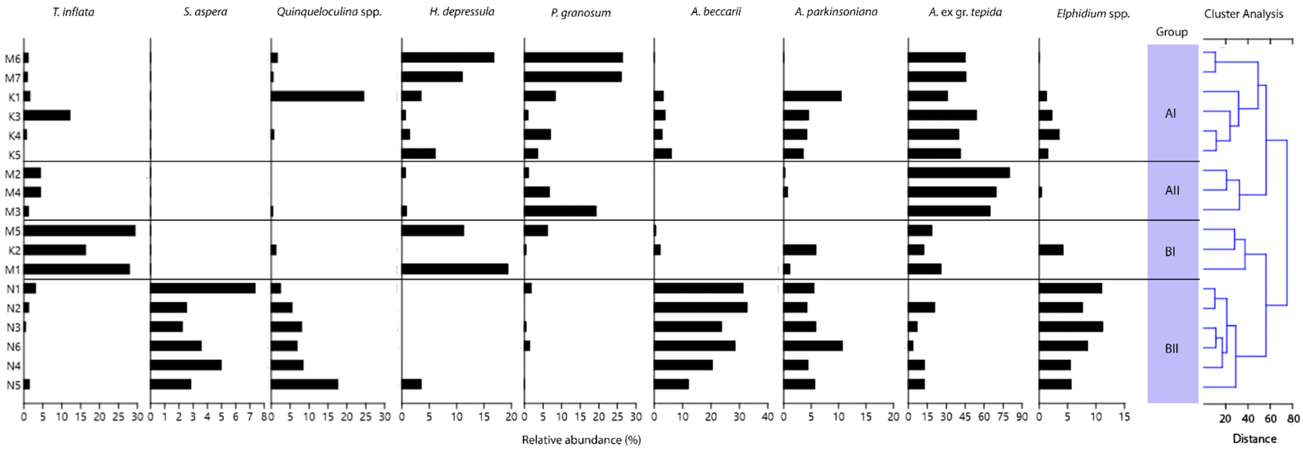

Fig. 2 Q-mode cluster analysis, using an unweighted pair-group average (UPGMA) algorithm and the Euclidean distance along with the presentation of the most numerous foraminifera. Dendrogram classification of sampling stations shows two clusters subdivided into four groups: AI, AII, BI, BII

Table 1 Distribution of foraminifera with relative abundance > 2.50% in at least one of the studied sample

Species	M1	M2	M3	M4	M5	M6	M7	K1	K2	K3	K4	K5	N1	N2	N3	N4	N5	N6
Trochammina inflata	27.90	4.34	1.20	4.40	29.40	1.10	0.90	1.59	16.32	12.18	0.70	-	3.07	1.27	0.45	-	1.41	-
Trochammina sp.	1.10	2.40	-	0.70	14.40	-	-	-	11.30	2.56	-	-	-	-	-	-	-	-
Siphonaperta aspera	-	-	-	-	-	-	-	-	-	-	-	-	7.36	2.54	2.23	4.97	2.82	3.56
Quinqueloculina spp.	-	-	0.40	-	-	1.60	0.50	24.45	1.26	-	0.70	-	2.44	5.51	8.04	8.40	17.61	6.84
Peneroplis pertusus	-	-	-	-	-	-	-	-	0.42	-	-	-	3.68	3.39	0.89	4.97	3.52	3.29
Bolivina spathulata	1.10	-	-	-	-	-	-	2.86	-	-	-	-	-	-	-	-	-	0.27
Eponides sp.	-	-	-	-	-	-	-	-	-	2.56	0.70	-	-	0.42	0.89	1.10	0.70	0.55
Cibicidoides sp.	-	-	-	-	-	-	-	-	3.35	-	-	-	0.61	0.42	-	-	-	-
Cibicides sp.	-	-	-	-	-	-	-	1.27	4.18	0.64	-	-	-	-	1.34	-	-	-
Haynesina depressula	19.35	0.65	0.80	-	11.30	16.80	11.00	3.49	-	0.64	1.40	6.09	-	-	-	-	3.52	-
Haynesina sp.	2.15	1.30	0.40	1.50	11.90	2.80	5.20	1.59	-	0.32	-	3.55	-	-	-	1.10	2.11	-
Porosononion granosum	-	1.10	19.30	6.70	6.20	26.40	26.00	8.25	0.42	0.96	7.00	3.55	1.84	-	0.45	-	-	1.37
Porosononion sp.	-	0.20	1.60	0.70	-	-	3.40	-	-	0.64	0.70	-	-	-	0.45	1.10	-	0.27
Ammonia beccarii	-	-	-	-	0.50	-	-	3.17	2.09	3.85	2.80	6.09	31.29	32.63	23.66	20.44	11.97	28.49
Ammonia parkinsoniana	1.10	0.20	-	0.70	-	-	-	10.48	5.86	4.49	4.20	3.55	5.52	4.24	5.80	4.42	5.63	10.68
Ammonia ex gr. *tepida*	25.8	80.04	64.66	69.30	18.60	45.00	45.60	30.79	12.13	53.85	39.86	41.12	-	20.76	6.70	12.71	12.68	3.56
Ammonia sp.	3.20	8.25	9.24	14.50	4.10	5.50	3.80	4.76	5.02	4.81	4.90	5.58	2.45	2.12	4.46	6.63	3.52	3.56
Elphidium spp.	-	4.19	-	0.40	-	-	-	1.28	4.19	2.24	3.50	1.53	11.03	7.63	11.17	5.52	5.63	8.5

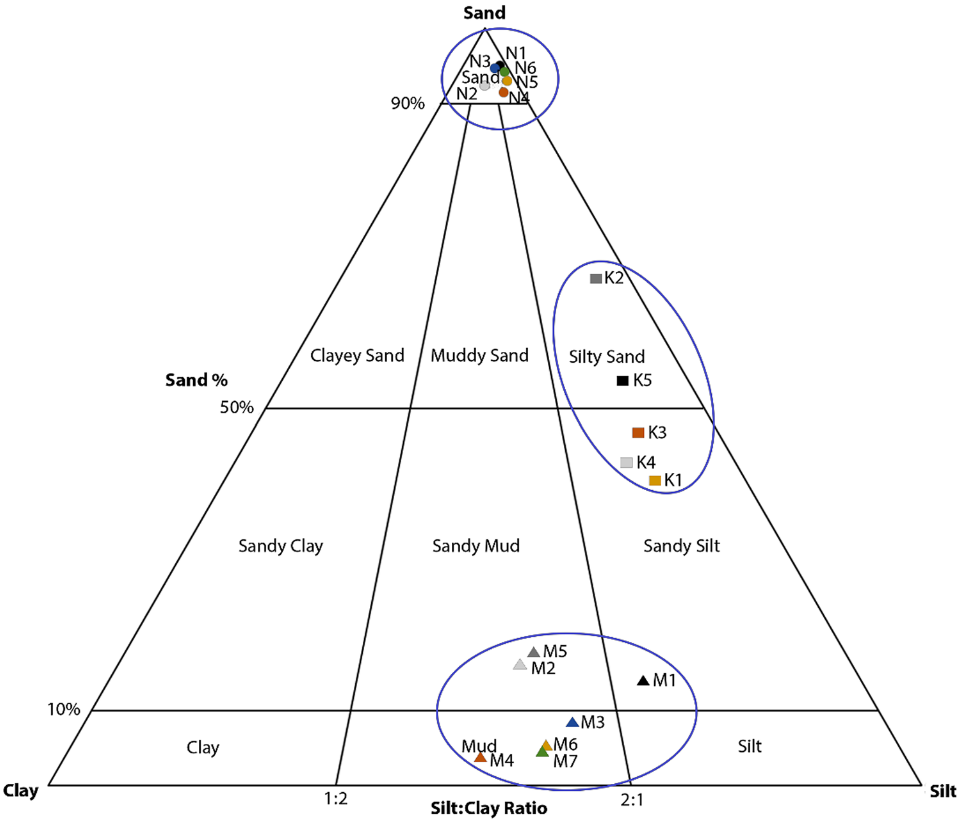

Fig. 3 Grouping of samples (Folk 1954) based on granulometric analysis: the Mirna salt marsh (M1–M7), the Soline mud plain (K1–K5), and the Nin intertidal plain (N1–N6)

3.2 Granulometric analyses, carbonate content, and organic content

The granulometric composition of the sediment, mean size, textural group, carbonate content, and organic content are given in Table 4. The Mirna salt marsh samples all belonged to the textural group of muds. Sandy fraction (very fine sand and fine sand) was biogenic in origin (foraminiferal tests and ostracod shells). Particles the size of pebbles were very rare (shells and plant remains). Carbonate content varied from the lowest value of 22% in sample M3 to the highest value of 47% in sample M7, whereas organic content showed high values (concentration from 2.8% in M5 to 6.4% in M3, Table 4). At the Soline intertidal plain, samples were composed of both mud and sand fractions equally. The dominance of the sand fraction was observed in samples K2 and K5, with the largest proportion in sample K2 (66.3%). The carbonate content and organic content were generally low. The lowest carbonate content was present in samples K2 and K4 (9%) and the highest in sample K5 (13%), (Table 4). Organic content (Table 4) ranged from low (1.0% in K5) to high (4.8% in K4). The coarser-grained component was partly of lithologic origin and partly consists of bivalve shells and foraminiferal tests. Sandy particles predominated in all samples from the Nin intertidal plain and their percentage ranged from 75.3% in sample N6 to 96.8% in sample N1. The gravel- and sand-sized particles were mostly lithogenic in origin. Carbonate content was very high in all samples and varied between a maximum of 97% in sample N6 to a minimum of 88% in sample N1 (Table 4). Organic content was very low and ranged between a minimum of 0.3% in N6 and a maximum of 1.4% in N1 (Table 4).

4 Discussion

In the studied TEs, benthic foraminiferal assemblages were dominated by representatives of the genus *Ammonia,* in both muddy and sandy sediments (Table 1). This is consistent with the studies on the distribution and adaptation to different ecological conditions of *Ammonia* species in the northern Adriatic (Žvab Rožič et al. 2022) and worldwide (Debenay et al. 1998; Donnici and Serandrei Barbero 2002; Murray 2006; Martinis et al. 2016, and references therein). Representatives of the genus *Ammonia* are able to tolerate a broad range of salinity, temperature, pH, and oxygen levels and are known to be dominant in shallow-water areas with the most variable conditions (Murray 2006; Frontalini et al. 2009). The preference of *H. depressula* specimens for the mud substrate (Jorissen 1988; Murray 2006; Melis and Covelli 2013; Melis et al. 2019) was confirmed by their greater abundance in the muddy Mirna salt marsh and their

Table 2 Number of species and specimens, diversity indices values, and relative number of reworked benthic and planktonic specimens in samples from each station

	M1	M2	M3	M4	M5	M6	M7	K1	K2	K3	K4	K5	N1	N2	N3	N4	N5	N6
Taxa (S)	8	10	10	10	9	9	12	22	25	19	19	15	25	23	31	23	21	37
Specimens (without indeterminable)	76	454	244	267	187	362	425	302	172	285	103	148	130	223	178	141	119	321
Simpson index ($1-D$)	0.72	0.33	0.52	0.49	0.81	0.69	0.69	0.85	0.83	0.62	0.67	0.67	0.82	0.81	0.88	0.88	0.90	0.86
Fisher (α) index	2.26	1.81	2.10	2.05	1.97	1.67	2.30	5.46	8.04	4.59	6.85	4.17	9.20	6.44	10.85	7.80	7.40	10.80
Shannon (H) index	1.47	0.83	1.10	1.13	1.84	1.44	1.49	2.34	2.33	1.53	1.82	1.70	2.39	2.21	2.71	2.51	2.62	2.67
Reworked benthic foraminifera	-	-	-	-	-	-	-	0.32	25.86	5.13	18.88	19.29	-	-	-	1.53	-	2.19
Reworked planktonic foraminifera	-	-	-	-	-	-	-	0.95	-	3.53	0.70	4.07	1.23	1.27	10.27	3.87	6.34	2.19

Table 3 Relative abundance of the foraminifera according to wall type and living strategy

	M1	M2	M3	M4	M5	M6	M7	K1	K2	K3	K4	K5	N1	N2	N3	N4	N5	N6
Textulariina (agglutinated)	35.50	6.80	1.20	5.20	54.50	1.10	1.00	1.65	40.22	16.14	0.97	-	4.07	1.50	0.61	-	1.90	0.34
Miliolina (imperforated)	-	-	0.40	-	-	1.70	0.70	25.50	3.36	0.35	2.92	-	23.58	15.00	22.06	30.22	35.24	24.49
Rotaliina (perforated)	64.50	93.20	98.40	94.80	45.50	97.20	98.30	72.85	56.42	83.51	96.11	100	72.36	83.50	77.30	69.78	62.86	75.17
Epifauna	-	-	-	-	-	2.10	0.20	1.59	9.63	1.60	2.80	1.53	22.07	12.70	16.53	15.99	12.67	19.98
Infauna	21.55	2.15	21.70	8.10	17.50	43.20	40.60	25.40	6.70	7.37	14.00	14.21	9.19	5.51	7.15	8.83	10.55	13.68
Epi-infauna	60.15	96.33	75.90	90.80	78.90	54.40	56.00	68.58	57.34	79.49	53.86	59.39	44.15	64.83	49.11	51.94	50.71	46.29
Indeterminable	18.30	1.52	2.01	1.10	3.60	0.30	3.20	4.13	25.10	8.97	29.37	24.87	24.54	15.22	27.24	23.20	26.06	20.00
Unknown living strategy	-	-	-	-	-	-	-	0.32	1.26	-	-	-	-	1.7	-	-	-	-

Table 4 Grain size distribution, granulometric characteristics, carbonate content, and organic content (LOI%) of the samples

	Gravel (%)	**Sand** (%)	**Silt** (%)	**Clay** (%)	**Mz** (µm)	**Textural group**	**Carbonate content** (%)	**LOI** (%)
M1	3.6	14.3	57.5	24.6	7.9	sgsM/sS	41	4.3
M2	0.3	17.4	43.7	38.6	5.5	sgsM/sM	40	4.1
M3	11.9	8.4	47.7	32.0	9.3	gM/M	22	6.4
M4	1.0	5.0	45.2	48.8	2.1	sgM/M	26	6.0
M5	1.6	17.9	44.5	36.0	6.6	sgsM/sM	38	2.8
M6	1.6	5.7	51.5	41.2	2.7	sgM/M	38	3.0
M7	0.7	5.6	52.1	41.6	2.7	sgM/M	47	4.0
K1	3.4	40.3	46.9	9.4	33.5	sgsM/sS	11	1.6
K2	2.9	66.3	27.5	3.3	83.6	sgmS/Ss	9	1.9
K3	0.4	46.9	44.1	8.6	35.6	sgsM/sS	10	1.6
K4	0.3	43.1	44.8	11.8	26.8	sgsM/sS	9	4.8
K5	0.4	54.0	37.2	8.4	43.5	sgmS/Ss	13	1.0
N1	0.2	96.8	2.1	0.8	533.9	sgS/S	88	1.4
N2	0.2	91.8	6.8	1.2	504.6	sgS/S	90	0.6
N3	0.2	96.7	1.9	1.2	532.0	sgS/S	94	0.6
N4	3.4	90.9	3.9	1.8	547.3	sgS/S	90	0.5
N5	0.4	95.1	3.4	1.1	461.8	sgS/S	94	0.5
N6	21.9	75.3	2.1	0.6	1134.7	gS/S	97	0.3

Mz mean size, *sgsM* slightly gravelly sandy mud, *sS* sandy silt, *Ss* silty sand, *sM* sandy mud, *gM* gravelly mud, *M*, mud *sgM,* slightly gravelly mud, *sgS* slightly gravelly sand, *gS* gravelly sand, *S* sand, *LOI* loss on ignition

almost complete absence in the Nin sandy samples. The occurrence of *T. inflata*, a typical salt marsh agglutinated species, was restricted to the areas of greater freshwater influence, i.e., the Mirna River and underground freshwater karstic streams, as well as the areas of Cres Island (Brunović et al. 2019) and the central Adriatic (Shaw et al. 2016). The key role played by elevation above sea level in the distribution of foraminifera (Scott and Medioli 1978; 1980b) was also found in the salt marshes of central Adriatic, where agglutinated-dominated assemblages predominated at higher elevations, whereas calcareous-dominated assemblages occupied the mid-low salt marsh environment (Shaw et al. 2016). Such foraminiferal distribution was evident in the Mirna salt marsh (Fig. 2). Although least represented, foraminifera with an imperforate wall, i.e., *Quinqueloculina* specimens, were numerous in sample K1 in the Soline mud plain and present in all samples in the Nin intertidal plain (Table 1, Fig. 2). Individuals of this genus tolerate a wide range of temperature and salinity and were often found in marine but also in hypersaline environments. Here, with increasing distance from the sea, the proportion of imperforated (miliolid) and agglutinated individuals increased, while at the same time, the number of perforated tests decreased (Table 3).

The foraminiferal assemblages of samples collected further away from the Mirna River (cluster AII) and Soline (cluster AI) were influenced by fine-grained substrate (mud and silty sand) in relation to parameters like organic matter and oxygen contents (Jorissen 1987, 1988, 1999) and somewhat lower carbonate content (Table 4, Fig. 4), in which the organic carbon content could be higher (Fig. 2). Therefore, opportunistic species, such as *A.* ex. gr *tepida* and *H. depressula* proliferated (cluster AI; Fig. 2). The fine-grained substrate, the low Fisher (α) values, and the lowest values of diversity were consistent with the samples collected in proximity to Mirna River (cluster BI), an area subject to greater freshwater influence (Fig. 2). The distinct composition of the assemblages in Nin (cluster BII) was the result of a coarse-grained sandy substrate with very high carbonate content and lowest organic content (Table 4, Fig. 4), the impact of waves and tides, and the redistribution of material (Fig. 2). The foraminiferal assemblages (cluster BII) at Nin site differed from the other sites in composition and highest diversity (Fig. 2). Granulometric analysis (Fig. 3) showed that sand-sized particles predominated, and the carbonate content was very high (Table 4, Fig. 4). The grains are of lithogenic and biogenic origin, foraminiferal tests and shells of bivalves, gastropods, and ostracods as well as eroded carbonate grains make them up. The proportion of silty and clayey particles was low; therefore, the organic content was also very low, which might be related to the effects of waves and washout of fine sediment fractions. A higher amount of mud (silt and clay) in sediment traps more organic particles than sand-dominated sediment, due to the presence of a larger surface area with higher adsorption capacity (Keil

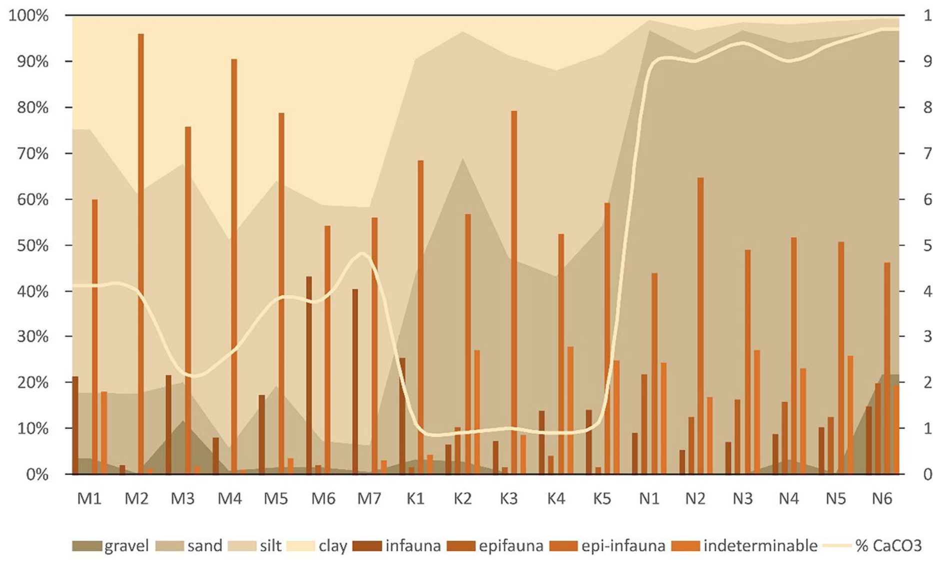

Fig. 4 Diagram of a relationship between the functional groups of the benthic foraminifera, granulometric composition and carbonate content of the sediment at all sampling point

and Hedges 1993; Burdige 2007). The highest values of the Shannon (*H*) diversity index of this cluster could be the result of the accumulation of tests due to wave action and not the result of a diverse biocenosis. The dominant species, *A. beccarii*, was characterized by large and ornamented tests, which is consistent with sandy sediment, and could also be related to the greater cooling of the sea in winter. Walton and Sloan (1990) concluded that the larger, ornamented specimens were more characteristic of cooler, stressful, or hypersaline environmental conditions. Jorissen (1988) noted and described that part of the population of *A. beccarii* on sandy substrates in the northern part of the Adriatic consists of just such specimens that do not occur on clayey bottoms. In addition to the genus *Ammonia*, the assemblage contained numerous individuals of the genus *Elphidium* in the marsh and *Quinqueloculina* in the lagoon, while *Elphidium*, *Peneroplis*, and *Quinqueloculina* alternate in the intertidal plain (Table 1, Fig. 2).

According to the foraminiferal functional groups, most infaunal individuals were found in the Mirna salt marsh, whereas in the Nin intertidal plain, most epifaunal individuals were found (Table 3, Fig. 4). The relative proportion of epi-infauna was significantly higher in almost all samples (Fig. 4), which is due to the pronounced dominance of the genus *Ammonia*. This was consistent with the results of granulometric analysis, since infaunal individuals prefer muddy sediment, which was characteristic of the sediment in the Mirna salt marsh (Figs. 3 and 4).

The Mirna salt marsh consisted dominantly of mud (high content of clay and silt; Fig. 3), which is a consequence of weathering and delivery of muddy sediment within the Mirna River drainage area which is built in some parts of fine-grained marls (Felja et al. 2015) and weaker marine influence (protected closed bay). The carbonate content (Table 4, Fig. 4) correlates with the mean grain size, which may be related to the higher abundance of bivalves, gastropods, ostracods, and foraminifera in the sediment (as noted in Nin samples, in areas under tidal influence). In the studied TEs, the higher carbonate contents fit well with the abundances of epifaunal foraminifera. On the other hand, in the Soline and Mirna samples, abundances of infaunal species coincide with lower carbonate contents, high organic content, and finer sediments (Table 4, Fig. 4). Analysis of the granulometric composition of the sediment in the Soline mud plain allowed identification of the predominant depositional processes. The uniform distribution of sandy (samples K2 and K5) and muddy (K1, K3, and K4) fractions without a specific trend is indicative of the role of waves and tides in redistributing the sediment (Fig. 3). The fine-grained muddy component is a characteristic of salt marshes and mud plains where deposition of fine particles was possible due to weak marine influence and low energy. The weak dynamics of the surrounding environment prevent the deposition and delivery of a larger quantity of larger particles, so given the geomorphological characteristics, a larger proportion of the sandy component is the result of mechanical abrasion and transport of the surrounding flysch deposits (especially pronounced in the Nin intertidal plain).

5 Conclusion

This study presented an analysis of the distribution of benthic foraminifera, granulometric properties, carbonate content, and organic content of sediment in transitional environments from three different locations: the Mirna salt marsh, the Soline mud plain, and the Nin intertidal plain. These transitional environments were different in grain size properties, which was a consequence of several factors: lithology of surrounding areas, geomorphology, marine influence (dynamics of waves and tides), and input of freshwater from the land. Mirna salt marsh was composed of mud, Nin intertidal plain almost completely composed of sand fraction, whereas Soline mud plain was composed of both muddy and sandy sediment. The carbonate and organic content varied greatly in all three TEs and is correlated to granulometry: the highest carbonate content and lowest organic content showed samples from Nin location and are related to the high percentage of biogenic and lithogenic sand fraction; muddy samples from Krk showed the lowest carbonate content (flysch hinterland); the Mirna salt marsh samples showed average carbonate content and higher organic content compared to other locations.

Different foraminiferal assemblages were recognized based on differences in species composition, abundance, dominance, and proportion of different life-strategy groups. The results of this study confirmed that the granulometric properties of the sediment play an important role in foraminiferal abundances and diversity in a way that granulometry influences organic content and food availability (mud sediment contains more organic matter than sandy sediment) and oxygen content. The foraminiferal assemblages generally showed low to moderate diversity. The sediment-sensitive *Trochamina inflata* and *Haynesina depressula* were almost absent from the coarse sediments, while the opportunistic epifaunal—shallow infaunal ammonidis—were abundant throughout. Mirna salt marsh samples had the lowest species diversity; however, most infaunal species were found in this environment as they prefer muddy sediment. In the Nin intertidal plain, composed of coarser sediment (sand), the species diversity was the highest. A large proportion of the sand component with many reworked foraminiferal tests in Nin and Soline indicated a strong input from the surrounding deposits.

This study provides original data on the distribution of recent benthic foraminifera in various transitional environments in the karstic coast of the northern Adriatic area, not previously investigated using these bioindicators. These results will help in a better understanding and environmental protection and preservation of these sensitive and vulnerable environments.

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Data availability The authors declare that data supporting the findings of this study are available within this paper and its Supplementary files.

Declarations

Competing interests The authors declare no competing interests.

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