Revue de micropaléontologie 62 (2019) 33–44

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Research paper

Benthic foraminiferal assemblages in the severely polluted coastal environment of Drapetsona-Keratsini, Saronikos Gulf (Greece)

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ARTICLE INFO

ABSTRACT

Surface sediments were collected from the coastal zone of Drapetsona–Keratsini (Saronikos Gulf, Greece) in December 2012 for determining the local benthic foraminiferal community, identifying their spatial distribution patterns, and evaluating the response of foraminiferal species to geochemical composition through the hierarchical cluster analysis, principal component analysis and Spearman's rho correlation. Foraminifera can be classified into three distinct assemblages associated with the granulometry, elemental geochemistry, particulate organic carbon content and degree of sediment contamination. A relatively low-diversity assemblage, dominated by stress-tolerant taxa with *Ammonia tepida Bolivina spathulata* and *Bulimina elongata* being the prevailing species, is characteristic of the silty seabed of the main part of Drapetsona coastal zone and the Keratsini Port central basin, where organic carbon content, aliphatic and polycyclic aromatic hydrocarbons concentrations and trace metal loads are greatly elevated. On the sandy bottom of the investigated area, relatively high frequencies of miliolids prevail. An epiphytic rotaliid-dominated assemblage is recorded in the slightly-polluted sedimentary bottom of the inner and western part of the Keratsini Port.

1. Introduction

Benthic foraminifera, a significant component of meiobenthic communities, are highly diverse, abundant and ubiquitous in all marine environments, responding quickly to environmental changes due to their short reproductive cycles. Many abiotic factors including temperature, salinity, flux of organic matter, oxygen availability, substrate type and organic and inorganic pollutants influence the foraminiferal composition and distribution (Murray, 2006). These characteristics recommend the benthic foraminifera as reliable indicators for the determination of the natural environmental and anthropogenic impact/pollution in estuarine and shallow coastal systems (e.g., Alve, 1991, 1995; Yanko et al., 1994, 1998, 1999; Geslin et al., 1998; Debenay et al., 2000; Hallock et al., 2003; Armynot du Châtelet and Debenay, 2010; Frontalini and Coccioni, 2011; Schönfeld et al., 2012; Barras et al., 2014; Dimiza et al., 2016a, b; Armynot du Châtelet et al., 2018).

A great effort has been made to understand the effects of anthropogenic stressors on foraminiferal assemblages. In this context, several studies have focused on estuarine and marine coastal environments exposed to direct anthropogenic contamination sources such as industrial (e.g., Ferraro et al., 2006; Cherchi et al., 2009; Coccioni et al., 2009; Romano et al., 2009; Elshanawany et al., 2011), urban (e.g., Mojtahid et al., 2008; Carnahan et al., 2009; Koukousioura et al., 2011; Martins et al., 2015, 2016; Tadir et al., 2017) and agricultural wastes (e.g., Samir and El-Din, 2001) or areas enriched with polycyclic aromatic hydrocarbons (e.g. Armynot du Châtelet et al., 2004; Ernst et al., 2006; Mojtahid et al., 2006; Lei et al., 2015). In most studies, the changes in the levels of organic matter, hydrocarbons and heavy metals have multiple effects on benthic foraminifera communities, ranging from modifications of their density, diversity and species composition with an increased dominance of pollution-tolerant species to changes in reproduction capability, or even to test morphology.

The Drapetsona–Keratsini coastal zone (Saronikos Gulf; Fig. 1) is considered as one of the most human-impacted coastal regions of Greece. Until the early 1990s, the area was receiving significant amounts of untreated wastes from many local pollution sources (industrial and urban effluents) along the extended Athens metropolitan coastal front that significantly degraded the environmental quality (Galanopoulou et al., 2005). An improvement of the environmental status has recorded over the last two decades

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https://doi.org/10.1016/j.revmic.2018.09.001

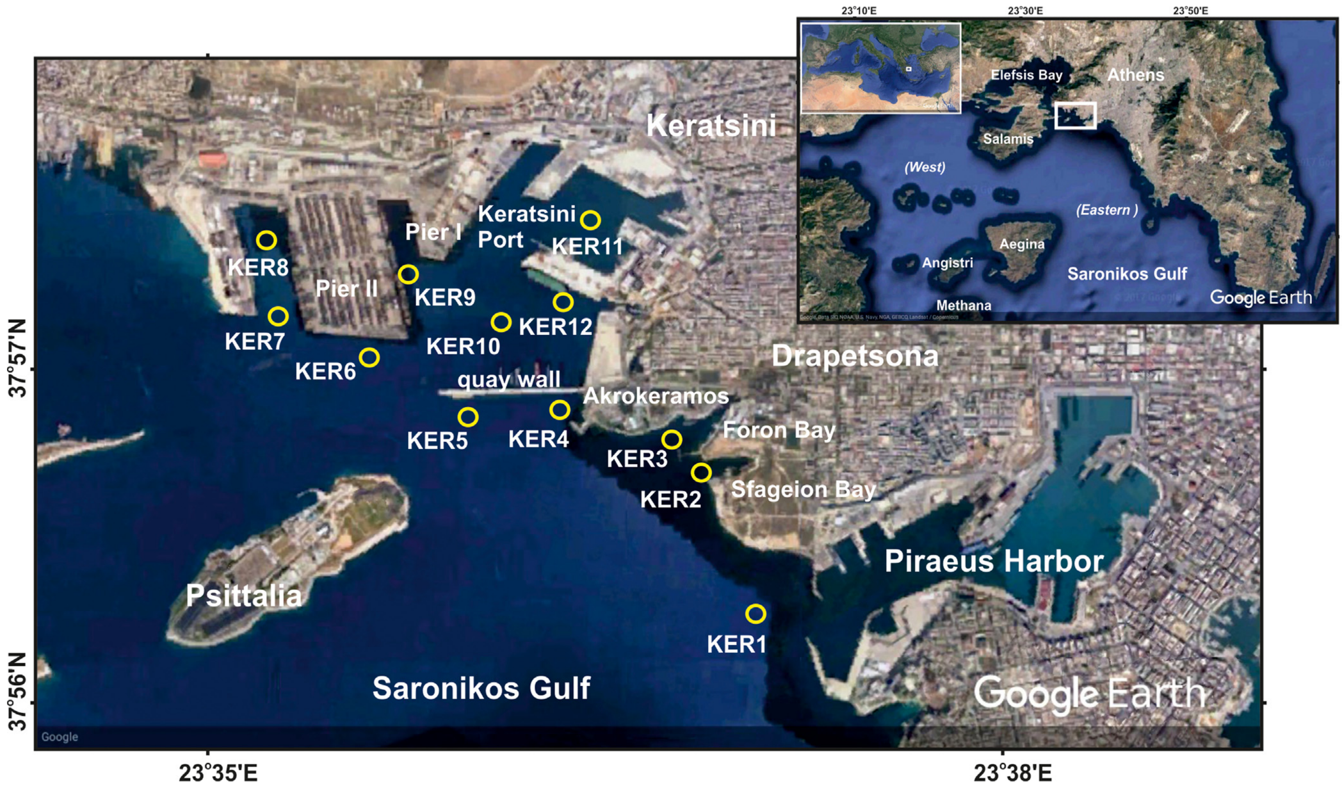

Fig. 1. Study area and sampling stations (modified from http://www.earth.google.com).

(Simboura et al., 2014) due to the closure of several major factories and the establishment of domestic and industrial waste treatment systems, such as the Waste Water Treatment Plant (WWTP) of Athens, which was constructed on the islet of Psyttalia and operated for first time in 1994. Up to 2008, the WWTP was discharging into the Saronikos Gulf approximately 8 10^5 m^3 d^{-1} of treated wastes (Zeri et al., 2009). However, many medium to small scale industrial as well as intense shipping activities from the commercial Piraeus Port, which is one of the biggest in the Mediterranean Sea, are still very present. As a consequence, the area is still being subjected to considerable pollution stresses. Two recent sedimentological and geochemical studies of the surface sediments of the Drapetsona–Keratsini coastal zone by Kapsimalis et al. (2013, 2014) have revealed extremely high concentrations of heavy metals and organic compounds at levels of threat for the marine environment. Recently Dimiza et al. (2016b) studied the living foraminiferal distribution at a network of 10 stations in Inner Saronikos Gulf sediments. Based on benthic foraminifera data and the ecological quality classification tool, Foram Stress Index (FSI), classified the western and central part of Gulf as moderate environment status and the coast of Salamis and the eastern sector were characterized by more diversified epiphytic foraminiferal assemblage as good quality environment.

The present paper investigates the species composition, density and diversity of the benthic foraminiferal assemblages occurring in the environmentally degraded Drapetsona–Keratsini coastal zone and attempts to determine the assemblage response in relation to the local abiotic characteristics of the sediments, such as texture, organic carbon content, hydrocarbon and heavy metal concentrations.

2. Study area

The area under investigation is located in the northern part of the Saronikos Gulf (Fig. 1), which is a neotectonic basin on the western edge of the central Aegean Plateau. The Gulf is divided into a deeper western sub-basin (depths > 400 m) and an eastern part by a very shallow N–S platform bounded to the south by Methana peninsula and the islands of Angistri, Aegina and Salamis. The northern sector of the eastern part, also known as Inner Saronikos Gulf, is relatively shallow (depths < 100 m). Sedimentation rates differ throughout the Gulf; is fairly low (< 0.6 cm per 100 years; Lykousis and Anagnostou, 1992) in the center basin and high (~0.30 cm per year; Hatzianestis et al., 2004; Eleftheriou et al., 2018) near the coastal areas.

The northern part of the Saronikos Gulf represents an intriguing marine environment, significantly influenced by anthropogenic pressures due to its proximity to the metropolitan city of Athens. The soft bottom consists of sandy and muddy sediments. The water temperature shows typical seasonal variation, ranging from 15 °C to 24 °C, while salinity is approximately 38–39 psu throughout the year. The area is not affected by significant freshwater runoff.

3. Material and methods

3.1. Sampling sites and sediment abiotic parameters

This study focuses on the Drapetsona–Keratsini coastal zone, which includes the rocky coast of Drapetsona, the bays of Sfageion and Foron, the Akrokeramos Harbour, the Drapetsona quay wall and the Keratsini Port (Fig. 1). Surface sediment samples (up to 2 cm thick) were collected from 12 locations (KER1–KER12, see Fig. 1 and Table 1), at water depths of 8–29 m, in December 2012, using an Ekman grab sampler. According to the local sedimentation rate (~0.30 cm per year; Hatzianestis et al., 2004; Eleftheriou et al., 2018; Hatzianestis et al., 2004; Eleftheriou et al., 2018) the sampled sediment represents approximately six years of accumulation. At each sampling site, the sediment texture (Table 1) as well as inorganic and organic sediment components, comprising heavy metals, aliphatic and polycyclic aromatic hydrocarbons and organic

Table 1
Sampling location, depth and sediment nomenclature according to Folk (1974).

Station	Location	Depth (m)	Sediment type
KER1	Piraeus Port exit	15	Sandy silt
KER2	Sfageion Bay	18	Silty sand
KER3	Foron Bay	12	Sandy silt
KER4	Akrokeramos Harbor	25	Silty sand
KER5	Drapetsona quay wall	29	Silty sand
KER6	In front of Pier II	24	Sandy silt
KER7	West of Pier II	24	Sandy silt
KER8	West of Pier II	21	Silty sand
KER9	East of Pier II	23	Silty sand
KER10	Central basin of the Keratsini Port	25	Sandy silt
KER11	Inner basin of the Keratsini Port	8	Silty sand
KER12	Central basin of the Keratsini Port	22	Sandy silt

carbon were determined (Figs. 2, 3). The detailed methodologies and analyses results can be found in Kapsimalis et al. (2013, 2014).

3.2. Laboratory procedure

For the determination of benthic foraminiferal communities, each sediment sample (4–5 g) was wet sieved through 63 μm and 125 μm mesh sieves and dried at 40 °C. Subsamples of the >125 μm sediment fraction were examined under a Leica APO S8 stereoscope and a total of at least 300 well-preserved tests from the total foraminiferal assemblage (living and dead specimens) for each sample was obtained, using an Otto microsplitter, when this was possible; otherwise all available specimens were picked. Specimens were identified according to the generic classification of Loeblich and Tappan (1987, 1994) and the standardized nomenclature of the World Register of Marine Species (WoRMS, 2014).

The total foraminiferal assemblages analyzed in this study do not correspond to species living in a community simultaneously, but reflect time-averaged successive generations including seasonal and spatial variability during a the short interval of < 10 years according to the local sedimentation rates, with possible modifications caused by post-mortem processes such as test transportation and destruction (Scott and Medioli, 1980; Alve and Murray, 1994; Debenay et al., 2001, Debenay et al., 2001, 2005; Armynot du Châtelet et al., 2004; Murray, 2006). Although the examination of the living assemblage is appropriate for the analysis of species ecological features, the total assemblage can be useful to assess the general environmental conditions, paying attention to the possible influence of taphonomic processes (Morvan et al., 2006; Carboni et al., 2009).

3.3. Data processing and statistical analyses

For the data interpretation, species richness (S), as the number of species in each sampling station, and total foraminiferal density (FD), as the number of specimens per gram of dry sediment (specimens g^{-1}), were defined. Two well-known standard diversity indices, i.e., Fisher's alpha parameter (a-index) and Shannon–Wiener (H') function, were calculated for each sampling location to estimate and better interpret the general community structure in the study area. Fisher's alpha index is a reliable measure of species diversity (Fisher et al., 1943; Murray, 1991), while Shannon–Wiener function provides one of the most widely used measures for heterogeneity evaluation, taking into consideration the distribution of individuals among the various species (Shannon, 1948; Murray, 1991). The diversity indices were calculated using the Past 3.05 software package (Hammer et al., 2001). In addition, each foraminiferal assemblage was expressed by the relative abundances (%) of the identified species and was further evaluated through the *Ammonia-Elphidium* Index (AEI), as an indicator of hypoxia. The AEI, which is considered reliable at depths less than 30 m (Platon and Sen Gupta, 2001), was calculated (Sen Gupta et al., 1996) as follows:

$$AEI = \left[N_A/(N_A + N_E)\right] \times 100,$$

where N_A and N_E were the numbers of *Ammonia* and *Elphidium* individuals, respectively. It must be noticed that the genus *Cribroelphidium* has been merged with *Elphidium* due to the uncertainty of the taxonomy of this group (see Carnahan et al., 2009). Finally, the relative abundances (%) of the stress-tolerant taxa (STR) comprising *Ammonia*, *Bolivina*, *Bulimina*, *Melonis*, *Nonion*, *Rectuvigerina*, *Fursenkoina* and *Textularia*; see Dimiza et al. (2016b) and pyritized tests in each of the benthic foraminiferal assemblages were determined.

R-mode and Q-mode Hierarchical Cluster Analysis (HCA) were carried out on the 15 species exceeding relative abundance of 5% in one sediment sample at least. The data were logarithmically transformed to reduce the score and bias of more abundant species that may have otherwise masked the effect of less abundant species.

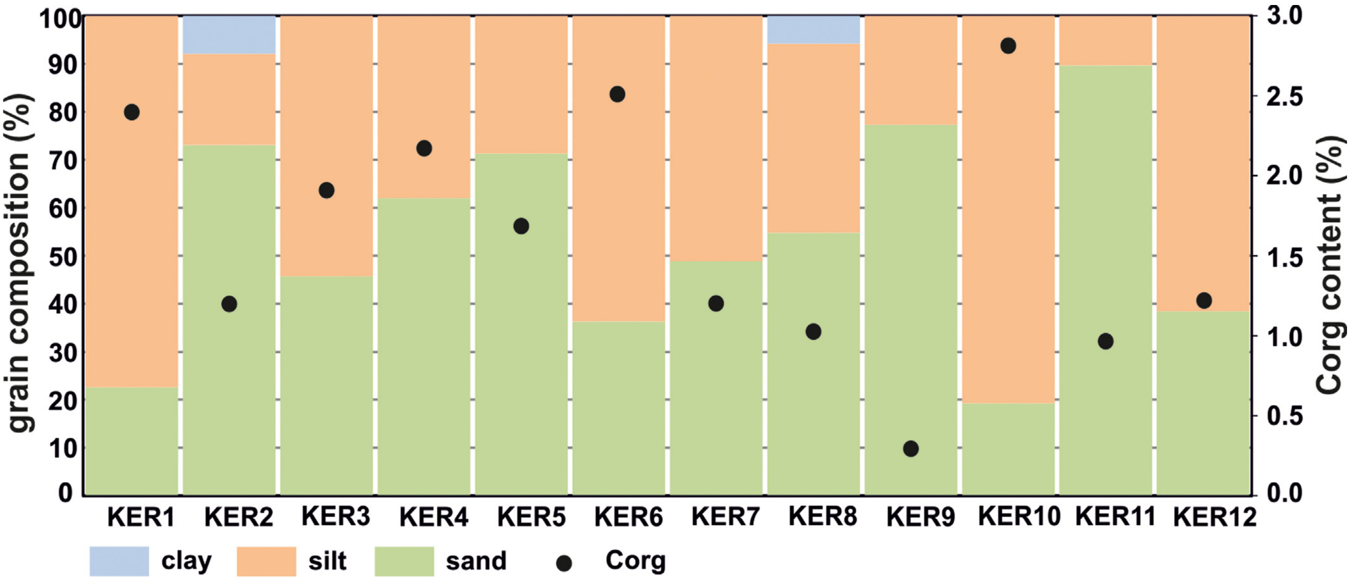

Fig. 2. Sediment fractions and Corg content.

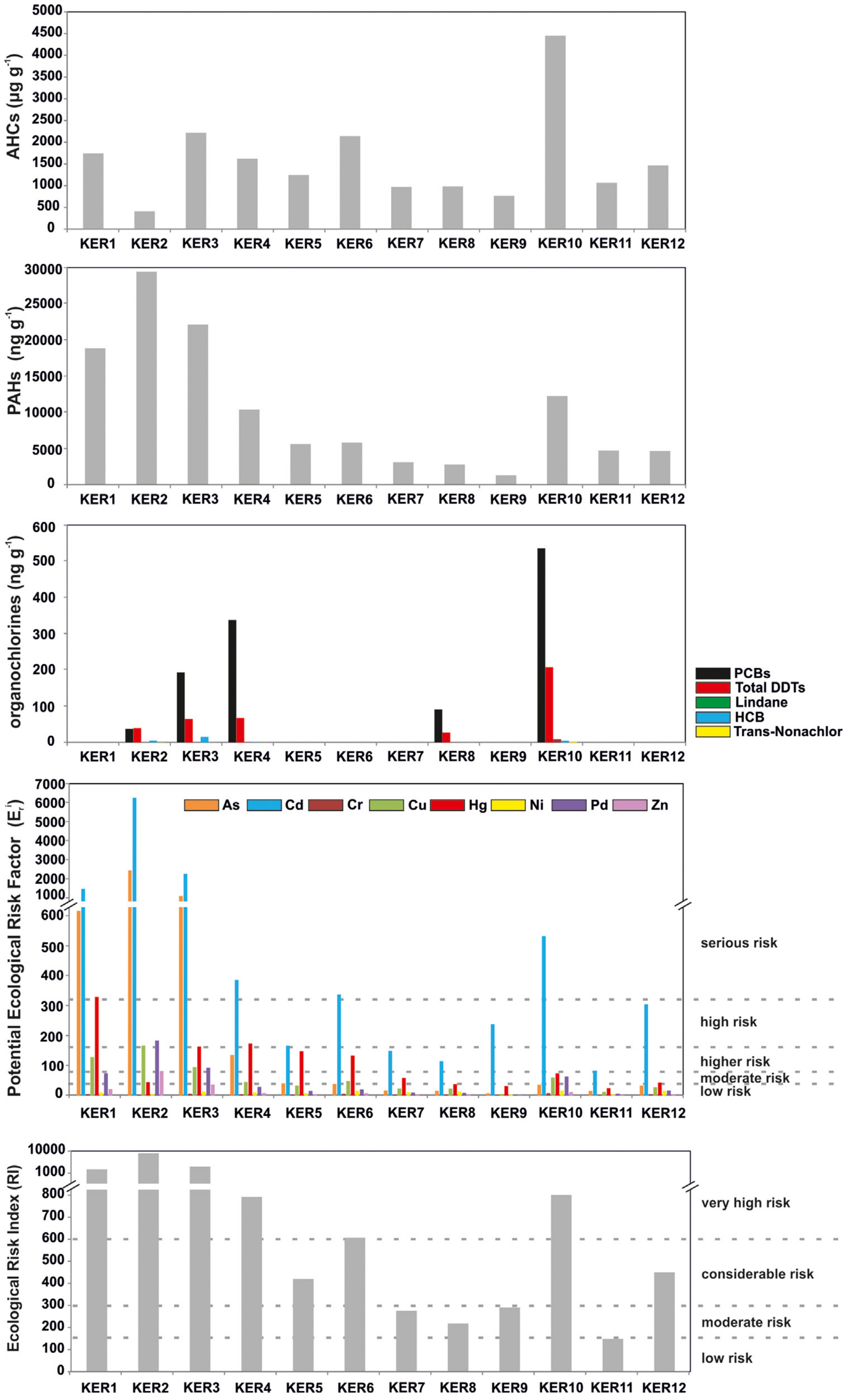

Fig. 3. Hydrocarbon concentrations (AHs, PAHs and organochlorines) and sediment status according to heavy metal pollution indices (E_r^i and RI) for the investigated sites. Sediment quality was classified following Håkanson (1980).

Euclidean distance as a metric system and Ward's method for combining clusters which produces dendrograms with exceptionally well-defined clusters (Parker and Arnold, 1999) were used for the R-mode (species) and Q-mode (stations) analysis.

The simple nonparametric Spearman's rho correlation was carried out to determine possible relationships between the common foraminiferal species and assemblage characteristics (i.e., FD, S, H', a-index, AEI, relative abundances of stress-tolerant

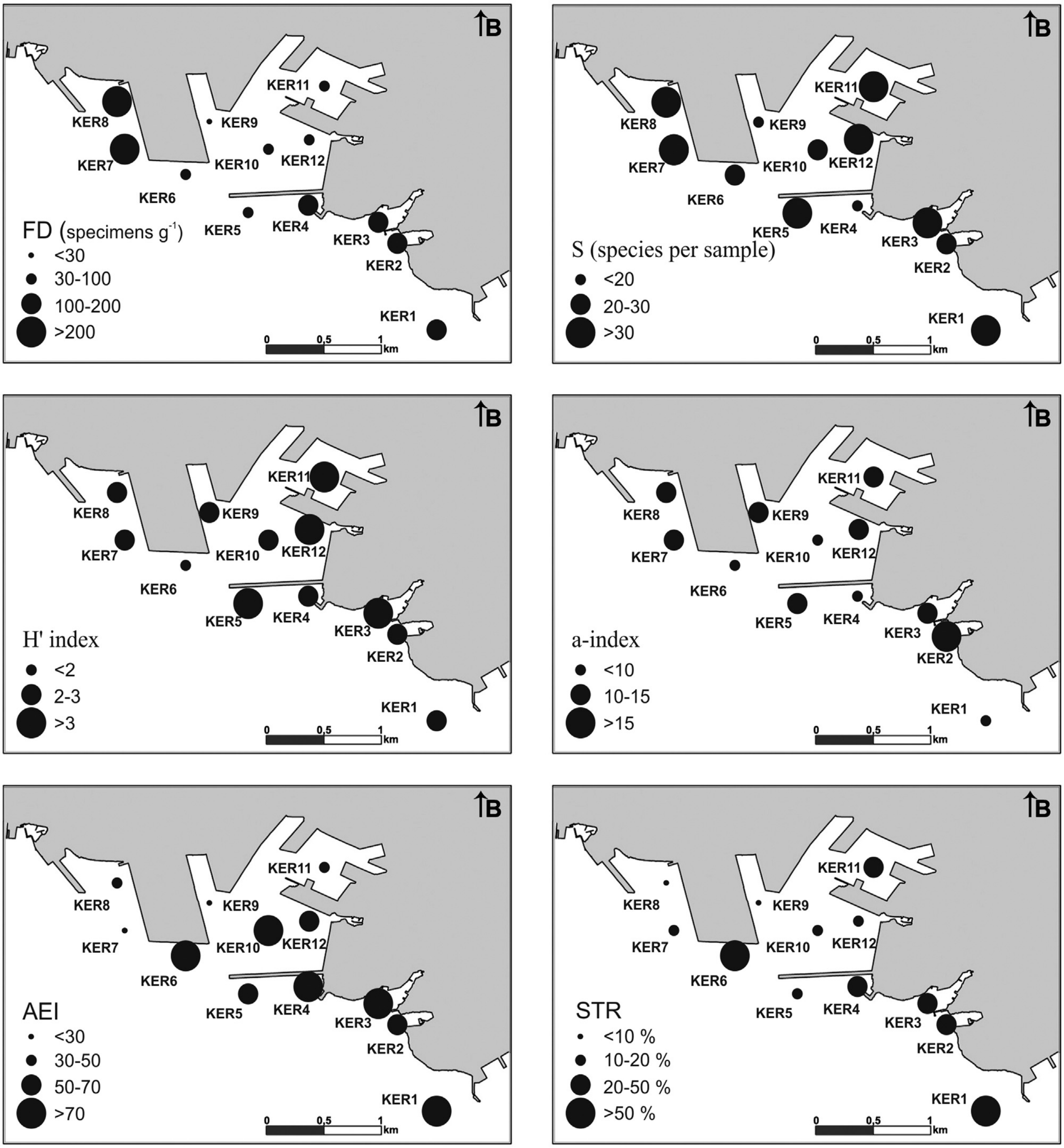

Fig. 4. Spatial distribution of the total abundances of foraminifera, diversity indices, AEI and STR.

taxa and pyritized specimens) and sediment abiotic parameters including sand content, particulate organic carbon (Corg) content, aliphatic hydrocarbons (AHs), polycyclic aromatic hydrocarbons (PAHs), organochlorines including PCBs, DDT, HCB Lindane and trans-Nonachlor, single and multi-element sediment quality indices (Potential Ecological Risk Factor E_r^i and Ecological Risk Index *RI*) (Kapsimalis et al., 2013). Moreover, Principal Component Analysis (PCA) was applied to examine the relationships among the sediment abiotic parameters and foraminiferal species, and also to identify the main components that explain most of the variance (Parker and Arnold, 1999). Varimax rotation was applied to facilitate of the interpretation components. All statistical analyses were performed using SPSS (version 10.1) statistical software.

4. Results

4.1. Benthic foraminifera

A total of 78 benthic foraminiferal species and 39 genera (see Appendix A2) are identified, comprising 37 hyaline, 40 porcellaneous and 1 agglutinated species. Only 15 species demonstrated a relative abundance higher than 5% in at least one sediment sample,

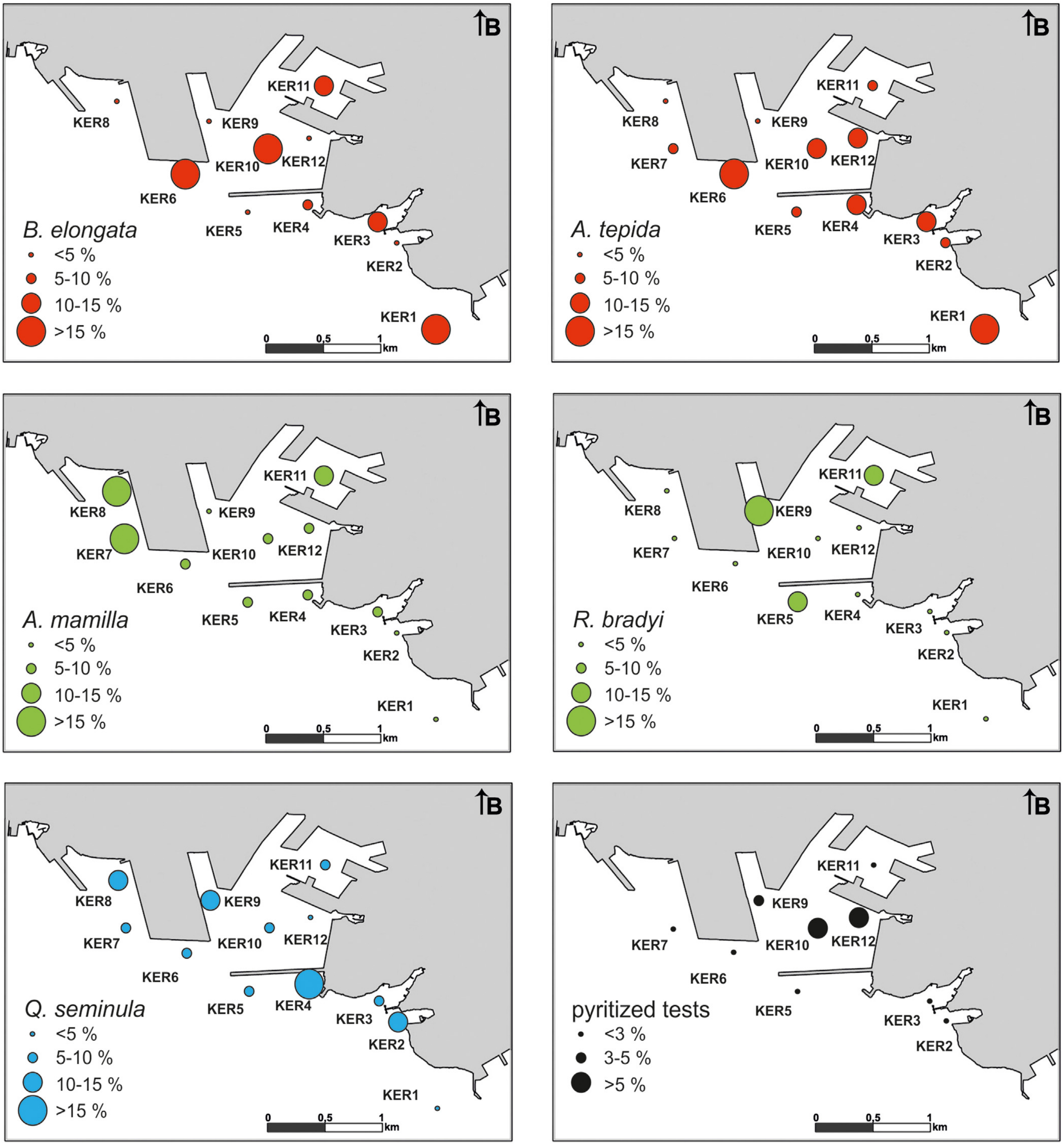

Fig. 5. Spatial distribution of the frequencies of the most abundant species (>15%) and observed pyritized tests.

with *Ammonia tepida*, *Asterigerinata mamilla*, *Bulimina elongata*, *Quinqueloculina seminula* and *Rosalina bradyi* showing high frequencies (i.e., > 15% in at least one sediment sample) (see Appendix A3). As illustrated in Fig. 4, the lower FD values are found in the central basin of the Keratsini Port (KER11; up to 61 specimens g^{-1}), whereas the higher FD values (exceeding 230 specimens g^{-1}) occur west of Pier II (KER8). Species diversity is relatively high. Species richness fluctuates between 13 and 46 with an average of ~30 species per sediment sample, while a-index and H' range between 7.3–15.1 and 1.9–3.2, respectively (Fig. 4). In all the examined sediment samples the genera *Ammonia* and *Elphidium* are found together, constituting 10–27% of the total assemblage, with AEI values fluctuating from 20 to 83, whilst stress-tolerant species display relative abundances varying between 7–70% (Fig. 4).

The spatial distributions of the dominant foraminiferal species are shown in Fig. 5. *Bulimina elongata* demonstrates the highest abundance, with the maximum value (49%) being recorded in front of Pier II (KER6). *Ammonia tepida* is one of the most dominant species in the study area and displays its highest percentage (18%) at the Piraeus Port exit (KER1). In contrast, *Ammonia beccarii* is generally poorly represented, with a single peak in abundance (5%) at the central basin of the Keratsini Port (KER12). *Asterigerinata mamilla* and *Rosalina bradyi* occur at all sampling stations with the higher percentages (~18%) appearing between Piers I and II (KER9). Also, *Elphidium crispum*, *Lobatula lobatula*, *Bulimina aculeata* and *Bolivina spathulata* are commonly observed.

Among porcelanaceous taxa, miliolids display high percentages (8–48%) in all sediment samples and are generally represented by several genera, e.g., *Quinqueloculina*, *Adelosina*, *Spiroloculina*, *Sigmoilina* and *Triloculina*. *Quinqueloculina seminula* (max = 17%) is the most frequent species and is followed by *Q. laevigata* (max = 11%), *Q. berthelotiana* (max = 8%) and *A. longirostra* (max = 5%). *Peneroplis* species (*P. pertusus* and *P. planatus*) are generally represented with relative abundances less than ~15%.

A great number of pyritized foraminiferal tests are detected within the foraminiferal assemblages. The most commonly pyritized specimens are primarily observed in porcelanaceous foraminifera such as *Spiroloculina excavata*, *Spiroloculina ornata*, *Sigmoilina costata*, *Quinqueloculina seminula*, *Quinqueloculina berthelotiana* and *Peneroplis pertusus*. However, pyritized tests are also traced in hyaline (*Elphidium crispum* and *Ammonia beccarii*) and agglutinated species (*Textularia agglutinans*). As shown in Fig. 5, the higher relative abundances (9% and 13%) of pyritized foraminifera occur in the central basin of the Keratsini Port (KER10 and KER12, respectively).

Finally, no significant morphological abnormalities are detected in the foraminiferal tests. Only some individuals of *Miliolinella subrotunda* are observed to have malformed chambers. However, their relative proportion is very low, representing less than 1.0% of the assemblage.

4.2. Statistical analyses

The dendrogram resulting from the Q-mode HCA displays three major clusters (see A, B and C in Fig. 6A). Cluster A is represented by four sampling locations, two in front of the Keratsini Port (KER6 and KER10), one at the Piraeus Port exit (KER1) and one in Foron Bay (station KER3), whereas Cluster B includes the sampling locations at Sfageion Bay (KER2), Akrokeramos Harbour (KER4), Drapetsona quay wall (KER5) and the central basin of the Keratsini Port (KER12). Cluster C incorporates the rest of the sampling stations located in the inner basin of Keratsini Port (KER11) and in both sides of Pier II (KER7, KER8 and KER9). R-mode HCA distinguishes three main Groups (see 1, 2 and 3 in Fig. 6B). Relative abundance of Group1 varies between 6% (KER8) and 66% (KER6), Group 2 ranges in relative abundance from 3% (KER1) to 49% (KER4), while Group 3 constituting 9% (KER6) to 40% (KER7) of the total assemblage (Fig. 7).

The Spearman's rho correlation between the common foraminiferal species and abiotic sediment parameters is presented in the matrix shown as Table 2. Species richness and H' do not reveal any significant correlation with the abiotic parameters, whereas FD and a-index show negative correlation with DDTs and PCBs respectively. Pyritized tests present a positive correlation with lindane. The stress-tolerant taxa and AEI are negatively correlated with the sand content and positively correlated with organic carbon, hydrocarbons and the majority of heavy metal indices. Among the foraminiferal species, *A. tepida* shows a negative correlation with the sand content, while *E. crispum*, *Q. seminula and R. bradyi* exhibit a positive correlation with the same parameter. Regarding pollutants, high similarity values are found for *A. tepida*, *B. elongata*, *B. spathulata*, while an opposite trend is indicated for *A. mamilla*, *E. crispum*, *R. bradyi* and *L. lobatula*. These features are also supported by the results of PCA. As shown in Fig. 8A, the Principal Component 1 (PC1) represents 27% and Principal Component 2 (PC2) explains a further 25% of the total variance. Only parameters with strong component loading (≥ 0.5 positive or negative) are considered as significant. PC1 is characterized by strong positive loadings for silt together with AHCs, Corg, moderate positive loadings for Hg and Cu and also strong negative loadings for sand (Fig. 8A, Table 3). Moreover, the dominant species in the Group 1 (*A. tepida* and *B. elongata*) are positively correlated to PC1, while species corresponding to the Groups 2 and 3 (*E. crispum*, *R. bradyi* and *Q. seminula*) are negatively correlated. PC2 shows strong positive loadings for PAHs, Cd, As, Pb, Cu and foraminiferal species *B. sphatulata*, while more abundant species in the Group 3 (*A. mamilla* and *R. bradyi*) appear significantly negative loadings (Fig. 8A, Table 3). A plot of PC1 versus PC2 scores groups the sampling locations similar as Q-mode HCA (Fig. 8B); the highest values for PC1 are observed in the stations of Cluster A and the lowest values for PC2 are noted in the stations of Cluster C.

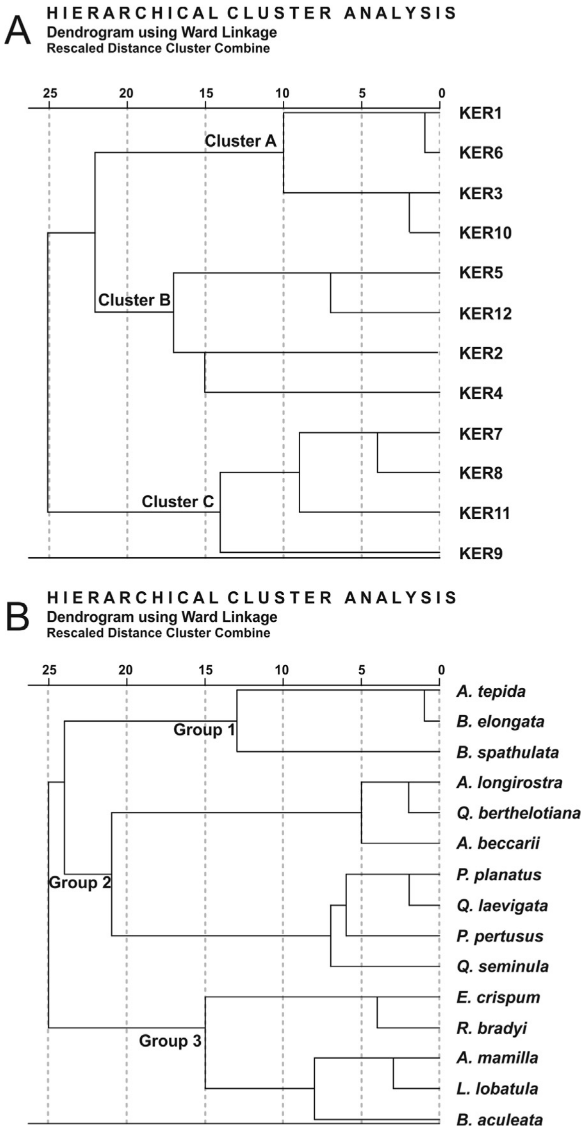

Fig. 6. A Dendrogram showing the clustering of sampling sites; B Dendrogram showing the clustering of the common foraminiferal species.

5. Discussion

As have been shown by Kapsimalis et al. (2013, 2014) the coastal environment of Drapetsona-Keratsini is considered as highly polluted area. AHs and organochlorines are present at high levels, with higher values constituting a significant threat to the marine

Table 2
Matrix of Spearman's rho correlation coefficients for foraminiferal and abiotic parameters.

	A. beccarii	*A. tepida*	*A. longirostra*	*A. mamilla*	*B. sphatulata*	*B. aculeata*	*B. elongata*	*E. crispum*	*L. lobatula*	*P. pertusus*	*P. planatus*	*Q. berthelotiana*	*Q. laevigata*	*Q. seminula*	*R. bradyi*	FD	S	H'	a-index	AEI	stress-tolerant taxa	pyritized tests
sand	0.15	−**0.67**	−0.05	0.02	−0.24	−0.05	−0.38	***0.74***	0.26	0.06	0.24	−0.19	0.46	**0.65**	**0.64**	−0.06	−0.07	0.27	0.51	−**0.60**	−**0.58**	−0.02
Corg	−0.15	***0.89***	−0.02	−0.07	0.30	−0.14	0.55	−***0.81***	−0.34	0.00	0.02	−0.14	−0.16	−0.48	−***0.74***	−0.03	−0.05	−0.31	−0.56	***0.89***	***0.71***	−0.08
AHCs	−0.29	***0.84***	0.11	0.08	0.12	0.01	**0.68**	−***0.86***	−0.39	0.27	0.18	−0.19	−0.20	−0.56	−**0.64**	−0.12	0.19	−0.10	−0.50	***0.85***	**0.66**	0.07
PAHs	0.12	**0.63**	−0.27	−0.39	**0.73**	−0.09	0.37	−0.44	0.28	−0.13	0.16	−0.45	0.37	−0.14	−**0.70**	0.23	0.22	−0.05	0.77	**0.64**	***0.78***	−0.04
PCBs	−0.71	0.80	0.45	0.30	−0.67	−0.34	**0.90**	−0.70	−0.80	0.70	0.34	−0.20	−0.30	−0.40	−0.30	−0.70	−0.50	−0.50	−**0.90**	0.80	0.50	0.41
TotalDDTs	−0.35	**0.90**	0.22	−0.10	−0.34	−0.67	0.80	−0.50	−**0.90**	0.60	0.34	−0.40	−0.10	−0.30	−0.50	−**0.90**	−0.60	−0.60	−0.70	**0.90**	0.70	0.56
Lindane	0.00	0.40	0.22	−0.60	0.22	−0.45	0.70	−0.60	−0.40	0.10	−0.11	−0.10	−0.40	−0.70	−**0.90**	−0.60	0.00	0.00	−0.20	0.40	***1.00***	***0.97***
HCB	0.35	0.10	−0.45	−**0.90**	0.78	−0.22	0.20	−0.10	−0.10	0.00	0.11	−0.40	0.10	−0.30	−**0.90**	−0.10	0.40	0.40	0.50	0.10	0.70	0.67
Trans–Nonachlor	0.35	0.30	0.45	−0.20	−0.11	−0.78	0.10	0.00	−0.30	−0.30	−0.45	0.20	−0.20	−0.10	0.00	−0.80	−0.70	−0.70	−0.40	0.30	0.40	0.36
E_r^iAs	0.28	0.57	−0.29	−0.44	***0.72***	−0.19	0.13	−0.37	0.01	−0.11	0.11	−0.30	0.51	−0.02	−**0.66**	0.29	0.19	−0.01	0.12	**0.60**	**0.58**	−0.14
E_r^iCd	0.16	0.53	−0.41	−**0.60**	***0.72***	−0.34	0.26	−0.36	−0.25	0.03	−0.12	−0.27	0.13	−0.04	−***0.73***	0.10	−0.06	−0.29	−0.04	0.57	**0.67**	0.13
E_r^iCr	−0.12	***0.80***	0.11	−0.01	0.25	−0.09	0.50	−***0.87***	−0.29	0.18	0.05	0.02	−0.18	−0.55	−***0.77***	0.02	0.16	−0.08	−0.42	***0.83***	**0.64**	0.09
E_r^iCu	0.18	**0.64**	−0.27	−0.47	***0.79***	−0.14	0.29	−0.51	0.01	−0.23	−0.14	−0.25	0.22	−0.21	−***0.76***	0.24	0.13	−0.19	−0.03	**0.63**	***0.76***	−0.07
E_r^iHg	−0.13	***0.78***	−0.27	−0.17	0.40	−0.05	0.34	−0.54	−0.29	−0.02	0.16	−0.33	0.22	−0.18	−0.52	0.20	0.09	−0.19	−0.32	***0.71***	0.53	−0.32
E_r^iNi	−0.08	0.45	0.18	0.23	0.00	−0.15	0.19	−**0.64**	−0.15	0.16	−0.09	0.37	−0.32	−0.40	−***0.71***	0.08	−0.08	−0.06	−0.34	**0.58**	0.31	0.15
E_r^iPb	0.20	**0.61**	−0.28	−0.42	***0.72***	−0.19	0.22	−0.44	−0.04	−0.08	−0.04	−0.25	0.30	−0.14	−***0.80***	0.30	0.14	−0.12	0.05	**0.65**	***0.72***	−0.01
E_r^iZn	0.18	**0.61**	−0.27	−0.41	***0.72***	−0.19	0.24	−0.46	0.01	−0.12	−0.05	−0.27	0.33	−0.11	−***0.77***	0.31	0.14	−0.10	0.05	**0.64**	**0.71**	−0.04
RI	0.20	0.57	−0.35	−**0.59**	***0.72***	−0.34	0.25	−0.41	−0.21	0.01	−0.08	−0.25	0.19	−0.07	−***0.74***	0.13	−0.01	−0.22	−0.02	**0.65**	**0.68**	0.11

r values greater than |0.58| are significant with 95% probability. PCBs, Total DDTs, Lindane, HCB and Trans-Nonachlor were computed from 5 data points hence critical value for their correlation at a probability level of 95% is |0.90|. Values in bold: correlation is significant at the 0.05 level (2-tailed). Values in bold and italic: correlation is significant at the 0.01 level (2-tailed).

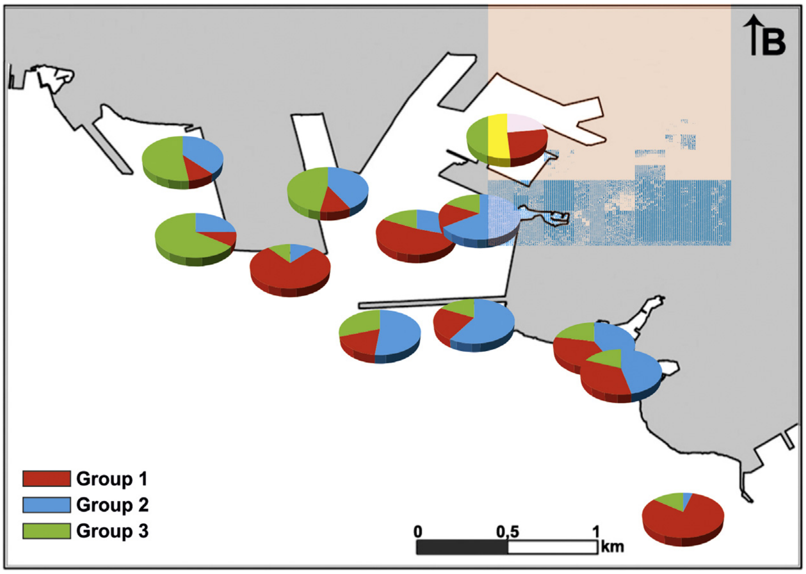

Fig. 7. Spatial distribution of the relative abundance of foraminiferal species.

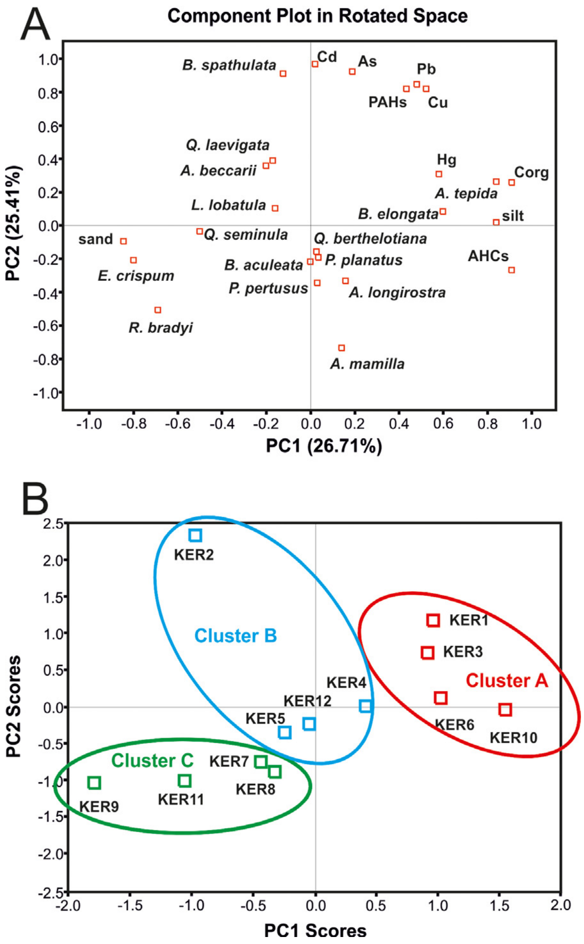

Fig. 8. A Bivariate plot of the first two principal component axes; B Plot of PC1 versus PC2 scores.

Table 3
Varimax rotated component matrix of PCA.

	Component 1	Component 2
Adelosina longirostra	0.157	−0.330
Ammonia beccarii	−0.203	0.360
Ammonia tepida	**0.839**	0.264
Asterigerinata mamilla	0.139	**−0.731**
Bolivina sphatulata	−0.125	**0.911**
Bulimina aculeata	−0.002	−0.218
Bulimina elongata	**0.598**	0.087
Elphidium crispum	**−0.802**	−0.206
Lobatula lobatula	−0.161	0.104
Peneroplis pertusus	0.029	−0.342
Peneroplis planatus	0.036	−0.182
Quinqueloculina berthelotiana	0.025	−0.159
Quinqueloculina laevigata	−0.172	0.390
Quinqueloculina seminula	**−0.501**	−0.036
Rosalina bradyi	**−0.691**	**−0.504**
sand	**−0.847**	−0.092
silt	**0.838**	0.020
Corg	**0.908**	0.259
PAHs	0.433	**0.820**
AHCs	**0.910**	−0.265
As	0.188	**0.923**
Cd	0.019	**0.968**
Hg	**0.579**	0.306
Cu	**0.520**	**0.819**
Pb	0.477	**0.845**

Significant loadings shown in bold type.

ecosystem. The application of the Potential Ecological Risk Factor (E_r^i) suggests the characterization of the major part of the study area as moderately-worse polluted regarding the Cd, Hg, As, Cu and Pb concentrations to estimate the degree of sediment contamination from heavy metals (Kapsimalis et al., 2014). In addition, the Ecological Risk Index (RI) usually exceeding 300 indicates considerable to very high ecological risk, except in the inner basin of the Keratsini Port (low risk) and the KER7–KER9 (moderate risk). The measured sediment Corg content reaches a maximum value of ~2.8% being considered as high but not extreme (Kapsimalis et al., 2013).

In the present study, the total (living and dead) foraminifera are investigated from the surface sediments of the Drapetsona–Keratsini coastal zone. Thus, the foraminiferal assemblage represents the shell accumulation of approximately the last six years, being also affected by weak post mortem influence such as mixing and transportation (e.g., waves and associated shore currents, boat traffic). Nevertheless, despite the possible influence of taphonomic processes, the total foraminiferal assemblage in harbour areas reflects an average environmental interpretation (e.g., Debenay et al., 2001; Armynot du Châtelet et al., 2004; Bergamin et al., 2009).

The results from Q-mode HCA separate three distinct clusters groups (Cluster A–C) within the studied samples (Fig. 6A). Q-mode clusters correspond to the faunal Groups (Group 1–3) distinguished by the R-mode analysis (Figs. 6B, 7). Furthermore, PCA and Spearman correlation results document the influence of sediment grain size, organic carbon content and degree of pollution on the distribution of the assemblages.

Cluster A-sites are found in sediments composed of sandy silts, with the silt content ranging from 54.3% to 80.7%. The organic carbon and hydrocarbons levels are overall high (Figs. 2, 3). Heavy metal concentrations according to RI (> 600) denote very high ecological risk, which is further confirmed by the high $E_r{}^i$ values of As, Cd and Hg (Fig. 3). The foraminiferal assemblage of these samples is strongly dominated by members of Group 1 (23–66%, median 51%; Fig. 7), represented by stress-tolerant species *B. spathulata*, *A. tepida* and *B. elongata*, with the latter two display their maximum relative abundances. This particular assemblage is analogue to that recently described in the neighboring highly polluted Elefsis Bay (Dimiza et al., 2016b). *Ammonia tepida*, in particular, is described as pollution-tolerant species in many studies (e.g., Samir and El-Din, 2001; Armynot du Châtelet and Debenay 2004; Frontalini and Coccioni, 2008, 2011). In general, all these species have an opportunistic behavior under natural and anthropogenic stressors that enhance the organic matter (e.g., Naeher et al., 2012; Mendes et al., 2015; Dimiza et al., 2016b; Jorissen et al., 2018), and/or the contaminants in muddy sediments (Schintu et al., 2015; Schintu et al., 2016). In this study, *B. elongata* and *A. tepida* are associated with finer sediments, and higher values of AHCs and Corg (Fig. 8), whereas *A. tepida* is also displaying good Spearman's rho correlation with PAHs, and $E_r{}^i$ values of Cr, Cu, Hg, Pb and Zn (see Table 2). Moreover, *B. spathulata* shows strong affinity with PAHs and heavy metal concentrations in both statistic exercises. Species diversity (a-index median = 9.1, H' median = 2.4) is the lowest of the two other Clusters and FD (31–138 specimens g^{-1}) is relatively low, comparable to other polluted coastal areas in the eastern Mediterranean Sea (Samir and El-Din, 2001). The severely stressful conditions occurring at Cluster A-sites are reflected in the STR (median ~57%), but also in the AEI values, which are constantly high (median = 79) implying the potential effect of hypoxic conditions (e.g., Sen Gupta et al., 1996).

Cluster B-sites are determined in samples mainly composed of silty sand, with the exception of sample KER12 that bears dominant silt fraction (61.6%). Despite that Corg and AHCs contents are lower compared to Cluster A-sites, the concentration of PAHs remains high (Figs. 2, 3). Regarding heavy metals concentrations, RI (> 300) suggests considerable to very high ecological risk, whereas $E_r{}^i$ values of As, Cd, Hg, Cu and Pb are maintained at high levels. The foraminiferal assemblage of these samples is dominated by Group 2 (26–49%, median 36%; Fig. 7); a diverse group which comprises *A. beccarii*, *Peneroplis* species and several miliolid taxa. All these are typical eastern Mediterranean species of shallow water sandy substrates (e.g., Sgarrella and Moncharmont Zei, 1993; Dimiza et al., 2016a). The most dominant, the miliolids are described as taxa very sensitive to pollution (e.g., Samir and El-Din, 2001). Nevertheless, some species like *Miliolinella subrotunda*, *Quinqueloculina parvula*, *Q. stelligera*, *Q. lata* (Bergamin et al., 2003, Romano et al., 2009), *Q. bicostata* (Foster et al., 2012) and *Q. seminula* (Martins et al., 2013) have been found to show a tolerant to metal polluted conditions. In this study, all species within Group 2 show no significant affinity with organic carbon, heavy metals and hydrocarbon content; and therefore seem to have an independent distribution in our study area. The species *Q. seminula*, being the most abundant within miliolids, shows positive correlation with the sand content according to the PCA and Spearman's rho correlation. It is noteworthy that the increase of species diversity (a-index median = 12.8 and H' median = 3.0) corresponds to an increment of several miliolid taxa, which seems to favour the sandy substrates of Cluster B-sites as in their natural habitats (e.g., Kaiho, 1994; Elshanawany et al., 2011; Li et al., 2015). Finally, FD (37–123 specimens g^{-1}) is similar to that of Cluster A (see Appendix A3). The assemblage is characterized by STR of lower frequency (median = 22%) in relation to Cluster A-sites (Table 3), whereas moderate values (median = 57) of AEI imply intermittent hypoxia.

The sediments of Cluster C-sites are characterized by high sand levels and lower contents of Corg, AHCs and PAHs (Figs. 2, 3). RI (< 300) suggests moderate risk; however the $E_r{}^i$ values of Cd and Hg may imply higher polluted conditions. Consequently, the sampling sites of Cluster C are located at the least contaminated part of the study area. The foraminiferal assemblage of these samples is dominated by members of Group 3 (32–40%, median 35%; Fig. 7), which includes small epiphytic hyaline taxa *A. mamilla*, *R. bradyi*, *E. crispum*, *L. lobatula*, and a sole infaunal representative *B. aculeata*. The increased frequencies of small epiphytic rotaliids along with the significant reduction of STR (median = 12%) reflect conditions similar to the relatively unpolluted Inner Saronikos Gulf sites (Dimiza et al., 2016b). Amongst Group 3, the dominant taxa *A. mamilla* (~15%) and *R. bradyi* (~11%) have been commonly found in shallow marine environments with well-oxygenated, vegetated, occasionally coarse-grained bottoms (e.g., Jorissen, 1987; Langer, 1988, 1993; Sgarrella and Moncharmont Zei, 1993; Bergamin et al., 2003; Triantaphyllou et al., 2005; Frezza and Carboni, 2009; Dimiza et al., 2016a, b). The PCA results verify the affinity of these species with the sand content and the negative influence of the contaminant concentrations (Fig. 8). More specific, *R. bradyi* displays significant negative Spearman's rho correlation with Corg and all of the pollutants, whereas *A. mamilla* exhibits the same trend for the concentration of HCB, RI index and $E_r{}^i$ values of Cd. These findings are consistent with the results of Cherchi et al. (2009) who have found that the hyaline forms decrease with increasing heavy metal pollution, suggesting that the hyaline foraminifera are more sensitive to chemical stress due to the presence of pores on their carbonate wall. Total FD (6–355 specimens g^{-1}) shows high variability, whilst the species diversity (a-index median = 13.0 and H' median = 2.9) is quite similar to that of Cluster B-sites. Finally, a much lower AEI (median = 33) is recorded.

The high frequency of pyritized foraminiferal tests in the Drapetsona-Keratsini benthic foraminiferal assemblages is a triggering observation as their presence is probably related to oxygen depleted environments (e.g., Kravchuk, 2006). Although the reasons for pyritization are not yet clear, these may be related to chemical processes that result in metabolization of organic matter through sulphate-reducing bacteria, diffusion of sulphate into sediments, or concentration and reactivity of the iron minerals (Alve, 1991; Yanko et al., 1999; Kravchuk, 2006; Cherchi et al., 2009). In this study, high frequencies of pyritized foraminiferal tests have been observed in the central basin of the Keratsini Port (muddy substrates of Cluster A-sites, Cluster B-sites) under increased metal and hydrocarbon contaminants and organic matter content.

6. Conclusions

The analysis of the benthic foraminiferal community in the surface sediments of the coastal environment of Drapetsona-Keratsini shows that sediment type, Corg contents and contaminant concentrations constitute the crucial factors that affect the foraminiferal composition and species distribution.

The highly elevated pollution levels (caused by the high $E_r{}^i$ values of As, Cd and Hg and increased hydrocarbon concentrations) of the silty surface sediments associated with Cluster A- sites (sand fraction less than 46%) are accompanied by relatively low species diversity assemblages dominated by the pollution-tolerant taxa *B. elongata*, *A. tepida* and *B. spathulata*.

More diverse assemblages develop in the sandier bottom of the moderately-polluted sites (As, Cd, Hg, Cu and Pb) related to Cluster B, mainly characterized by high relative proportions of miliolids (mostly *Q. seminula*). Miliolids are impressively thriving in the sandy substrates, being practically unaffected by the occurring polluted conditions.

Cluster C-sites are featured by an epiphytic rotaliid-dominated assemblage (i.e., Group 3) in the relatively unpolluted study area's sites.

Overall, the most tolerant species to Corg and contaminant concentrations (hydrocarbons and heavy metals) are *A. tepida*, *B. elongata* and *B. spathulata. Quinqueloculina seminula* and total miliolids present no response to pollution within sandy sediment deposits; in contrast the epiphytic rotaliids *A. mamilla* and *R. bradyi* also related with the sandier sediments, show an obvious sensitivity to pollutants. It is evident that the different contaminant levels in the surface sediments of the Drapetsona–Keratsini coastal zone have a significant impact on the occurring benthic foraminiferal assemblages. However, the evaluation of the effects on the foraminiferal species distribution seems to be rather complicated, since the combination of several stressors, e.g., the simultaneous action of excessive heavy metal and organic contaminant loads, in respect to single contaminants, may result to unexpected impacts on the foraminiferal assemblage composition and abundance.

Disclosure of interest

The authors declare that they have no competing interest.

Acknowledgments

This work has been made possible thanks to the financial support provided by the NKUA/SARG 70/3/13087 project. The constructive and helpful criticism of two anonymous reviewers is greatly appreciated.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.revmic.2018.09.001.

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