FORAMINIFERA AS INDICATORS OF ENVIRONMENTAL STRESS: NEW EVIDENCE FROM THE ROMANIAN SHELF

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Introduction

The river-dominated shelves of the Black Sea, e.g., the northwestern shelf adjacent to the Danube delta, are characterized by highly dynamic conditions. Their ecosystems are constantly under environmental stress caused by uneven riverine discharge of freshwater enriched with organic and inorganic compounds that provide a local increase in primary productivity and contribute to eutrophication of the water column and export of organic matter to the sea floor. This in turn affects the geochemical processes in bottom sediments and benthic life on both short- (i.e., seasonal) and long-term scales.

The main goal of our study is to discover whether there is any correlation between distributional patterns of river input and response to it by the benthic ecosystem (exemplified by foraminifera); the study area is the NW Black Sea shelf adjacent to the Romanian part of the Danube delta. The study consists of two parts: (1) investigation of seasonal (early spring and fall) foraminiferal distribution with regard to environmental parameters, and (2) application of obtained knowledge to the study of sediment cores on both short and long time scales, respectively.

In this paper, we present our results on the study of benthic foraminifera in superficial sediments recovered in early spring 2012. Our intent is to demonstrate the interrelation between foraminiferal (e.g., abundance, taxonomic content, and diversity) and environmental parameters that we measured in bottom water (e.g., depth, salinity, transparency, conductivity, T°C, DO, O2, pH, ORP, ō15N, C/N) and superficial sediments (Corg, grain size). The aim of this study is to gain insight into whether the benthic ecosystem experiences environmental stress caused by river discharge into the sea.

Study area

The Danube is the second largest river in Europe (after the Volga River) with a width up to 1.2 km, an average depth of 5-7 m, and a velocity of 0.5-1.0 ms-1. Its catchment basin embraces 15 highly industrialized European countries with a population of 76 million people that together produce enormous anthropogenic pressure on the river ecosystems and, via them, on the marine environment. The Danube is a delta-type river with four main branches: the St. George I, the Sulina, the St. George II, and the Chilia (or Kilia). The delta area is about 5640 km2 and is located in two countries (Ukraine and Romania). The Romanian part of the delta is 4400 km2 in area and is bordered by the Burgas Plateau on the north and the Dobrogea orogenic area on the south (Panin and Jipa, 2002).

The NW Black Sea littoral zone consists of Ukrainian and Romanian sections. The former is north of the Danube Delta (from Jibriany to Odessa) and is characterized by a sediment starving regime. The latter consists of two units: the Danube Delta coastal zone, and the so-called Southern Unit (from Cape Midia to the Romanian-Bulgarian border). The former is characterized by longshore sediment drift along the delta generated by winds, waves, and longshore currents with potential values varying in different places from 0 to 1230 million m3/yr (Giosan et al., 1997), while the latter is strongly influenced by the Midia harbor jetties. The sandy supply of the longshore drift is trapped upstream of the Midia harbor protection dikes, causing sediment starvation of the entire Southern Unit, where most of the public beaches and tourism centers are located. In addition, this zone is surrounded by an almost continuous loess cliff up to 12-29 m high, which is more stable to erosion than the northern deltaic unit.

The dispersal patterns of the Danube sediment supply to the NW shelf indicate two main areas with different depositional processes: the Danube-fed inner shelf (before isobath 50 m) and the sediment starving outer shelf (behind isobath 50 m). The area under study includes the littoral zone, inner and partially outer shelf (up to isobath 80 m) within the Romanian part of the NW Black Sea shelf (Fig. 1).

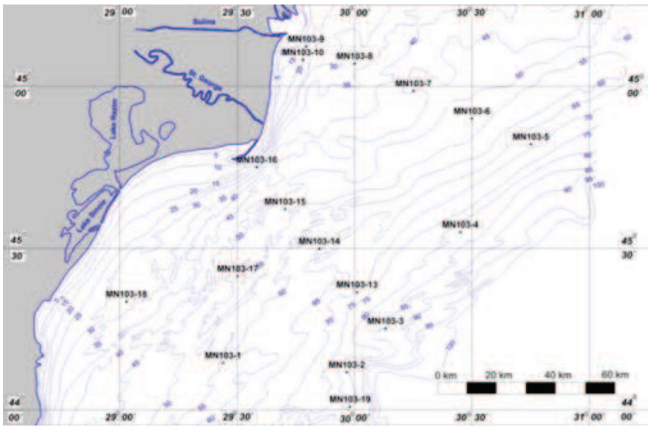

Figure 1. Study area and location of sampled stations.

Material and methods

Material was collected in the Romanian part of the NW Black Sea shelf on May 3-9, 2012 using Romanian R/V "Mare Nigrum." Seventeen stations (Fig. 1) were sampled by 0.1 m2 van Veen grab and by Multicorer Mark II-400 with four tubes, each 60 cm long and 10 cm in diameter. In this report, we present results of the study of the grab samples. Hydrological parameters of the water column were measured using the Neil Brown Instrument Systems (CTD) with a General Oceanic rosette and Niskin bottles. The transparency of the water column was measured by Secchi disk. Corg in the sediments was measured by Method of Ignition .

For the foraminiferal analysis, sediment samples were collected from the uppermost 2 cm of the sediment column with the help of two rings, each 10 cm in diameter and 2 cm in height, using a wooden spatula, and fixed in a 4% formalin solution buffered with sea water and Rose Bengal in order to identify live (stained) specimens. After 48 hours, the samples were washed in a sea water trough sieve with a mesh size of 63 µm, dried at air temperature, placed in small plastic containers, and studied in the micropaleontological laboratory of Odessa I.I. Mechnikov National University. Foraminifera were picked by hand under the binocular microscope. Large samples were randomly split with a splitter into sub-samples containing at least 300 specimens. The total assemblage, including live (stained) and dead foraminifera, was calculated together and expressed as the number of tests (abundance) per 50 g dry sediment. All the shells present in the samples were identified and counted, and the data were expressed as percentages (relative frequencies) of the total number of foraminifera. Species diversity is defined by simple species richness (number of species) and the Shannon-Wiener index (H'). All identified species were imaged with an SEM at the University of Manitoba, Winnipeg, Canada.

According to their ecological preferences, foraminifera are divided into oligohaline (1-5 psu), strictoeuryhaline (11-26 psu), polyhaline (18-26 psu), holoeuryhaline (1-26 psu), shallow (0-30 m), relatively deep (31-70 m), and deep (71-220 m) species (Yanko and Troitskaya, 1987; Yanko, 1990a; Yanko-Hombach, 2007).

Statistical treatment

All obtained parameters were treated statistically using the Statistics-7 package in order to find out whether there is any correlation between the abundance, diversity and taxonomic distribution of foraminifera and environmental parameters. The Q-mode cluster, factor and dispersion analyses, as well as multidimensional scaling were applied.

Results

Foraminifera

The limited number of live foraminifera did not allow a reliable study of their distributional patterns. Therefore, we studied the total assemblages, including live (stained) and dead individuals. The presence of live specimens shows that these species most likely live in the study area and that their empty tests are most probably autochthonous. No planktonic species were discovered. Benthic foraminifera are represented by 15 species (14 calcareous and one agglutinated) from 3 orders, 7 families, and 14 genera (Fig. 2).

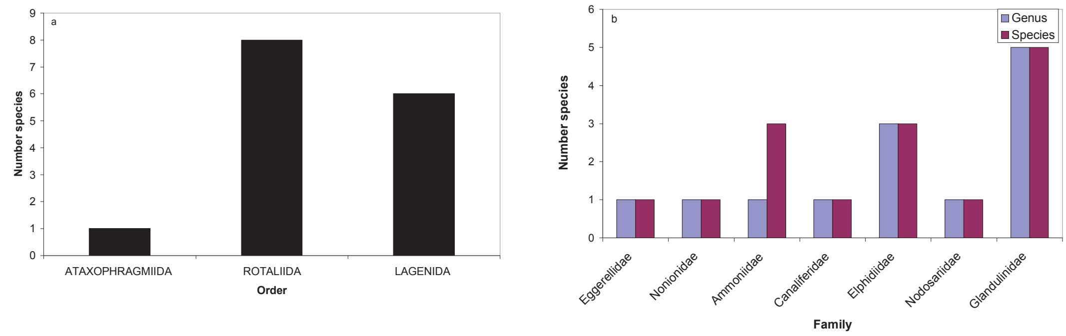

Figure 2. Taxonomic content of benthic foraminifera showing the number of orders (a), families, and species (b).

The orders Rotaliida, Lagenida, and Ataxophragmiida are represented by 8, 5, and 1 species, respectively. Among the Rotaliida, the most abundant are three species of Ammonia (A. tepida, A. compacta, A. ammoniformis), and among the Lagenida, Fissurina lucida.

Q-mode cluster analysis of the matrix consisted of 17 cases (stations) and 15 variables (relative frequencies of foraminiferal species) and produced a dendrogram (Fig. 3a) in which two, three, or four clusters corresponding to Linkage Distance 3, 1, and 0.6, respectively, can be recognized. The question appeared where to "trim" the tree in order to get the optimal number of clusters. Because "…this problem is still among unsolved problems of cluster analysis" Kim et al. (1989: 184), multidimensional scaling of stations was performed. This analysis distinguished three groups of stations, suggesting that the tree can be trimmed at Linkage Distance 1 (dotted line in Fig. 3a).

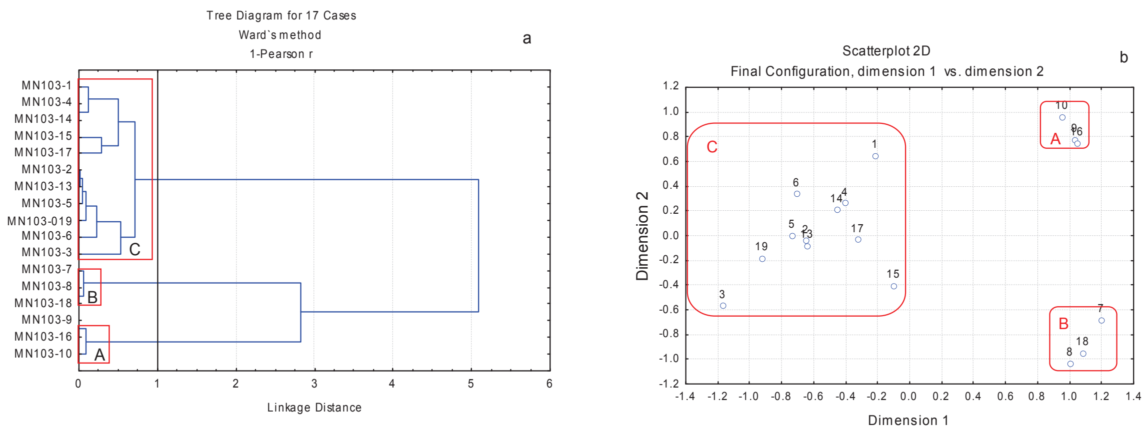

Figure 3. Grouping of stations with similar foraminiferal species composition: a. Dendrogram from a Q-mode cluster analysis based on species population in which separation of the three clusters A, B, and C can be recognized; b. MDS plot of stations showing groups distributed on a metric scale suggesting that the dendrogram of Fig. 3a should be "trimmed" at Linkage Distance 1 (dotted vertical line). For clarity, the cruise number "MN103" has been omitted from the station numbers.

The spatial distribution of clusters A, B, and C is shown in Fig. 4.

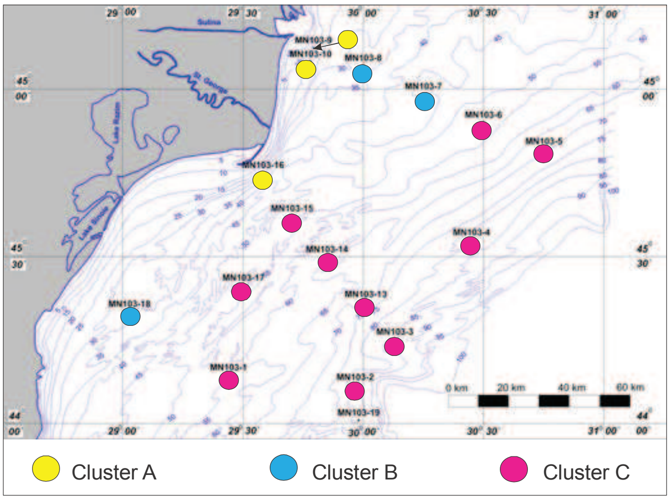

Figure 4. Map showing the spatial distribution of sample localities falling within the three clusters obtained by cluster analysis (Fig. 3a) and multidimensional scaling (Fig. 3b).

Cluster A includes the shallowest stations MN103-9, MN103-10, and MN103-16, with depths ranging between 17.5 m and 24.6 m. These stations are located within the littoral zone and as such are under the strong influence of freshwater discharge from the Sulina (Stations MN103-9 and MN103-10) and St. George (St. MN103-16) arms of the Danube River (Fig. 1). Therefore, the salinity here is the lowest of all other stations, ranging between 17.8 and 18 psu. The foraminiferal abundance varies from **11,123** to **15,616 specimens**/50 g dry sediment. The Shannon-Wiener Index varies from **0.38 to 1.47.** The number of species per station varies between **3** and **4**; the total number of species per cluster is **6**; the number of common species that present at all stations is **2**. They are *Ammonia tepida* and *Porosononion subgranosus mediterranicus* with relative frequencies up to 60% and 35%, respectively (Fig. 5). Both species are holoeuryhaline shallow-water species, well adapted to salinity variations, being distributed mostly on the inner shelf of the Black Sea (Yanko, 1990 a,b).

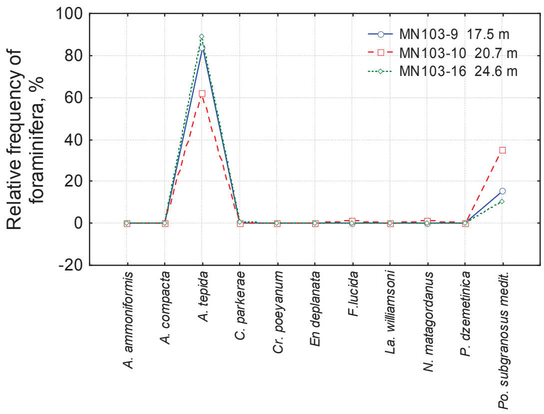

Figure 5. Species composition of foraminifera in cluster A, showing the dominant role of *Ammonia tepida,* and to a lesser degree, *Porosononion subgranosus mediterranicus* .

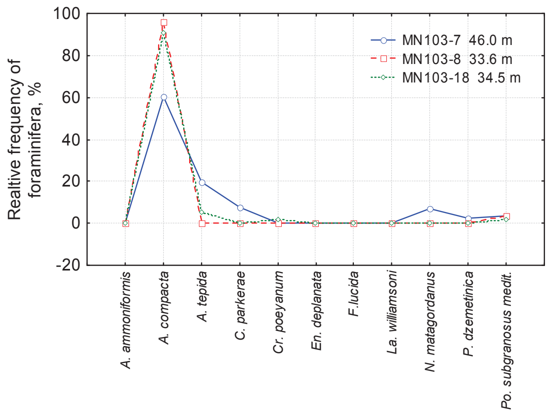

Figure 6. Species composition of foraminifera in cluster B showing the dominant role of relatively deep- water polyhaline *Ammonia compacta*.

Cluster B includes stations MN103-7, MN103-8, and MN103-18, located on the inner shelf, with water depths ranging between 33.6 m and 46 m, and salinity 18.2-18.3 psu. The foraminiferal abundance is lower compared to littoral assemblages, varying between **5540** and **10,368** specimens/50 g dry sediment, but the total number of species per cluster is higher at **8** species. The Shannon-Wiener Index varies between **0.19 and 1.21**. The number of species per station varies between **3 and 6**; the number of common species that present at all stations is **2**. They are *Ammonia compacta* and *Porosononion* *subgranosus mediterranicus*, with relative frequencies up to **95.8** and **3.2%,** respectively (Fig. 6). Compared to cluster A, the relative frequency of *Ammonia tepida* and *Porosononion subgranosus mediterranicus* sharply decreases. The most significant among the newly appearing species are *Canalifera parkerae* and *Nonion matagordanus* (each up to 7%), both strictoeuryhaline and relatively deep-water species that, together with the dominant polyhaline *Ammonia compacta*, are widely distributed on the inner shelf of the Black Sea (Yanko, 1990 a,b).

Cluster C includes stations MN103-1, MN103-2, MN103-3, MN103-4, MN103-5, MN103-6, MN103-13, MN103-14, MN103-15, MN103-17, and MN103-19, located on the outer shelf with depths ranging between 50.4 m and 80.0 m (Fig. 7).

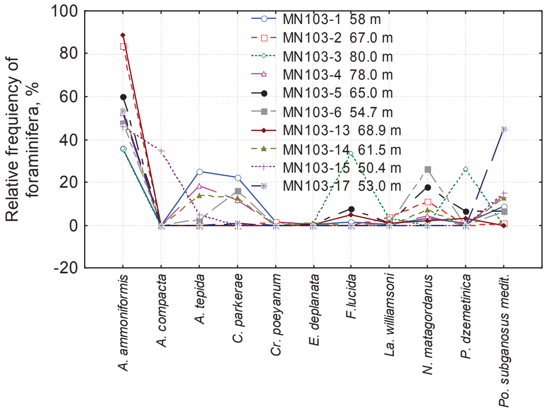

Figure 7. Species composition of foraminifera in cluster C showing that this group of stations is dominated by relatively deep-water strictoeuryhaline *Ammonia ammoniformis* with numerous lagenids.

Being the farthest from the shore, this cluster of stations is much less affected by freshwater input compared to stations of clusters A and B. Therefore, the salinity here is the highest, ranging between 18.2 psu and 18.9 psu. Foraminiferal abundance ranges from **2519** to **13,348** specimens/50 g dry sediment, but the total number of species per cluster is much higher, 14 species, compared to clusters A and B. However, the Shannon-Wiener Index is almost the same, varying from **0.6** to **1.34**. Both the lowest and highest values were calculated at stations located at the same water depth, 67 m. The number of species per station varies between **4** and **11**; the number of common species that present at all stations is **one**, the strictoeuryhaline and relatively deep-water *Ammonia ammoniformis*; it is mostly distributed on the outer shelf (Yanko, 1990 a,b; Yanko-Hombach, 2007). This cluster is characterized by the presence of six Lagenida species (*Entolingulina deplanata*, *Esosyrinx jatzkoi*, *Fissurina lucida*, *Lagena vulgaris*, *Laryngosigma williamsoni*, and *Parafissurina dzemetinica*) with total frequencies up to 69% at the deepest station MN103-3, located at a water depth of 80.0 m. In the Black Sea, Lagenida species are polyhaline and are mostly distributed on the outer shelf below isobath 70.0 m under salinities above 18 psu (Yanko, 1990 a,b; Yanko-Hombach, 2007).

Environmental parameters

Factor analysis of environmental parameters revealed three factor units called here Groups of Environmental Parameters (GEP) with eigenvalues listed in Table 1.

Table 1. Eigenvalues of environmental parameters of bottom water extracted by factor analysis.

Value	Eigenvalues Extraction: Principal components			
	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
1	5.650478	47.08732	5.650478	47.08732
2	2.325936	19.38280	7.976414	66.47012
3	1.861694	15.51412	9.838108	81.98424

All together, they explain 82% of the information from the original variables and are therefore statistically satisfactory. GEP 1, accounting for 47.08% of the variance of the revised raw data, includes transparency, salinity, conductivity, T°C, and C_{org}, where the highest factor loading is conductivity. GEP 2, accounting for 19.38% of the variance of the revised raw data, consists of O_2 and DO, with equally important factor loadings. GEP 3, accounting for 15.5% of the variance of the revised raw data, consists of ORP and pH, with equally important factor loadings (Table 2).

Table 2. Rotated component matrix of environmental parameters: the first column lists the names of the variables originally entered into the analysis; the second, third, and fourth columns contain factor loadings to match the components from Table 1 that have corresponding eigenvalues. In bold are the most significant factor loadings. Note that neither δ15N nor C/N show significant loading to any of the factors. However, C/N obviously trends with water depth as can be seen in Table 3.

	Factor Loadings (Varimax normalized) Extraction: Principal components (Marked loadings are >.700000)		
Variable	Factor 1	Factor 2	Factor 3
Water depth	**0.905389**	-0.034129	0.317102
Transparency	**0.807886**	0.022799	0.193598
O_2	-0.164564	**-0.974761**	-0.022073
DO	-0.142755	**-0.973969**	0.055470
Salinity	**0.860709**	0.362823	0.166104
Conductivity	**0.954194**	0.149351	0.098880
T°C	**0.802046**	0.253112	-0.032223
pH	0.163148	-0.184154	**0.893834**
ORP	0.198201	0.038048	**0.841562**
Corg, %	**0.835773**	-0.255905	0.026209
C/N	0.560049	0.318123	0.623442
d15N	0.253105	-0.476924	-0.506961
Expl.Var	4.956587	2.547975	2.333546
Prp.Totl	0.413049	0.212331	0.194462

The 2D diagram of Factor Analysis (Fig. 8) shows that GEP 1 and GEP 3 are located in opposite corners of the graph, while GEP 2 takes an intermediate position. C/N and $\delta^{15}N$ are located outside of all three groups.

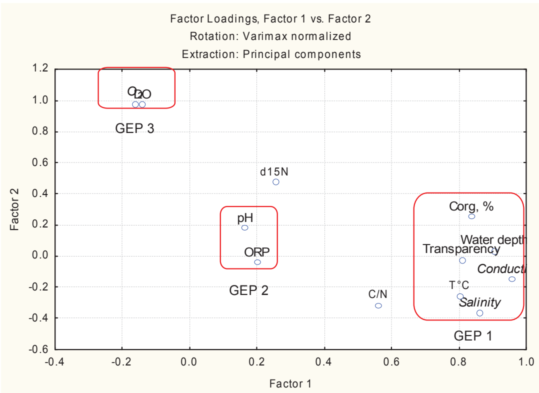

Figure 8. 2D diagram of the factor analysis shows three main Groups of Environmental Parameters (GEP): GEP 1 unites conductivity, Corg, salinity, temperature, and transparency; GEP 2 unites pH and ORP; and GEP 3 includes O_2 and DO. Note: GEP 1 and GEP 3 are located in an opposite corners of the graph, while GEP 2 takes an intermediate position between them.

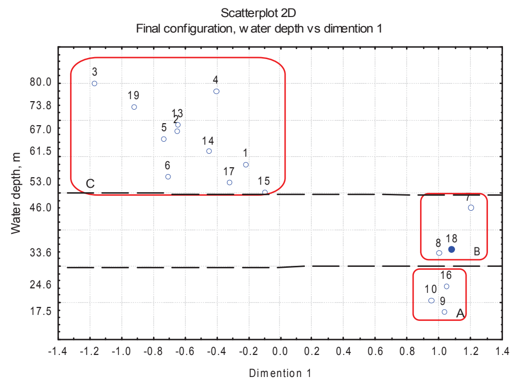

Figure 9. 2D scatterplot of clusters A, B, and C, graphing water depth against Dimension 1. The plot shows a clear trend of increasing water depth from cluster C to B, and then to A without overlap.

The position of clusters A, B, C in the two-dimensional coordinate system shows that they are clearly separated from each other along Factor 1 (Fig. 9). Factor 1 is associated with water depth and related to GEP 1 and C/N (Table 3),

Table 3. Correlations between Dimension 1 and GEP 1, GEP 2, and GEP 3, $\delta^{15}N$ and C/N. In bold correlations significant at $p < .05000$.

	GEP 1						GEP 2		GEP 3		$\delta^{15}N$	C/N
Parameter	Water depth	Trans-parency	Salin-ity	Conduc-tivity	T°C	C_{org}	pH	ORP	O_2	DO		
Dimen-sion 1	-0.88	-0.70	-0.64	-0.77	-0.47	-0.79	-0.31	-0.34	0.08	0.04	-0.01	-0.67

No correlation between Dimension 1 and sedimentological parameters has been discovered (Table 4).

Table 4. Correlations between Dimension 1 and lithological parameters. In bold are correlations significant at $p < .05000$. No significant correlation has been discovered.

Granulometry	Pebble	Granule	Very coarse sand	Coarse sand	Medium sand	Fine sand	Very fine sand	Silt	Clay	Md	So
Dimen-sion 1	-0.19	0.17	-0.29	0.17	0.13	0.31	0.06	-0.19	0.17	-0.30	0.14

Discussion

The results obtained show the influence of three main factors that predefine the distributional patterns of environmental parameters and foraminiferal assemblages. Factor 1, which is the strongest among all the factors, represents distance from the shore and amount of Danube freshwater enriched with organic compounds discharged into the Black Sea. It affects all measured hydrological parameters as well as C/N of bottom water and Corg in the sediments.

Factor 2 has a negative relationship to Factor 1 according to the factor loadings (Table 2) and as such, it has a different meaning compared to Factor 1. It affects GEP 3, which is supposed to be a function of water depth, T°C, water circulation, and photosynthesis (REF). Logically speaking, it should be grouped together with water depth, but in fact it is located in an opposite corner of the factor diagram (Fig. 8). Therefore, the influence of temperature and water depth on concentration of oxygen in the bottom water of the study area should be excluded. We think that Factor 2 can be related to eutrophication and contamination of the surface and bottom seawater, respectively, which in turn, depend upon photosynthetic processes and the circulation of water masses. The intermediate position of GEP 2 between the two axes of the other factors (Fig. 8) suggests that Factor 3, which is the least powerful among all the factors, is influenced by both Factor 1 and 2. At the same time, its location in the same plane with GEP 1 to the left of the vertical axis (Fig. 8) speaks in favor of water depth acting upon GEP 2. We hypothesize that GEP 2 depends equally upon the distance from the shore, freshwater input, eutrophication, and hydrogen sulphide contamination of surface and bottom water, respectively. The pH parameter evaluates the hydrogen content in the sea water, being a measure of acidity. The ORP parameter indicates the activity or strength of oxidizers and reducers in relation to their concentration, and is associated only with the partial pressure of oxygen and the pH of the water (Cooper, 1937). This explains why pH and ORP are grouped together on the factor diagram. ORP serves as a measure of the ability of the aquatic environment to cleanse itself or break down waste products, such as contaminants and dead plants and animals. When the ORP value is high, there is lots of oxygen present in the water. This means that bacteria that decompose dead tissue and contaminants can work more efficiently. The higher the ORP value, the healthier is the aquatic environment. Thus, together with DO, the ORP provides additional information on water quality and the degree of pollution. In this way, we suggest that Factor 3 is related to contamination of the bottom water.

Foraminiferal distributional parameters are clearly correlated with GEP 1 and probably C/N, definitely not with grain size distribution. The closer to the shore, the less foraminiferal species can resist the freshening of the bottom water caused by Danube inflow. Farther from the shore, the influence of the Danube inflow decreases and foraminifera flourish.

Conclusions

With the help of benthic foraminifera, the distributional patterns of the Danube River inflow into the Romanian part of NW Black Sea can be traced. The study is in good agreement with our previous data obtained in other parts of the NW Black Sea adjacent to the Dniester and Dnieper Rivers, and it confirms once again that foraminifera can be used as reliable *in situ* instruments to monitor environmental stress caused by river input (Yanko and Troitskaia, 1987; Yanko, 1990 a,b; Yanko et al., 1999; Yanko-Hombach, 2007). The study is in progress. More results will be published elsewhere.

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References

Cooper, L. H. N.1937. Oxidation-reduction potential in sea water. Marine Biol. Assn. U. K., Jour. 22: 167–176,

Giosan, L., Bokuniewicz, H.J., Panin, N., Postolache, I., 1999. Longshore sediment transport pattern along the Romanian Danube delta coast, Journal of Coastal Research 15(4): 859-871.

Kim, J.O., Muller, H.U., Klekka, U.P., Oldenderfer, M.S., and Blashwild, R.K. 1989. Factorniy, discriminantniy i klasterniy analiz [Factor, Discriminant, and Cluster Analysis], Enyukov, I.E., ed. Finansy i statistica (translation from English), 215 p.

Panin, N., and Jipa, D. 2002. Danube River sediment input and its interaction with the north-western Black Sea. Estuarine, Coastal and Shelf Science 54(3): 551–562.

Yanko, V. 1990a Stratigraphy and paleogeography of marine Pleistocene and Holocene deposits of the southern seas of the USSR. Memorie della Società Geologica Italiana 44:167–187.

Yanko, V. 1990b. Chetvertichnie foraminiferi roda Ammonia v Ponto-Kaspiiskom regione [Quaternary foraminifera of genus Ammonia in the Pontic-Caspian Region]. Paleontologicheskii zhurnal 1:18–26. (In Russian)

Yanko, V., and Troitskaia, T. 1987. Pozdnechetvertichnye foraminifery Chernogo moria [Late Quaternary Foraminifera of the Black Sea]. Nauka, Moscow, 111p. (In Russian)

Yanko. V., Arnold, A., and Parker, W. 1999. The effect of marine pollution on benthic foraminifera. In Modern Foraminifera, Sen Gupta, B.K., ed. Kluwer Academic Publishers, Dordrecht. pp. 217–238.

Yanko-Hombach, V., 2007. Controversy over Noah's Flood in the Black Sea: geological and foraminiferal evidence from the shelf. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P.M. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 149-203.