

# Calcareous benthic foraminiferal biofacies along a depth transect on the southwestern Marmara shelf (Turkey)

Mark D. Phipps<sup>1</sup>, Michael A. Kaminski<sup>2\*</sup>, and Ali E. Aksu<sup>3</sup>

<sup>1</sup>Laboratory of Recent and Fossil Bio-Indicators (BIAF), UPRES EA 2644, University of Angers, 2 boulevard Lavoisier, Angers, 49045, France

<sup>2</sup>Department of Earth Sciences, University College London, Gower Street, London, WC1E 6BT, U.K.

<sup>3</sup>Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, Canada, A1B 3X5  
email: mark.phipps@univ-angers.fr

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**ABSTRACT:** A total of 200 calcareous benthic foraminiferal species were identified in 30 surface samples collected across a depth transect in the southwestern Marmara Sea. Q-mode cluster and canonical correspondence analyses performed on the foraminiferal species abundance data revealed three clusters. Environmental parameters collected at each sampling station allowed the correlation between foraminiferal clusters and watermass characteristics, such as water depth, temperature, salinity and dissolved oxygen concentrations. Cluster A (55–130 m) is characterized by species typical of muddy substrates in the circa-littoral zone and related to declining dissolved oxygen values. Cluster B (140–350m) is characterized by deep-infaunal dysoxic and suboxic species indicative of circa-littoral and upper epibathyal environments and strongly related to low dissolved oxygen values and increased water depth. Cluster C (15–50m) is characterized by neritic species typical of the infra-littoral environment. This cluster is further subdivided into three subclusters that reflect brackish surface flow (influenced by low salinity, higher temperature), pycnocline (rising salinity, falling temperature) and infra-littoral to circa-littoral transitional environments (higher oxygen from the Mediterranean countercurrent and the subsurface chlorophyll maximum), respectively.

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## INTRODUCTION

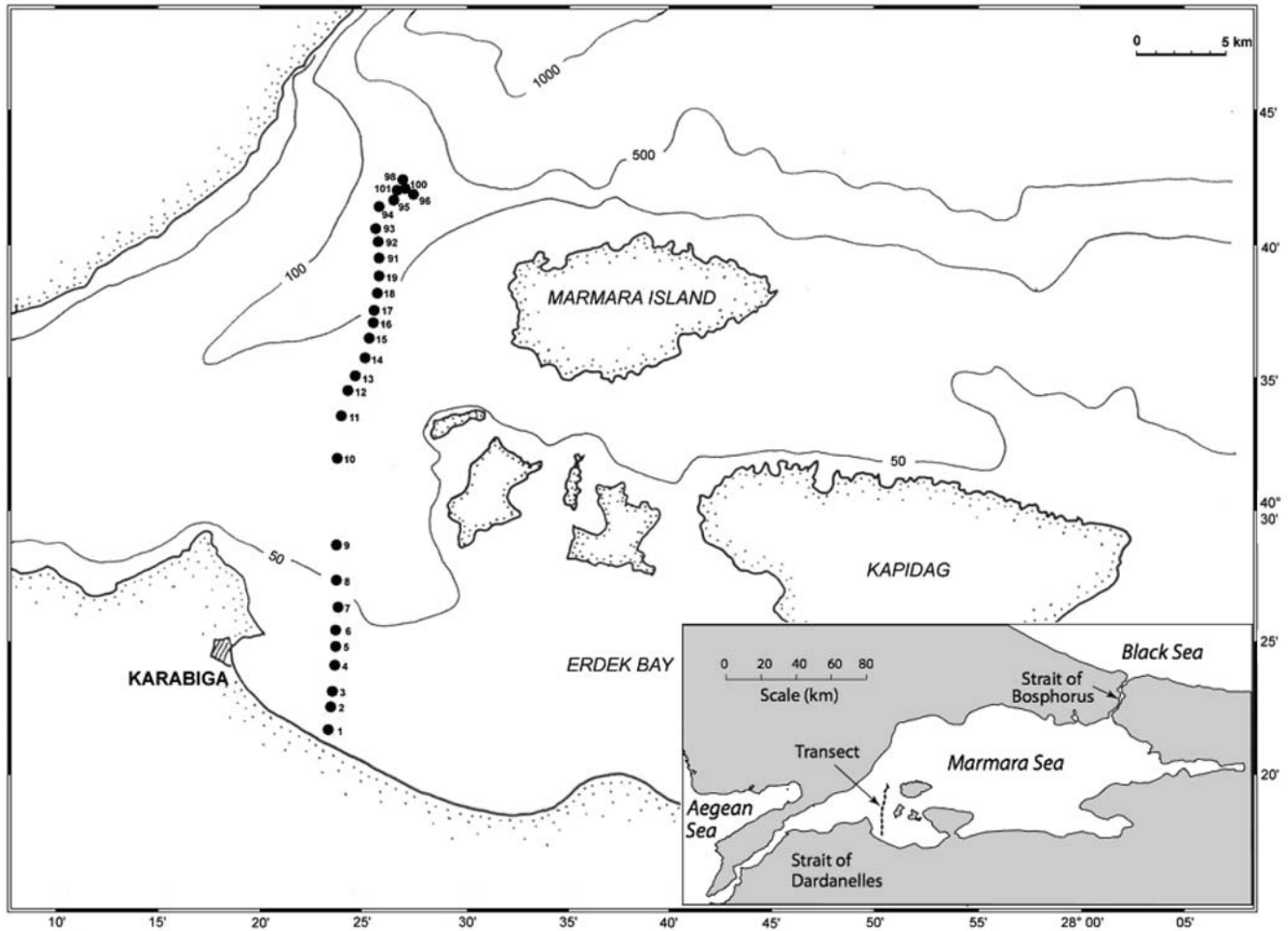
Species diversity and spatial distribution of benthic foraminiferal assemblages are strongly controlled by environmental parameters, particularly the salinity, temperature and dissolved oxygen concentration of the bottom water masses, and the availability of food (e.g., Parker 1958; Schnitker 1994). However, there is still much debate as to which environmental factors have the most significant effect on calcareous assemblages. Dissolved oxygen (Kaiho 1991, 1994, 1999), organic carbon flux (Jorissen 1988), sediment substrate (Basso and Spezzaferri 2000) and, increasingly, the detrimental effects of various types of pollution (Yanko et al. 1998), have all been proposed as principal factors that control the abundance and distribution of benthic foraminifera and their morphotypes. The present study describes the calcareous benthic foraminiferal thanatocoenosis in order to document depth-related faunal patterns and investigate the influence of environmental parameters on modern foraminifera from the Marmara Sea. The southwestern Marmara Sea was selected for study because strong environmental gradients are present in this area, and there is less impact from shipping and other human activities compared to the eastern part of the Sea (Ikis et al. 2008). An additional purpose of this study was to provide depth calibration for modern foraminiferal biofacies in order to better constrain the Holocene foraminiferal record analysed in piston cores from the southwestern Marmara Sea by Aksu et al. (2002) and Kaminski et al. (2002).

The Marmara Sea forms a gateway between the world's largest permanently anoxic basin, the Black Sea, and the Aegean Sea (text-fig. 1). It is connected to the Black Sea through the Bosphorus Strait (sill at ~40m depth) and to the Aegean Sea through the Dardanelles Strait (sill at ~70m). The water exchange between the Black Sea and the eastern Mediterranean Sea occurs through the Bosphorus and Dardanelles and the intervening Marmara Sea as a two-layer flow (e.g., Besiktepe et al. 1994; Mudie et al. 2004). A cooler (5–15°C) and lower-salinity (17–20) surface layer originates from the Black Sea, and flows south and southwest across the straits, and upon entry forms a surface layer up to 30m thick in the Marmara Sea. The warmer (15–20°C) and high-salinity (38–39) Mediterranean water flows north and northeast across the Strait of Dardanelles and occupies the Marmara basin below the low salinity surface layer. The brackish Black Sea outflow creates a strong halocline throughout the Marmara Sea, generating low-oxygen and stratified conditions below the thin surface layer (Aksu et al. 2002; Kaminski et al. 2002).

In a preliminary study of the influence of water-mass properties on calcareous benthic foraminiferal thanatocoenosis, Chendeş et al. (2004) identified two distinct assemblages across a N-S transect in southwestern Marmara Sea: a shallow-water assemblage consisting of genera such as *Ammonia* and *Elphidium* corresponded to the brackish surface water mass, and a deeper assemblage characterized by genera such as *Brizalina*, *Bulimina* and *Globobulimina*, associated with the more saline and stratified water mass. The present study builds upon the preliminary findings of Chendeş et al. (2004), and aims to (i) provide more detailed taxonomic census of the calcareous benthic foram-

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\*Current address: Michael Kaminski, Earth Sciences Department, King Fahd University of Petroleum and Minerals (P.O. Box 701, KFUPM), Dhahran, 31261, Saudi Arabia



TEXT-FIGURE 1  
Positions of the sites where grab samples were collected along a depth transect on the southwestern Marmara shelf and slope during the MAR-02 Cruise.

inifera across an inner neritic to upper bathyal transect on the southwestern Marmara Sea shelf, and (ii) assess the degree to which calcareous benthic foraminiferal death assemblages reflect various hydrographic parameters measured at the same stations.

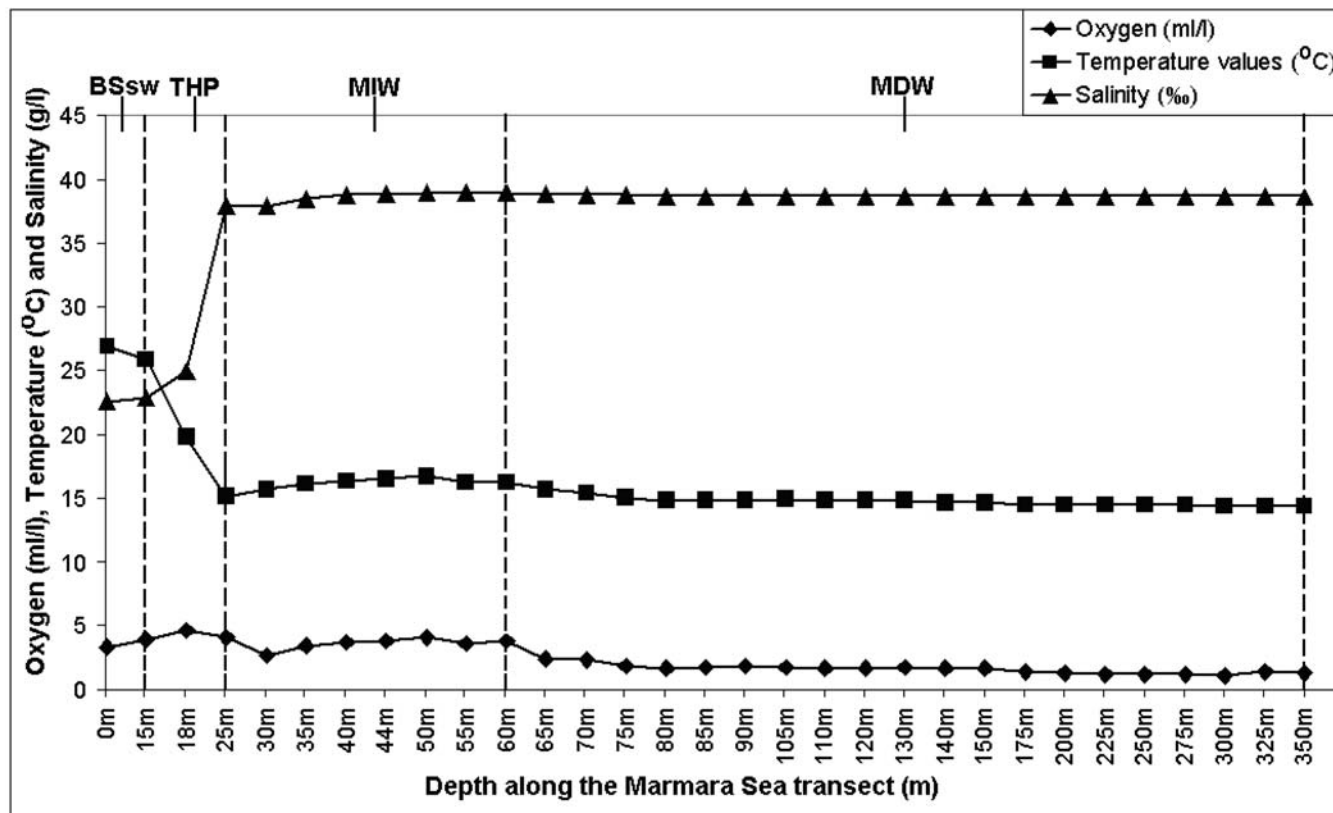
#### Previous studies

Benthic foraminifera from the Eastern Mediterranean have been studied by Parker (1958) and Cimerman and Langer (1991), who produced a workable taxonomic framework for the region. This framework has been expanded by faunal studies in the Gulf of Naples (Italy) by Sgarrella and Moncharmont Zei (1993) and more recently the Kallithea Bay Section from Rhodes (Greece) by Rasmussen (2005). Shallow-water benthic foraminifera have been studied from Iskundrun Bay on the Mediterranean coast of Turkey (Basso and Spezzaferri 2000). These studies provide calibration of the depth ranges of neritic benthic foraminifera in these sectors of the eastern Mediterranean and Aegean Seas. Many of the same species are found in our samples from the southwestern Marmara Shelf. However, the eastern Mediterranean and Aegean Seas have a much higher salinity than the Marmara Sea. Black Sea foraminifera have been documented by Yanko and Troitskaja (1987), and their ecology summarized by Yanko (1990). These studies are rele-

vant to ours because Black Sea surface water flows out into the Marmara Sea. The only published studies of benthic foraminifera from the Marmara Sea include: (1) the early work of Alavi (1988), who examined two sediment cores collected from a depth of 1200m in the deep basin south of Istanbul, (2) descriptions of upper Pliocene to Holocene foraminifera from geotechnical boreholes in the Gulf of Izmit (Meriç et al. 1995), (3) initial studies of Kaminski et al. (2002) on benthic foraminifera from three gravity cores, one of which was from the southern Marmara Shelf, (4) a preliminary study by Chendeş et al. (2004) of modern benthic foraminiferal assemblages and water mass properties along a transect of the southern shelf of the Marmara Sea and (5) an assessment of benthic foraminiferal assemblages, comprising 74 species, from 15 bottom samples (29-57m water depth) collected in Erdek Bay to the southeast of our study area (Avşar et al. 2006).

#### MATERIALS AND METHODS

Surface sediment samples were collected using a Shipeck grab from the R/V *Koca Piri Reis* of the Institute of Marine Sciences and Technology, Dokuz Eylül University (Izmir, Turkey) during the MAR-02 cruise (text-fig. 1). Samples were obtained at 30 stations along a 350m depth transect across the infralittoral



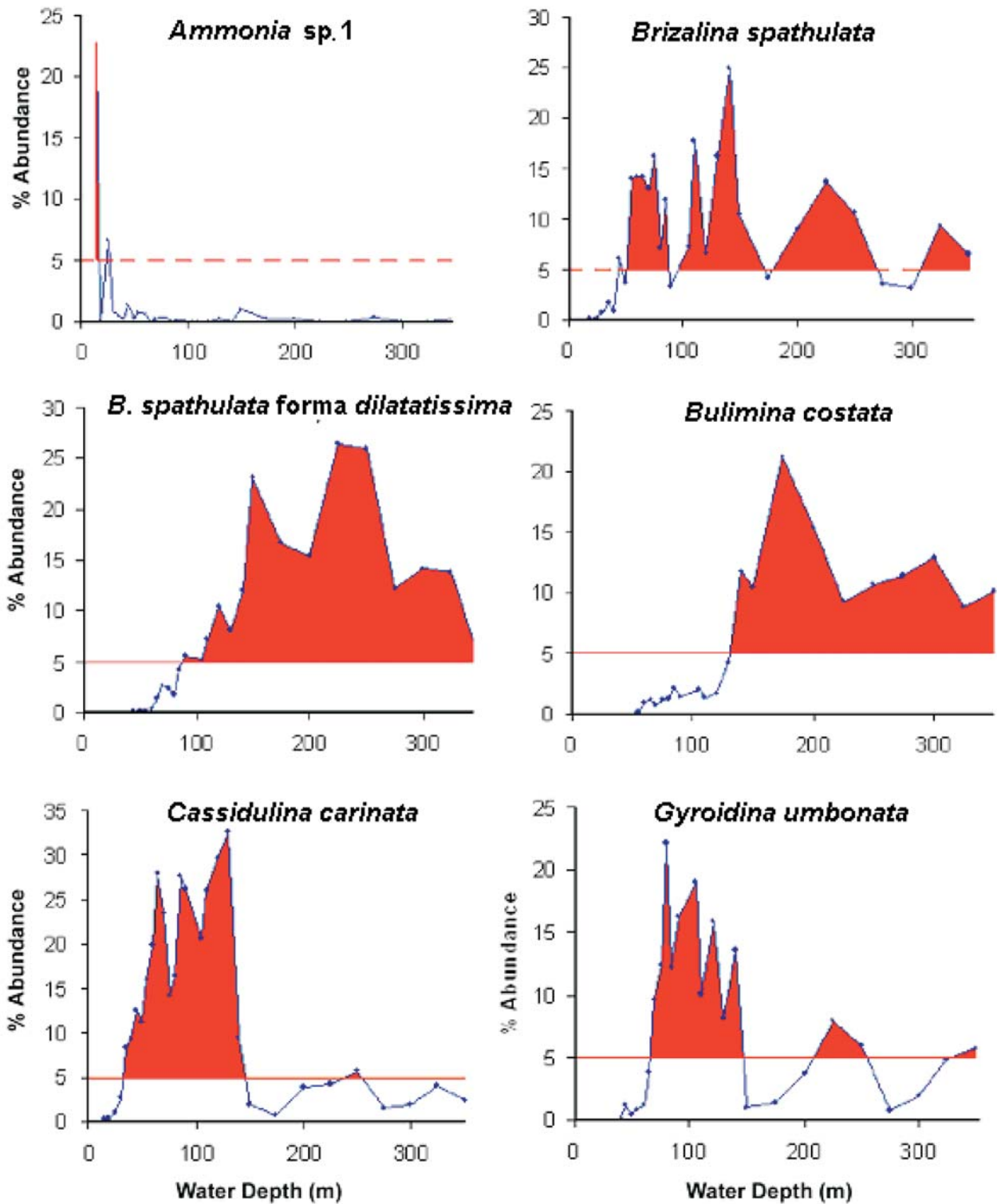
TEXT-FIGURE 2

Dissolved Oxygen content (ml/l), Temperature (°C), and Salinity (measured at 1 meter above the sea floor) plotted against water depth along the south-western Marmara Sea transect. The four dashed intervals represent the following water masses: BSsw = Black Sea surface water (0-15m); THP = Thermocline, Halocline and Pycnocline (15m-25m); MIW = Marmara Intermediate Water (25m-60m); MDW = Marmara Deep Water (60m-350m).

(0m-40m), circalittoral (40m-100m) and epibathyal (100m-350m) environments. They were collected at 10m intervals, except in the bathyal zone where the depth increments were increased to 25m. Sediment samples were washed on board ship through a 63µm sieve, and preserved in ethanol with Rose Bengal. Samples were subsequently washed again, dried, and split into aliquots using a modified Otto microsampler. Dead benthic foraminifera were picked from the >125µm fraction and mounted on cardboard reference slides. Calcareous benthic foraminiferal specimens were identified according to Parker (1958), Cimerman and Langer (1991), Sgarrella and Moncharmont Zei (1993) and Rasmussen (2005). Species such as *Ammonia beccarii*, *Ammonia parkinsoniana*, *Bulimina marginata*, *Elphidium granosum* and *Elphidium poeyanum* were further split into forms and morphotypes following criteria outlined by Jorissen (1988). This was done in order to observe any differences in the distributions of morphotypes of individual species along the transect. Only complete tests devoid of Rose Bengal stained protoplasm were included in the thanatocoenosis count and reported in this study. Stained calcareous foraminiferal tests, as well as all agglutinated foraminiferal species were omitted from the study as it is planned to use the data matrix for testing the BFOI method of Kaiho (1991, 1994, 1999) in the

Marmara Sea (Kaminski et al. in prep.). Throughout this paper all references to oxic, suboxic and dysoxic environments follow the definitions outlined by Kaiho (1994). The thanatocoenosis count was analysed by multivariate statistical methods (Q-mode hierarchical cluster analysis and canonical correspondence analysis) using the PAST statistical software. Only taxa with abundances >5% in at least one sample were used to create a matrix of data for statistical analysis. Rare and accessory taxa (<5% relative abundance) were omitted and assumed to have an insignificant effect on the formation of the major groups. *Elphidium crispum* and *Elphidium macellum* and *Nonionella opima* and *Nonionella turgida* were grouped together for statistical treatment into the *Elphidium crispum* group and *Nonionella turgida* group following the taxonomic proposals of Jorissen (1988) and Rasmussen (2005), respectively. Diversity (Fisher  $\alpha$  index) values and percent dominance values were also calculated to further characterize the assemblage structure.

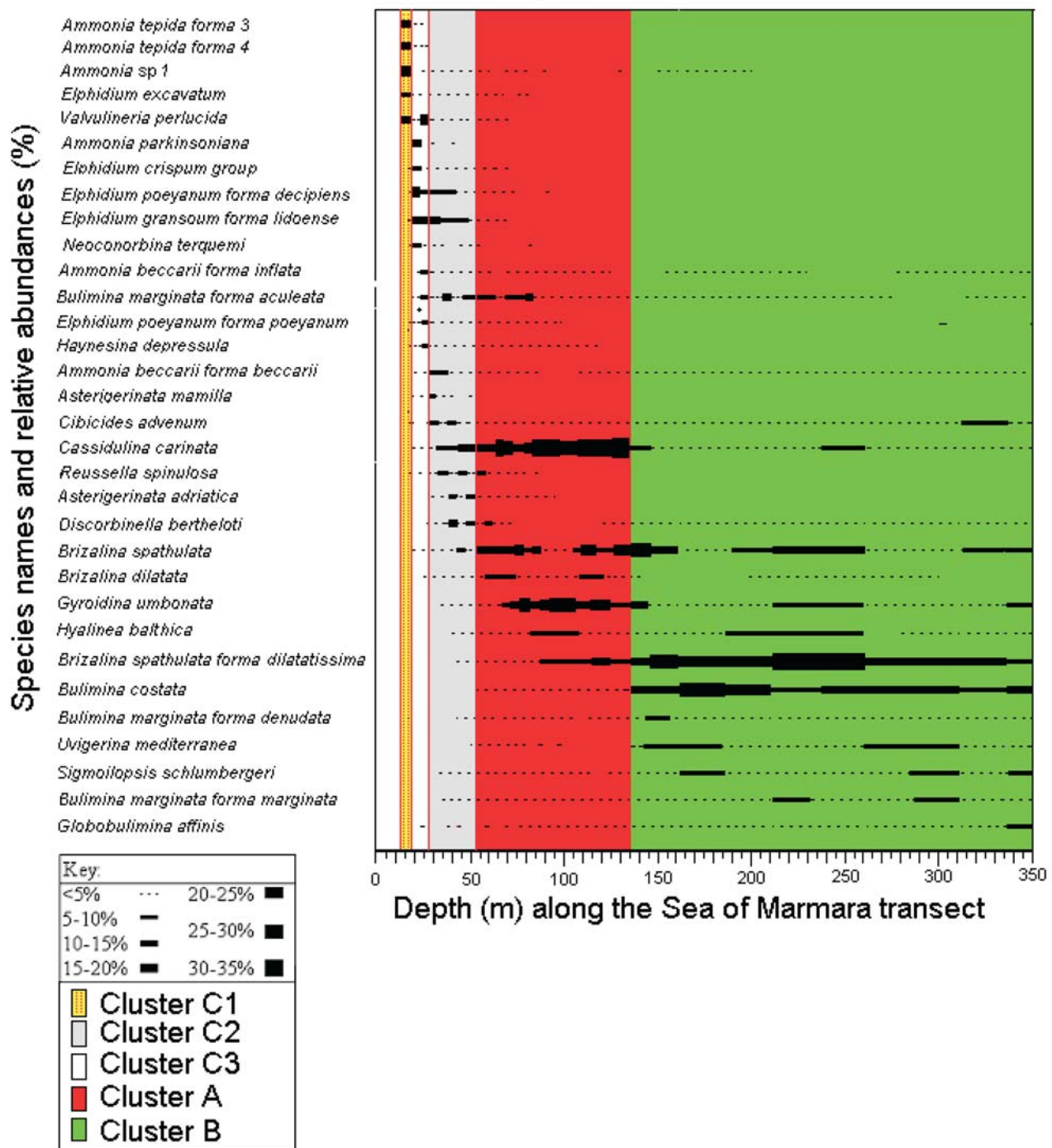
Environmental parameters, including water depth (m), temperature (°C), salinity (‰) and dissolved oxygen (ml/l), were measured at each sampling station at 1-meter intervals using a SBE-9 CTD, equipped with pressure, temperature, conductivity and dissolved oxygen sensors.



TEXT-FIGURE 3

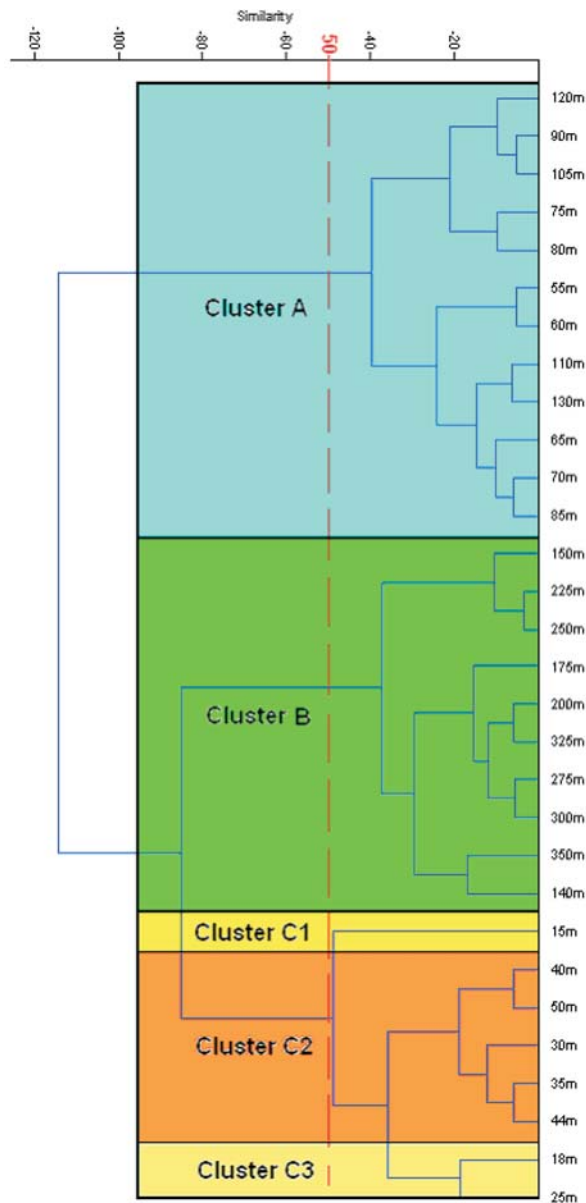
Percent abundances vs. water depth (m) of the dominant taxa (>20% abundance in at least one sample) in the southwestern Marmara Sea transect.

% Relative abundance vs depth (m) plots along the Sea of Marmara transect



TEXT-FIGURE 4

Distribution of common benthic foraminifera plotted against water depth on the southwest Marmara Sea. Thickness of line is proportional to abundance classes, with thickest lines representing proportions >30%.



TEXT-FIGURE 5  
Q-Mode cluster analysis dendrogram of the sample stations, based on the total abundances of species >5%. The arbitrary value of 50% dissimilarity that represents a statistically significant cluster is marked with a dashed red line.

## RESULTS

### Water mass properties

The physical oceanographic data collected during the MAR-02 cruise reveal the presence of three distinct water masses in the southwestern Marmara Sea (text-fig. 2). The surface water mass originates from the Black Sea. It extends from the sea surface to a depth of ~15m, and is brackish (salinity 22.6–22.8) with seasonally variable temperatures and oxygen values reaching 4.3ml/l. The thermocline, halocline, and pycnocline occur between 15m and 25m water depth, and are seasonally variable (Doğan Yaşar,

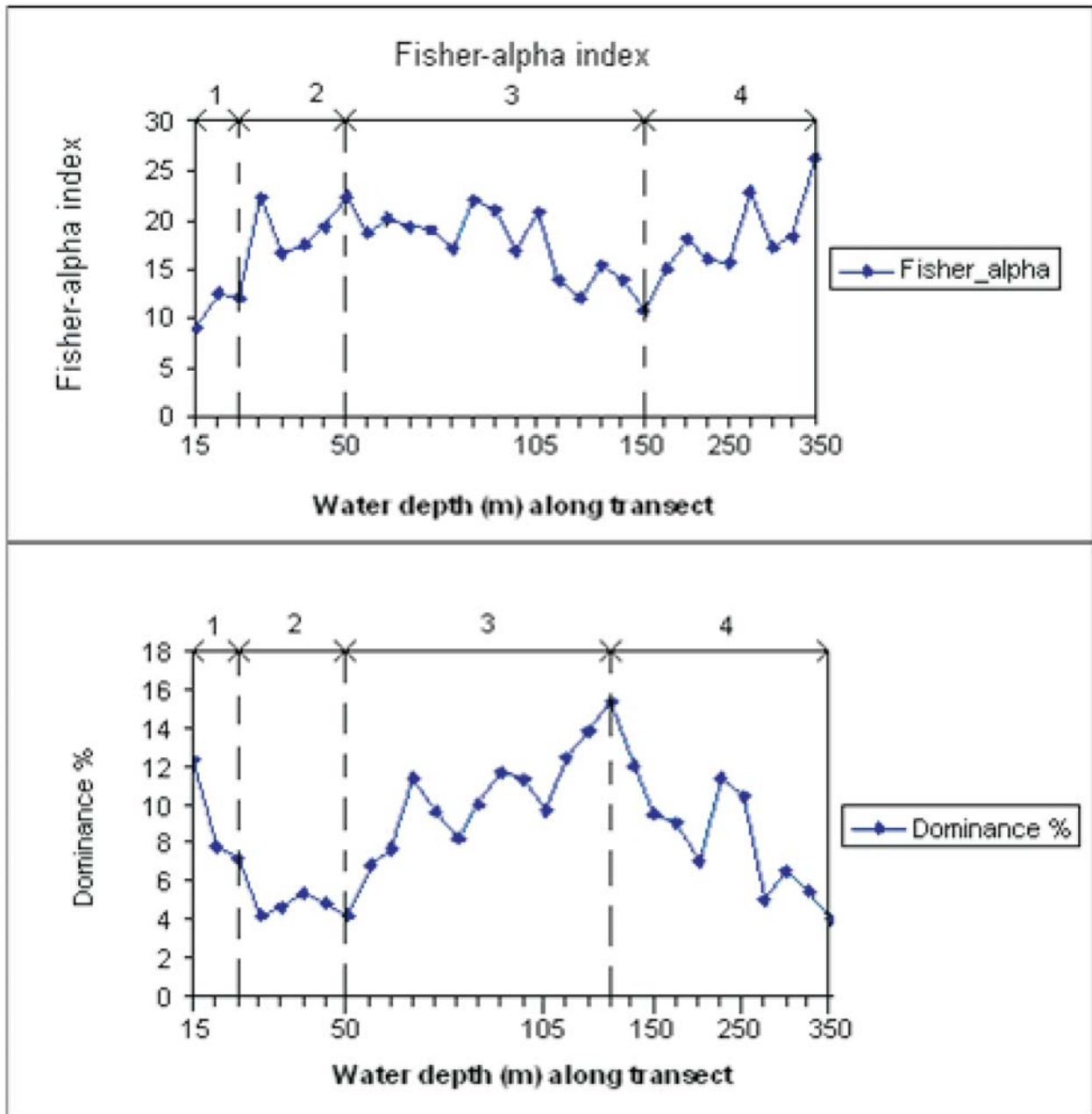
personal communication). This zone is characterized by a rapid decline in temperature from 25.8 to 19.8°C, and an increase in salinity from 22.8 to 37.9. The relatively high dissolved oxygen values across this zone are attributed to seasonal photosynthetic activity within the subsurface chlorophyll maximum. The Marmara intermediate water mass extends from the base of pycnocline to about 60m depth. It is characterized by a rise in dissolved oxygen, temperature and salinity values. This zone represents the inflow of the warm, saline Mediterranean water mass from the Straits of Dardanelles. The Marmara Sea deep water mass extends from 60m to 350m depth, and is characterized by gradually declining temperature (16.2–14.4°C), salinity (38.6–38.8), and dissolved oxygen (3.79–1.09ml/l) values.

### Benthic foraminiferal distribution

The samples yielded few ‘living’ (Rose Bengal stained) calcareous benthic foraminifera; they are present in elevated percentages only at 70m where they represent 7.8% of the total (live plus dead) assemblage. In this sample, living calcareous foraminifera show a strong relationship with the dead assemblage. For example, the majority of stained tests belong to *Cassidulina carinata*, the most abundant taxon in the dead assemblage. This study therefore concentrates on the thanatocoenoses formed by the dead specimens.

A total of 200 calcareous benthic foraminiferal species belonging to 67 genera were identified in the 30 surface samples from the southwestern Marmara Sea (Appendix 1). Among these, 26 species (32 including associated morphotypes) show relative abundances higher than 5% in at least one sample from the Marmara transect. *Ammonia* sp. 1 (*sensu* Cimerman and Langer 1991), *Brizalina spathulata*, *Brizalina spathulata* forma *dilatatissima*, *Bulimina costata*, *Cassidulina carinata* and *Gyroidina umbonata* are the dominant species in the samples from the southwestern Marmara Sea, exhibiting abundances exceeding 20% (text-fig. 3). *Ammonia parkinsoniana*, *A. tepida* morphotypes 3 and 4, *Bulimina aculeata*, *Elphidium granosum* forma *lidoense*, *E. poeyanum* forma *decipiens* and *Valvulineria perlucida* are common with abundances ranging between 10 and 20%.

When species are plotted against water depth, five depth-related intervals are apparent (text-fig. 4). These intervals are represented by faunal breaks, notably the sharp fall in the relative (%) abundance of *Cassidulina carinata* and the appearance of *Bulimina costata* between 130m and 140m, which separate clusters A and B. These intervals are confirmed by cluster analysis. The resulting dendrogram of Q-mode cluster analysis (text-fig. 5) represents the grouping of samples according to the relative abundance of calcareous species. At < 50% dissimilarity, the dendrogram reveals three distinct clusters, A, B, and C, with Cluster C further subdivided into three subclusters. Subcluster C1 (one sample from 15m) is dominated by morphotypes of *Ammonia tepida* (note that morphotypes 3 and 4 were combined for Q-mode analysis), *Ammonia* sp. 1, *Elphidium excavatum* and *Valvulineria perlucida*. Subcluster C2 (samples from 30–50m) is represented by *Bulimina marginata* forma *aculeata*, *Cassidulina carinata*, *Discorbinella bertheloti* and *Elphidium granosum* forma *lidoense*. Subcluster C3 (two samples from 18–25m) is dominated by *Ammonia parkinsoniana*, *Elphidium granosum* forma *lidoense*, *Elphidium poeyanum* forma *decipiens*, *Neoconorbina terquemi* and *Valvulineria perlucida*. Cluster A (12 samples from 55–130m) is dominated by *Brizalina spathulata*, *Cassidulina carinata* and



TEXT-FIGURE 6  
Variation of Fisher  $\alpha$  index diversity values and percent dominance against water depth along the southwestern Marmara Sea transect.

*Gyroidina umbonata*. Cluster B (10 samples from 140 to 350m) is characterized by *Brizalina spathulata*, *Brizalina spathulata* forma *dilatatissima* and *Bulimina costata*. These clusters represent six distinct foraminiferal assemblages that may be viewed as foraminiferal biofacies and are interpreted as reflecting different ecological conditions, such as oxygen, temperature and salinity, which are associated with bathymetry, shelf morphology and substrate.

#### Diversity and Dominance

Fisher  $\alpha$  index values along the southwest Marmara Shelf transect range from 8.9 in the shallowest sample (15m depth) to 26.7 in the deepest sample (350m depth), while dominance generally shows an inverse pattern to Fisher  $\alpha$  index values (text-fig. 6). A high Fisher  $\alpha$  index value indicates high diversity while high dominance is associated with low diversity. Along the transect, four distinct depth-related intervals were identified, reflecting changes in diversity and dominance.

1. The depth interval from 15–25m displays the lowest diversity and declining dominance, likely related to strong environmental gradients across the pycnocline.
2. The interval from 25 to 50m depth shows a rise in the Fisher  $\alpha$  index and minimal dominance values. It correlates well with elevated temperature and oxygen concentrations associated with the Marmara Intermediate Water (text-fig. 2). This part of the Marmara Shelf is influenced by the summer influx of warmer, more oxygenated water of Mediterranean origin (Kaminski et al. in preparation).
3. The interval between 50 and 150m depth shows variable but generally declining Fisher  $\alpha$  index values and (between 50 and 130m) rising dominance. It correlates well with a gradual but steady decline in temperature and oxygen concentrations. This depth interval represents the upper part of the Marmara Sea deep water (text-fig. 2), which is characterized by comparatively constant temperature and salinity below the main body of summer Mediterranean water flowing into the Marmara Sea. The slight mismatch between the dominance peak at 130m and the Fisher  $\alpha$  minimum at 150m reflects the maximum percentage abundance of *Cassidulina carinata* at 130m.
4. The depth interval from 150 to 350m depth shows a steady rise in the Fisher  $\alpha$  index and declining dominance values. This does not correlate with any observed trend identified in the hydrographical data in text-figure 2. However, a small rise in oxygen values at 325m depth (text-fig. 2) has been interpreted as possible evidence for a stronger winter Mediterranean inflow current that introduces better oxygenated water at this depth.

## DISCUSSION

### Benthic Foraminiferal Assemblages

The Q-mode cluster analysis identifies three depth-related associations of dead calcareous foraminifera across the Marmara transect:

#### Cluster A (55m – 130m)

Calcareous benthic foraminiferal assemblages are characterized by *Brizalina spathulata*, *Cassidulina carinata* and *Gyroidina umbonata*. These taxa are characteristically found in suboxic and dysoxic environments (definitions following Kaiho 1994). *Brizalina dilatata*, *Brizalina spathulata*, *Bulimina aculeata*, *Discorbinella bertheloti*, *Hyalinea balthica* and *Reussella spinulosa* are other important taxa. Elsewhere in the eastern Mediterranean, *Brizalina spathulata* (often confused with *Brizalina catanensis*) is reported from the infralittoral, and more commonly from the circalittoral zones and in epibathyal muds. It is found along with *Brizalina spathulata* forma *dilatata* in areas with low dissolved oxygen content on muddy substrates (Parker 1958). *Cassidulina carinata* is typical of circalittoral and bathyal muds from 70 to 700m (Parker 1958; Sgarrella and Moncharmont Zei 1993). *Gyroidina umbonata* is also typical of bathyal muds from 50–70m and deeper (Sgarrella and Moncharmont Zei 1993). *Brizalina dilatata* is reported as a mud dwelling species distributed from shallow to very deep water (Parker, 1958). *Brizalina spathulata* forma *dilatata* is a mud dweller found at all depths from near-shore environments to the deep ocean. In the Mediterranean, it is most common on the continental shelf and upper slope (Sgarrella and Moncharmont Zei 1993) in the depth range 100–200m. *Bulimina marginata* forma *aculeata* is widespread

in the infralittoral area between 15 and 35m and is abundant at circalittoral and epibathyal depths down to about 300m (Sgarrella and Moncharmont Zei 1993). *Discorbinella bertheloti* is reported as frequent in the infralittoral and circalittoral zone, particularly on sandy substrates in the depth range 60–100m (Jorissen 1988). *Hyalinea balthica* is typical of the circalittoral zone and is more frequent in epibathyal muds between 90 and 500m (Parker 1958).

The Fisher  $\alpha$  index values of samples comprising Cluster A range from 21.9 to 12.1 with a mean value of 18.0. This cluster coincides with interval 3 in text-fig. 6 and is characterized by decreasing diversity values with depth along the transect. Temperature and salinity are stable and oxygen values gradually decline, reflecting a water mass below the body of Mediterranean water flowing into the Marmara Sea. It is likely that the declining values of dissolved oxygen in this poorly mixed water mass promote lower diversity (Martins et al. 2007). This interpretation is supported by an observed rise in dominance, with peak of 15.3% at 130m (text-fig. 6).

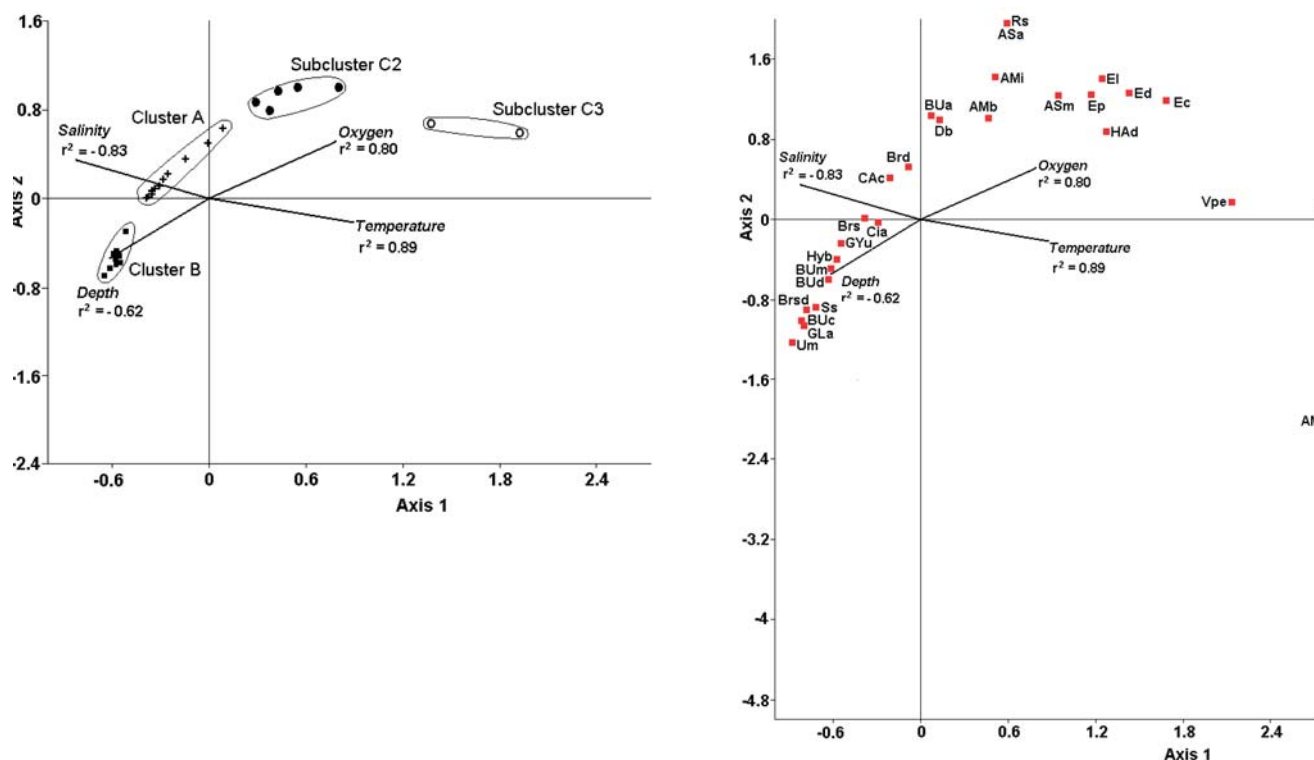
Cluster A contains taxa that typically occur in circalittoral, mud-rich, suboxic to dysoxic settings. It can be characterized as the *Cassidulina carinata* - *Brizalina spathulata* - *Gyroidina umbonata* assemblage. This assemblage is comparable to the *Cassidulina carinata* and *Brizalina spathulata* assemblages from the eastern Mediterranean, which typically occur in the circalittoral zone and are associated with high productivity and low oxygen conditions (Rasmussen 2005).

#### Cluster B (140m – 350m)

Cluster B is dominated by *Brizalina spathulata*, *Brizalina spathulata* forma *dilatata* and *Bulimina costata*. Other abundant taxa include *Bulimina marginata* forma *denudata*, *Bulimina marginata* forma *marginata*, *Cibicides advenum*, *Globobulimina affinis*, *Gyroidina umbonata*, *Hyalinea balthica*, *Sigmoilopsis schlumbergeri* and *Uvigerina mediterranea*.

*Bulimina costata* is recorded from the circalittoral zone and becomes abundant at deeper localities below 90–100m in bathyal muds (Sgarrella and Moncharmont Zei 1993). *Bulimina marginata* forma *denudata* is recorded from the infralittoral zone, is frequent in circalittoral and bathyal muds and able to live in seasonally stressed environments (Jorissen 1988). *Bulimina marginata* forma *marginata* is recorded in deep-water assemblages down to 1,016m (Parker 1958) and is found frequently in circalittoral and bathyal muds (Sgarrella and Moncharmont Zei 1993). *Cibicides advenum* occurs in close association with *Cibicides lobatulus* in the Marmara Sea samples. They share similar morphologies (distinguished mainly by the lobateness of the test) and therefore may have similar ecological characteristics. *Cibicides lobatulus* lives attached to firm substrates in turbulent or current-influenced environments (Sgarrella and Moncharmont Zei 1993). *Globobulimina affinis* is recorded from circalittoral and bathyal depths (Sgarrella and Moncharmont Zei 1993) and tolerates dysoxic conditions. *Sigmoilopsis schlumbergeri* is reported from muddy circalittoral and bathyal substrates at depths to 1,000m (Sgarrella and Moncharmont Zei 1993). *Uvigerina mediterranea* is recorded from the circalittoral zone downwards, but is more abundant in bathyal muds, with maximum abundances recorded between 400 and 1000m. It has been suggested that the bathymetric range of this species in the Eastern





**Species markers:**

- |  |                                      |  |
|--|--------------------------------------|--|
| AM1 = <i>Ammonia</i> sp.1                  | BUa = <i>Bulimina aculeata</i>       | El = <i>E. lidoense</i>                |
| AMt = <i>A. tepida</i>                     | BUc = <i>Bu. costata</i>             | Ep = <i>E. poeyanum</i>                |
| AMb = <i>A. beccarii beccarii</i>          | BUd = <i>Bu. denudata</i>            | GLa = <i>Globobulimina affinis</i>     |
| AMi = <i>A. beccarii inflata</i>           | BUm = <i>Bu. marginata</i>           | GYu = <i>Gyroidina umbonata</i>        |
| AMP = <i>A. parkinsoniana</i>              | CAc = <i>Cassidulina carinata</i>    | Hd = <i>Haynesina depressula</i>       |
| ASa = <i>Asterigerinata adriatica</i>      | Cia = <i>Cibicides advenum</i>       | Hb = <i>Hyalinea balthica</i>          |
| ASm = <i>As. mamilla</i>                   | Db = <i>Discorbinella bertheloti</i> | Nt = <i>Neoconorbina terquemi</i>      |
| Brd = <i>Brizalina dilatata</i>            | Ec = <i>Elphidium crispum</i>        | Rs = <i>Reussella spinulosa</i>        |
| Brs = <i>Brizalina spathulata</i>          | Ee = <i>E. excavatum</i>             | Ss = <i>Sigmoilopsis schlumbergeri</i> |
| Brsd = <i>Br. spathulata dilatatissima</i> |                                      | Um = <i>Uvigerina mediterranea</i>     |
|  |                                      | Vp = <i>Valvulineria perlucida</i>     |

TEXT-FIGURE 7

Canonical correspondence analysis biplots of (a) sample-environment and (b) foraminiferal species-environment for the Marmara Sea transect. In a) the lone triangle represents the 15 m station; open circles represent stations 18m–25m; closed circles represent stations 30m–50m; crosses represent stations 55m–130m; squares represent stations 140m–350m. Only species with relative abundances higher than 5% were included.

Mediterranean is reduced by poorer ventilation (Sgarrella and Moncharmont Zei 1993).

The Fisher  $\alpha$  index values of samples included in Cluster B range from 14.0 to 26.3 with a mean value of 17.4. This cluster coincides with interval 4 in text-fig. 6 and is characterized by an increasing trend in Fisher  $\alpha$  index values with depth along the transect. Temperature and salinity are stable and there is a rise in dissolved oxygen at 325m (text-figure 2). This could reflect the inflow of a more oxic water mass below the less well-ventilated body of Mediterranean water that characterizes Cluster A. The rise in oxygen promotes a higher diversity and consequently higher Fisher  $\alpha$  index values (Martins et al. 2007). This

interpretation is supported by a fall in percent dominance, with a minimal value of 4% at 350m (text-fig. 6).

This assemblage contains both circalittoral and upper epibathyal environmental indicators. It can be characterized as the *Brizalina spathulata* forma *dilatatissima* – *Bulimina costata* assemblage and is comparable to deep-water faunas reported from the Adriatic Sea (Jorissen 1988).

**Cluster C (15m – 50m)**

Cluster C comprises typical infralittoral and upper circa-littoral species. It is subdivided into three subclusters.

Subcluster C1 is the shallowest (at 15m) and is characterized by *Ammonia* sp 1 (*sensu* Cimerman and Langer 1991), *Ammonia tepida* (morphotypes 3 and 4), and *Valvulineria perlucida*. *Elphidium excavatum* is also found here in significant numbers. These species are known to tolerate hyposaline conditions and to be resistant to pollution (Rasmussen 2005). This subcluster, which is present at a single station, coincides with the interval of the lowest Fisher  $\alpha$  index values (8.96) observed on the transect (text-fig. 6). It is associated with the brackish conditions observed at 15m, to which relatively few species are adapted. Species such as *Ammonia tepida* and *Valvulineria perlucida* are tolerant to hyposaline conditions and therefore dominate the assemblage. This is reflected in the high (12.43%) dominance value found at this station.

Subcluster C2 (the deepest of the three subclusters at 30–50m) is characterized by *Bulimina marginata* forma *aculeata*, *Cassidulina carinata*, *Discorbinella bertheloti* and *Elphidium granosum* forma *lidoense*. Other significant taxa include *Ammonia beccarii* forma *beccarii*, *Asterigerinata adriatica*, *Asterigerinata mamilla*, *Cibicides advenum*, *Elphidium poeyanum* forma *decepiens* and *Reussella spinulosa*. The assemblage contains taxa typical of infralittoral and circalittoral environments and both sandy and muddy substrates (Sgarrella and Moncharmont Zei 1993; Rasmussen 2005). This biofacies corresponds to the infralittoral–upper circalittoral zone. The Fisher  $\alpha$  index ranges from 16.7 to 22.4 with an average of 19.6; there is a rising trend in diversity in this subcluster corresponding to interval 2 in text-figure 6. This rise in diversity is attributed to the inflow of the Mediterranean countercurrent that brings better-oxygenated, highly saline and warmer waters into the Marmara Sea at these depths during the summer. A corresponding decline in percent dominance is also observed in this cluster, with a low value of 4.9% at 50m.

Subcluster C3 (18m–25m) is characterized by *Ammonia parkinsoniana*, *Elphidium granosum* forma *lidoense*, *Elphidium poeyanum* forma *decepiens*, *Neonorbina terquemi* and *Valvulineria perlucida*. Other significant taxa include *Ammonia beccarii* forma *inflata*, *Bulimina marginata* forma *aculeata*, *Elphidium crispum*, *Elphidium poeyanum* forma *poeyanum* and *Haynesina depressula*. These species are reported from muddy sands of the infralittoral zone (Sgarrella and Moncharmont Zei 1993; Rasmussen 2005). Fisher  $\alpha$  index values range from 12.6–12.1 and indicate a rise in diversity deeper into the pycnocline. This is associated with an increase in salinity at 18–25m that provides favourable conditions, allowing more species to survive at these depths. The dominance values fall to 7.2% as a result.

The cluster C assemblage consists of predominantly infralittoral species that inhabit muddy and sandy substrates. The assemblage can be characterized as the *Ammonia* spp - *Elphidium* spp assemblage and is comparable to many Mediterranean neritic assemblages (Jorissen 1988; Rasmussen 2005).

#### Relationship between foraminiferal assemblages and environmental parameters

The canonical correspondence analysis confirms the presence of the three clusters and subclusters identified in the Q-Mode cluster analysis when plotted in ordination space (text-fig. 8a). The method involves a correspondence analysis of a site/species matrix where each site has known values for one or more environmental variable; in the present study these variables are

temperature, salinity, oxygen and depth. The ordination axes are linear combinations of the environmental variables that allow a direct gradient analysis. Any changes in species abundances are considered to be a response to these gradients. The lengths of the environmental arrows indicate their relative importance in explaining the variance in the foraminiferal data. The orientation of the arrows represent their correlation to the ordination axes. Within the present data set, correlations of environmental variables with axes 1 and 2 show that temperature and salinity are correlated to axis 1 and depth and oxygen are jointly correlated to axis 1 and 2. The ordination can be divided into two sections. Clusters A and B plot on the left side and are related to greater water depth, lower oxygen and temperature and higher salinity. The more neritic assemblages represented by the three subclusters of cluster C plot on the right side and are related to shallower water depths, higher oxygen and temperature, and low salinity. In addition, subcluster C1, represented by a single station at 15m, is the most positively associated with axis 1 and the most negatively associated with axis 2; it represents the high temperature, low salinity, shallow depth, and high oxygen conditions characteristic of Black Sea surface water. Conversely, subclusters C3 and C2, which reflect the pycnocline and the Mediterranean countercurrent, respectively, weigh progressively more negatively along axis 1 and are shifted to positive positions along axis 2, where high oxygen concentration becomes the dominant environmental factor, while temperature falls and salinity increases. Cluster A, which represents stations of intermediate depths, plots negatively along axis 1 and positively against axis 2 and is associated with increasing salinity and a shift from high to progressively lower oxygen conditions as depth increases. Cluster B corresponds to the deepest stations and plots negatively on axes 1 and 2, which represent the influence of depth and dissolved oxygen as important controls on foraminiferal distributions.

On the species–environment biplot, the position of species (projected perpendicularly onto the environmental arrows) approximates their weighted average optimum along each environmental variable (text-fig. 8b), making it possible to identify species characteristic of a particular environment. For example, neritic genera such as *Ammonia*, *Elphidium* and *Asterigerinata* plot on the right side of the biplot (associated with high temperature, low salinity, shallower water and high oxygen concentrations). In contrast, genera such as *Brizalina* and *Bulimina* are found on the left side of the biplot (related to lower temperature, higher salinity, deeper water depth and lower oxygen concentrations). In addition, most species share ordination spaces that are comparable to the six clusters observed in the station–environment plot (text-fig. 8a), a pattern that is consistent with our interpretations of the different foraminiferal assemblage clusters discussed above. From the deepest to the shallowest cluster, the patterns observed are as follows:

**Cluster B:** Of all the environmental parameters, increased depth and reduced bottom-water oxygen concentrations seem to exert the dominant controls on species such as *Bulimina costata*, *Bulimina marginata* formas *marginata* and *denudata*, *Brizalina spathulata* forma *dilatatissima* that plot negatively on both axes. These species are characteristic of Cluster B (stations between 140 and 350m) and plot within their ordination range (see figure 8a).









**Cluster A:** Species that plot negatively with axis 1 but positively with axis 2 include *Brizalina dilatata*, *Brizalina spathulata* and *Cassidulina carinata*. These species are characteristic of Cluster A (stations between 55 and 130m) and plot within their ordination range. However, it remains unclear whether salinity plays a significant role in foraminifera distributions here as taxa plot on a linear trend similar to that of taxa plotting within Cluster B. Species appear to be significantly influenced by low oxygen concentrations and increased depth, suggesting that these are key factors in determining species distribution between 55 and 130m with a third factor (salinity or perhaps another factor not taken into account in this study such as substrate) offsetting the trend.

**Cluster C2:** Species that plot positively on both axes include *Bulimina marginata* forma *aculeata*, *Discorbinella bertheloti* and *Elphidium granosum* forma *lidoense*; these species are characteristic of Cluster C2 (stations between 30 and 50m) and plot broadly within their ordination range, although there is more scatter in their distribution than in other clusters. In this case, high dissolved oxygen values (elevated by the introduction of the Mediterranean countercurrent) seems to be the dominant environmental factor influencing foraminiferal distributions. However, the amount of scatter suggests that other factors not considered in this study, in addition to oxygen and depth, may significantly influence some species.

**Cluster C3:** This cluster, which corresponds to the pycnocline (between 18 and 25m), seems to comprise two groups of species that are influenced by different environmental variables. Species that plot positively on axis 2 but are close to 0 on axis 1, such as *Ammonia parkinsoniana*, *Valvulineria perlucida* and *Neoconorbina terquemi*, are characteristic of the pycnocline and are influenced significantly by temperature and salinity rather than dissolved oxygen and depth. On the other hand, species such as *Elphidium crispum*, *Elphidium poeyanum* forma *decipiens* and *Haynesina depressula* correlate with dissolved oxygen.

**Cluster C1:** Species that plot positively with axis 1 and negatively with axis 2 include *Ammonia tepida*, *Ammonia* sp. 1 and *Elphidium excavatum*; these species are characteristic of Cluster C1 and reflect the Black Sea surface water. Elevated temperature and reduced salinity appear to be the dominant influences on the distribution of these species.

## CONCLUSIONS

The continental shelf and upper slope of the southwestern Marmara Sea is characterized by a diverse assemblage of dead calcareous benthic foraminifera, with 200 species recognized and Fisher  $\alpha$  index values ranging from 8.9 to 26.7. A total of 26 species and their respective morphotypes show a relative abundance >5% in at least one sample. Q-Mode Cluster Analysis based on these common species allows the recognition of three distinct foraminiferal assemblages:

Cluster A occurs at depths between 55 and 130m and comprises characteristic dysoxic and suboxic, circalittoral taxa, notably *Brizalina spathulata*, *Cassidulina carinata* and *Gyroidina umbonata*. Diversity (Fisher  $\alpha$  index) decreases with depth while dominance increases. This assemblage is related to a fine-grained, muddy substrate and a poorly ventilated watermass leading to decreasing bottom-water oxygen concentrations.

Cluster B occurs at depths between 140 and 350m and is characterized by suboxic and dysoxic species typical of circalittoral and upper epibathyal environments. A small rise in oxygen concentration at 325m coincides with higher diversity and a fall in dominance.

Cluster C is found in the shallower samples ranging from 15 to 50m depth and comprises characteristic infralittoral species. The cluster can further be subdivided into subclusters C1, C3 and C2, representing assemblages associated, respectively, with the brackish Black Sea surface flow (0-15m), the pycnocline (15-25m), and the inflow of warm, saline Mediterranean water within the Marmara intermediate water mass (30-50m). Subcluster C1 exhibits low diversity and high dominance values at the shallowest brackish sites, with higher diversity values and lower dominance associated with more saline Mediterranean waters (C2).

Canonical correspondence analyses suggest that depth, dissolved oxygen, temperature and salinity all have significant influences on the distribution of foraminiferal assemblages along the transect. Above 25m, temperature and salinity are the dominant factors influencing species present in Cluster C1 (15m) and C3 (18-25m), representing the Black Sea surface water and pycnocline respectively. Below 25m, clusters C2 (30-50m), A (55-130m), and B (140-350m) are influenced predominantly by dissolved oxygen and depth. The C2 assemblage is influenced by higher oxygen concentrations, whereas Clusters A and B are related to a trend of decreasing oxygen, with increasing depth.

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## REFERENCES

- AKSU, A. E., HISCOTT, R. N., KAMINSKI, M. A., MUDIE, P. J., GILLESPIE, H., ABRAJANO, T. and YASAR, D. 2002. Last Glacial to Holocene paleoceanography of the Black Sea and Marmara Sea: Stable isotopic, foraminiferal and coccolith evidence. *Marine Geology*, 190: 119-149.
- ALAVI, S. N. 1988. Late Holocene deep-sea benthic foraminifera from the Sea of Marmara. *Marine Micropalaeontology*, 13: 213-237.
- AVŞAR, N., AKSU, A. and DINCER, F. 2006. Benthic foraminiferal assemblages of the Erdek Bay (SW Marmara Sea). [in Turkish]. *Yerbilimleri* [Journal of the Earth Sciences Application and Research Center of Hacettepe University], 27: 125-141.
- BASSO, D. and SPEZZAFERRI, S. 2000. The distribution of living (stained) benthic foraminifera in Iskenderun Bay (Eastern Turkey): a

- statistical approach. *Bollettino della Società Paleontologica Italiana*, 39: 359-379.
- BESIKTEPE, S., SUR, H. I., OZSOY, E., LATIF, M. A., OGUZ, T. and UNLUATA, U. 1994. Circulation and hydrography of the Sea of Marmara. *Progress in Oceanography*, 34: 285-334.
- CHENDEŞ, C., KAMINSKI, M. A., FILIPESCU, S., AKSU, A. E. and YAŞAR, D. 2004. The response of modern benthic foraminiferal assemblages to water-mass properties along the southern shelf of the Marmara Sea. *Acta Palaeontologica Romaniae*, 4: 69-80.
- CIMERMAN, F. and LANGER, M. R. 1991. *Mediterranean Foraminifera*. Ljubljana: Slovenska Akademija Znanosti in Umetnosti, 118 pp.
- GOODAY, A. J., BETT, B. J., SHIRES, R. and LAMBSHEAD, P. J. D. 1998. Deep-sea benthic foraminiferal species diversity in the NE Atlantic and NW Arabian sea: a synthesis. *Deep-Sea Research II*, 45: 165-201.
- IKIS, D., TONTA, S. and SÜZEN, M. 2008. "Temporal and spatial changes of primary productivity in the Sea of Marmara obtained by remote sensing" Unpubl. presentation, International Congress for Conservation Biology. Annual meeting, Chattanooga, TN
- JORISSEN, F. J. 1988. Benthic foraminifera from the Adriatic Sea; principles of phenotypic variation. *Utrecht Micropalaeontological Bulletins*, 37: 1-174.
- KAIHO, K. 1991. Global changes of Paleogene aerobic/anaerobic benthic foraminifera and deep-sea circulation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 83: 65-85.
- , 1994. Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen levels in the modern ocean. *Geology*, 22: 719-722.
- , 1999. Effect of organic carbon flux and dissolved oxygen on the benthic foraminiferal oxygen index (BFOI). *Marine Micropalaeontology*, 37: 67-76.
- KAMINSKI, M. A., AKSU, A. E., BOX, M., HISCOTT, R. N., FILIPESCU, S. and AL-SALAMEEN, M. 2002. Late Glacial to Holocene benthic foraminifera in the Marmara Sea: implications for Black Sea – Mediterranean Sea connections following the last deglaciation. *Marine Geology*, 190: 165-202.
- MARTINS, V., DUBERT, J., JOUANNEAU, J. M., WEBER, O., DA SILVA, E. F., PATINHA, C., JOÃO M. DIAS, A. and ROCHA, F. 2007. A multiproxy approach of the Holocene evolution of shelf-slope circulation on the NW Iberian Continental Shelf. *Marine Geology* 239: 1-18.
- MERİÇ, E., YANKO, V. and AVSAR, N. 1995. Foraminiferal fauna of the Quaternary sequence in the Gulf of Izmit (Hersek Burnu-Kaba Burun) [in Turkish]. In: Meriç, E., Ed., *Izmit Körfezi Kuvaterner İstifi (The Quaternary succession in Izmit Bay)*, 105-155. Izmir: Deniz Harp Okulu Komutanlısı Basımevi (Maritime Military School Printing Office)
- MUDIE, P., ROCHON, A., AKSU, A. E. and GILLESPIE, H. 2004. Late glacial, Holocene and modern dinoflagellate cyst assemblages in the Aegean-Marmara-Black Sea corridor: statistical analysis and re-interpretation of the early Holocene Noah's Flood hypothesis. *Review of Palaeobotany and Palynology*, 128: 143-167
- PARKER, F. L. 1958. Eastern Mediterranean foraminifera. Sediment cores from the Mediterranean and Red Sea. *Report of the Swedish Deep Sea Expedition*, 8: 219-283.
- RASMUSSEN, T. L. 2005. Systematic paleontology and ecology of benthic foraminifera from the Plio-Pleistocene Kallithea Bay section, Rhodes, Greece. *Cushman Foundation Special Publications*, 39: 53-157.
- SCHNITKER, D. 1994. Deep-sea benthic foraminifera: food and bottom water masses. In: Zahn, R., Pedersen, T. F., Kaminski, M. A. and Labeyrie, L. (eds), *Carbon cycling in the glacial ocean: Constraints on the ocean's role in global change*, 539-554. Brussels: NATO ASI Series I, no. 17
- SGARRELLA, F. and MONCHARMONT ZEI, M. 1993. Benthic foraminifera of the Gulf of Naples (Italy): Systematics and autoecology. *Bollettino della Società Paleontologica Italiana*, 32: 145-264.
- YANKO, V. V. 1990. Stratigraphy and paleogeography of the marine Pleistocene and Holocene deposits of the southern seas of the USSR. *Memorie della Società Geologica Italiana*, 44: 167-187.
- YANKO, V. V. and TROITSKAJA, T. S. 1987. Late Quaternary Foraminifera of the Black Sea (in Russian). *Trudy Instituta Geologii I Geofiziki, Akademiya Nauk SSSR, Novosibirsk*, 694: 111 pp.
- YANKO, V. V., AHMAD, M. and KAMINSKI, M. A. 1998. Morphological deformities of benthic foraminiferal tests in response to pollution by heavy metals: implications for pollution monitoring. *Journal of Foraminiferal Research*, 28: 177-200.