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Benthic Foraminiferal Assemblages in a Restricted Environment - An Example from the Mljet Lakes (Adriatic Sea, Croatia)

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Abstract

Benthic foraminiferal assemblages from a peculiar restricted marine environment, the Mljet Lakes (Mljet Island, Adriatic Sea, Croatia) have been studied. These lakes are drowned karst dolines, which are connected with the Adriatic Sea through a narrow, shallow channel. Occasional stagnant conditions in the marine lakes cause hypoxic and anoxic conditions in the bottom waters. Such stressed conditions are reflected in oligospecific benthic foraminiferal assemblages with a Shannon-Wiener species diversity index (H) ranging from 0.8 to 1.0 and equitability index (E) ranging from 0.18 to 0.26, identified in samples from each marine lake. In the more dysoxic Malo Jezero, *Haynesina depressula* dominates an assemblage of 12 benthic foraminiferal species. In the less (and less frequently) hypoxic Veliko Jezero, we found an *Asterigerinata mamilla* assemblage with 18 foraminiferal species. A more diverse assemblage containing 55 different benthic foraminiferal species occupies an adjacent open-sea station.

Long-term salinity measurements indicate that *H. depressula* tolerates higher salinity than formerly presumed (up to 38‰), and is well adapted to stressed hypoxic conditions.

1. INTRODUCTION

Veliko and Malo Jezero (the Mljet Lakes) are natural phenomena on Mljet Island (Adriatic Sea). Due to its scenic beauty, ecological peculiarities, and environmental values the western part of the island was proclaimed a National Park in 1960 (Fig. 1). Veliko and Malo Jezero (Large and Small Lake = Mljet Lakes) are semi-enclosed depressions connected with the open sea by a narrow, shallow channel. The lakes are typical karst depressions (*dolines* or sinkholes), which were formed under subaerial exposure and are now submerged due to Holocene sea-level rise. Being connected with the sea, they have saline marine water and therefore are not true lakes, but can be termed *marine lakes*. Morphometric characteristics of the Mljet Lakes were reported in VULETIĆ (1953), along with their geological setting and sediment characteristics.

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Weak tidal currents and feeble wind influence cause expressed stratification of the water column, giving rise to temporary stagnant conditions in the marine lakes, especially in Malo Jezero (BULJAN & ŠPAN, 1976; BENOVIĆ et al., 2000). Therefore the Mljet Lakes are restricted environments not only in a spatial sense, but also in the sense of stress-producing factors (SEIBOLD & BERGER, 1996).

The aim of this preliminary research was to compare benthic foraminiferal assemblages, including foraminiferal morphological variations, with hydrological, sedimentological, and ecological characteristics of such a peculiar, restricted, unstable environment in the karstified marine depressions. In spite of the worldwide distribution of karstic phenomena, there are very few papers dealing with the various organisms inhabiting such areas (CIMERMAN et al., 1988; SOKAČ & BAJRAKTAREVIĆ, 1995).

CIMERMAN et al. (1988) found two different foraminiferal assemblages in Veliko Jezero. In coarse-grained sediment at 30 m depth miliolids occurred in large number, while in the muddy bottom (at 42 m depth) agglutinated foraminifera were dominant, implying low temperature, low oxygen content and reduced light (*ibid*, p. 745). In contrast, SOKAČ & BAJRAKTAREVIĆ (1995, p. 130) have described in the same marine lake, but at 8 m depth in the >250 μm size fraction a typical shallow-marine foraminiferal assemblage with a prevalence of porcellaneous and agglutinated species. In a sample from 30 m depth they found that hyaline foraminifera dominate the assemblage.

Salinity data in this paper are reported simply as numbers, because the salinity has been defined since the early 1980's as the ratio between conductivity of seawater and of standard KCl solution (OPEN UNIVERSITY COURSE TEAM, 1989).

2. STUDY AREA

2.1. HYDROGRAPHY

Water exchange between the open sea and Veliko Jezero and Malo Jezero is driven by tidal currents. However, the average tidal amplitude in this area is only 11±0.5 cm (BULJAN & ZORE-ARMANDA, 1976). The Veliki Most (Large Bridge) strait between

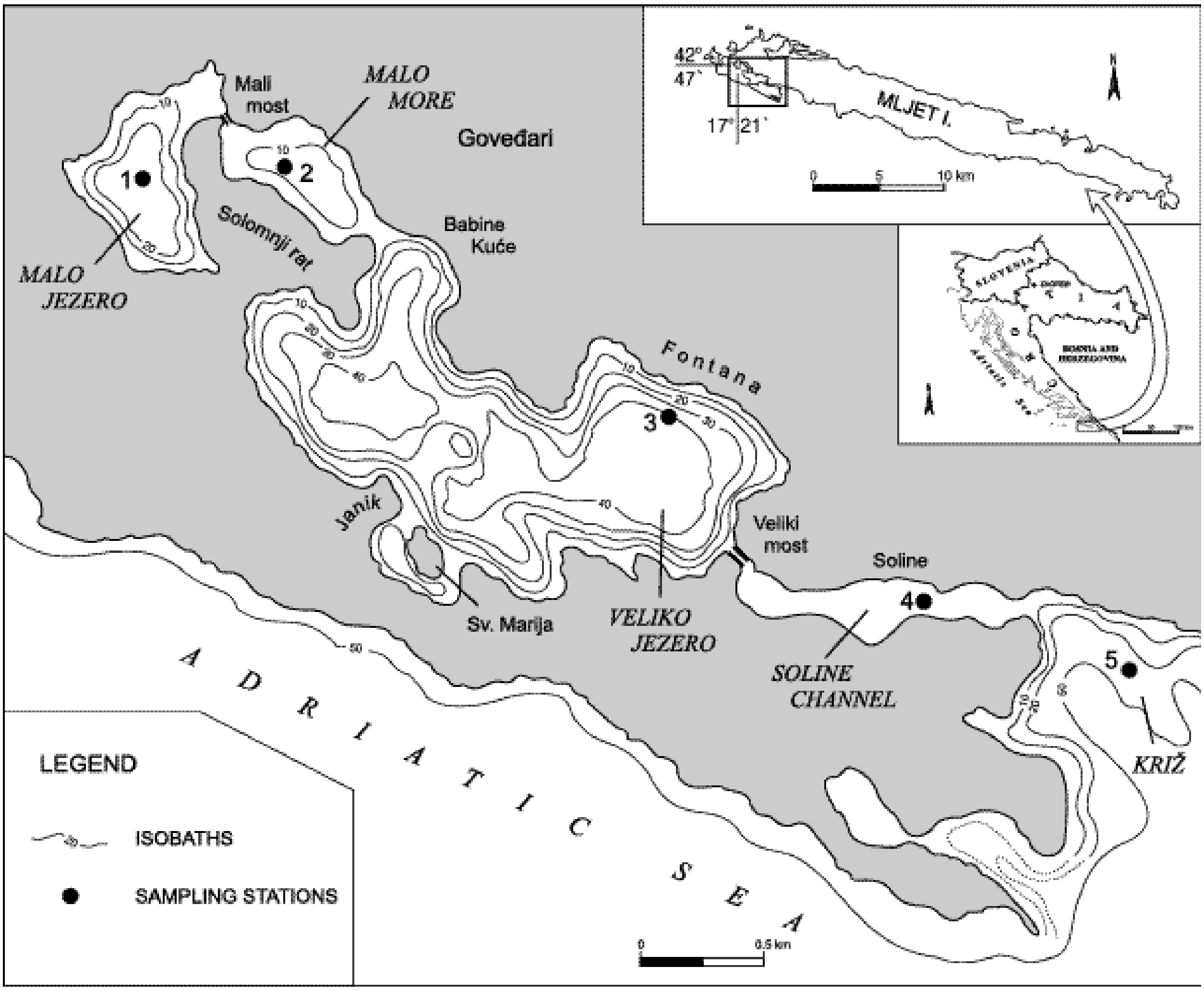

Fig. 1 Map of Mljet Island, Croatia, showing the study area and sampling stations.

the Soline Channel and Veliko Jezero is only 10 m wide and 2.5 m deep. Prior to artificial enlargement in 1960 it was only 4.5 m wide and 0.6 m deep (STRAŽIČIĆ, 1979). The Mali Most (Small Bridge) strait between Veliko and Malo Jezero is even smaller: 2.5 m wide and 0.2 m deep. Therefore the masses of water exchanged are small. Mean annual precipitation (1981-1990) at the nearby meteorological station Goveđari is 765 mm, and potential evapotranspiration is 692.6 mm/year, indicating the slightly humid climatic characteristics of the region. However, precipitation is concentrated in winter, whereas during summer evaporation prevails (VUČETIĆ & VUČETIĆ, 1995). Therefore, during the warm part of the year, due to excessive heating of the surface layer, large differences in density between surface and bottom waters occur. Dense bottom water formed in winter cannot be exchanged during summer. The concentration of organic matter increases in summer, and this causes enhanced bacterial degradation and oxygen undersaturation in the deepest parts of the Mljet Lakes (CARIĆ & JASPRICA, 1995).

The summarized hydrographic data (Table 1, after BULJAN & ŠPAN, 1976; BENOVIĆ et al., 2000) indicate high salinity (36-38 ‰), relatively cold water (9-18 °C), and episodic anoxic conditions in bottom water in both depressions (in Malo Jezero and in Veliko Jezero). For example, BULJAN & ŠPAN (1976) report that in 1951 to 1953 there was a permanent anoxia in the bottom waters in the Malo Jezero. BENOVIĆ et al. (2000) found that dissolved oxygen saturation near the bottom in October 1997 was 4.3% in Malo Jezero and 17% in Veliko Jezero. Moreover, they registered an anoxic event in the Veliko Jezero between August 26-28, 1996, when below the thermocline layer (at 18.5 m) oxygen concentration rapidly decreased to 0% in the layer from 39 m to the bottom. Open marine hydrographic conditions were found at the Križ station (Figs. 1, 2).

Due to vertical differences in temperature and salinity, the formation and depth of the seasonal thermocline differs at the locations investigated. In the open waters of Mljet Island (Križ station), the seasonal thermocline depth ranges between 11 and 42 m and its average depth is at 25 m. In Veliko Jezero, the thermocline is shallower (12-22 m) and shows little vertical change. In Malo Jezero, the thermocline is the shallowest (5-12

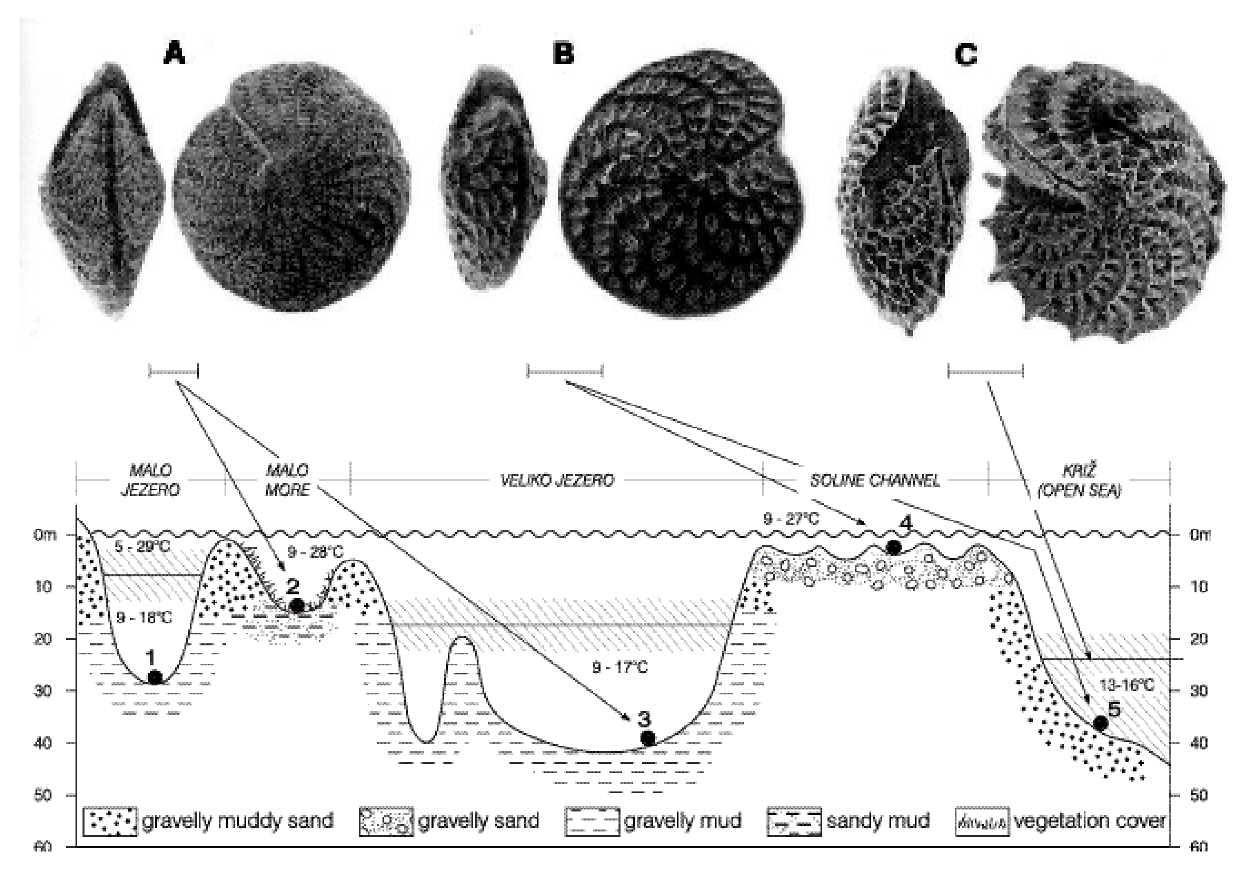

Fig. 2 Schematic profile through the Mljet Lakes showing annual oscillation of temperature and the position of the thermocline, bottom sediment type, and prevalent distribution of morphotypes of *Elphidium crispum* (A = morphotype #1; B = morphotype #2) and occurrence of *Elphidium aculeatum* (C). Scale bar is 200 µm.

m), but also the most stable and the strongest, because of large temperature differences (Fig. 2). Occasionally, the thermocline formed during summer in Malo Jezero remains stable even during winter, thus preventing bottom water mixing for a period longer than a year (BULJAN & ŠPAN, 1976).

2.2. SEDIMENTS

Previous sedimentological research in the Mljet Lakes (VULETIĆ, 1953; SEIBOLD, 1958; CIMERMAN et al., 1988; JURAČIĆ et al., 1995) indicated similar sediment distribution in both lakes. The deepest part of Malo Jezero is covered with muddy sediment, whereas the bottoms above 17 m contain mainly zoogenous sand. A change in sediment type with depth can also be observed in Veliko Jezero, but it is not as regular as in Malo Jezero. The shallower parts of Veliko Jezero are covered with biogenous carbonate sands, whereas in the deeper parts (42 m) clay minerals and authigenic pyrite are present.

In sediment cores taken from both Malo Jezero and Veliko Jezero, microlamination is common. The laminae have been interpreted either as annual layers (varves) as a consequence of seasonal anoxic conditions (SEIBOLD, 1958; SEIBOLD & BERGER, 1996), or

	STATIONS				
	1. Malo Jezero (28 m)	2. Malo More (13 m)	3. Veliko Jezero (40 m)	4. Soline Channel (1.5 m)	5. Križ (Open Sea) (38 m)
salinity	36-38	34-36	35.5-37	36-38	38
temperature	9-18 °C	9-28 °C	9-17 °C	9-27 °C	13-16 °C
oxygen concentration	0.0-6.6 ml/l	4.8-6.4 ml/l	0.0-6.6 ml/l	5-6 ml/l	4.2-6.6 ml/l

Table 1 Ranges of bottom water characteristics at investigated stations. Summarized data after BULJAN & ŠPAN (1976) and BENOVIĆ et al. (2000).

SAMPLE	WATER DEPTH (m)	MEAN SIZE, Mz (μm)	SORTING So	MUD (%)	SEDIMENT TYPE (Folk, 1954)	CARBONATE (%)
1. Malo Jezero	28	10.9	1.61 poorly sorted	95.1	slightly gravelly mud	72
2. Malo More	13	176.8	2.81 very poorly sorted	48.4	slightly gravelly sandy mud	89
3. Veliko Jezero	40	59.5	3.45 very poorly sorted	73.3	gravelly mud	62
4. Soline Channel	1.5	692.6	1.44 poorly sorted	5.1	gravelly sand	76
5. Križ (Open Sea)	38	1659.8	2.02 very poorly sorted	12.2	gravelly muddy sand	59

Table 2 Granulometric properties, types of sediments, and carbonate content. Surface sediment sample (0-2 cm), Mljet, May 1995.

lamination due to episodic bottom-water anoxic events which need not necessarily correspond to annual variations (JURAČIĆ et al., 1995).

3. SAMPLING AND METHODS

3.1. SAMPLING AND SAMPLE PREPARATION

Scuba divers collected sediment cores up to 80 cm long from five stations in the Mljet Lakes and the adjacent open sea (Fig. 1) in May 1995. Sediment cores were frozen within 4 hours, and transported frozen to the laboratory.

In the laboratory, frozen cores were cut into subsamples, and the first 2-cm subsamples were used for our research. After defrosting, a subsample of 10 ml of wet sediment was taken for foraminiferal analysis, and the rest of the subsample was used for grain-size analysis.

3.2. METHODS

The grain size of the sediment samples was analyzed by wet sieving, using ASTM standard stainless steel sieves for >32 μm fraction. A Coulter Counter (mod. TA II) was used for the <32 μm sizes. The sediments were classified according to their gravel - sand - mud (mud = silt + clay) ratio (FOLK, 1954).

Carbonate content was determined volumetrically by measuring CO_2 evolved by dissolving a 0.5 g dry sample in 15% HCl.

The subsamples for foraminiferal analysis were stained with rose Bengal (MURRAY, 1973), in spite of the disadvantages and limitations of this method (MURRAY, 1991; JORRISEN et al., 1995). After staining, subsamples were wet sieved through 250 and 125 μm sieves.

In each sample foraminifera were identified after FORAMINIFERI PADANI (1982), JORRISEN (1988), LOEBLICH & TAPPAN (1987), and CIMERMAN & LANGER (1991), and all specimens (stained and unstained) were counted. The absolute abundance in 10 ml, and the relative abundance of each species was determined. For each station, dominant and accessory species were defined according to their relative abundance. An estimation of the species diversity was performed using the following parameters: number of species, number of specimens, Shannon-Wiener species diversity index (H), equitability index (E) (BUZAS, 1979), and percentage of Miliolina (=porcellaneous), Textulariina (=agglutinated) and Rotaliina *s.l.* (=hyaline). Species diversity and abundance were compared with the known ecological conditions (temperature, salinity, substrate). The morphotype variations were described from >125 μm size-group foraminifera. Existing corollary hydrographic data gave a better understanding about the ecological affinity of investigated species. Sedimentation rate was estimated according to the relative abundance of specimens of sessile species (POAG et al., 1980).

4. RESULTS

4.1. GRANULOMETRIC ANALYSES

Results of granulometric analyses (mean size, sorting, mud percent, and sediment type), along with carbonate content of investigated samples, are reported in Table 2.

The sample from the deepest part of Malo Jezero (sample #1; 28 m depth) has only 4.9% biogenous particles/fragments of gravel and sand size, and the rest is silt and clay. The surface sediment is 71% carbonates, mostly aragonite, with lesser amounts of calcite, magnesian calcite, and dolomite. The remaining part is quartz and feldspar (SONDI et al., 1995). In the shallow part of Malo More (sample #2; 13 m depth), the

SAMPLE	DRY WEIGHT IN 10 ml (g)	SPECIMENS IN GRAM OF SEDIMENT	NUMBER OF SPECIES	UNSTAINED SPECIMENS (U)	STAINED SPECIMENS (S)	Ratio U/S	TOTAL SPECIMENS
1. Malo Jezero	8.29	15.9	**12**	120	12	10:1	**132**
2. Malo More	9.59	102.0	**32**	887	91	10:1	**978**
3. Veliko Jezero	6.29	23.2	**18**	122	24	5:1	**146**
4. Soline Channel	9.23	196.1	**38**	1462	348	4:1	**1810**
5. Križ (Open Sea)	10.02	87.4	**55**	771	105	7:1	**876**

Table 3 Number of species, unstained and stained individuals and total number of specimens in each sample, Mljet, May 1995.

sediment has 51.5% biogenous gravel and sand; the remainder is mud. Sample #3 (40 m depth) in Veliko Jezero contains 26.5% biogenous particles (>125 µm). The bottom of the shallowest part of the Soline Channel (sample #4; 1.5 m depth) contains carbonate gravely sand, which forms symmetrical ripples. Their wave lengths are 3-6 m, as a consequence of the relatively strong tidal currents in that shallow channel. Sediment sorting is therefore better than in other samples (although still low =1.44). The nearshore marine sample #5 (Križ, 38 m depth) had the largest mean size (1660 µm), with 21.42% gravel, 66.43% sand, and the minimum carbonate.

4.2. DIVERSITY OF SPECIES AND ASSEMBLAGES, MORPHOTYPE VARIATIONS, AND SEDIMENTATION RATE

The numbers of stained, unstained, and total specimens, along with the number of species present in each sample, are reported in Table 3. In total, 67 benthic foraminiferal species were determined, and 44 species were represented by stained specimens in at least one sample (Table 4). The ratio between unstained and stained specimens (U/S) varies from 10:1 (#1 and 2) to 4:1 (#4) (Table 3). Six species were found only in the marine lakes, and 10 were restricted to the open water. Dominant and accessory species were determined at each station (Table 5). In Table 6 the Shannon-Wiener index (H), equitability index (E), and percentage of Textulariina, Miliolina and Rotaliina are shown.

In the sample from **Malo Jezero** (Station #1; 28 m depth), we found 12 species, represented by only 132 specimens in the standard 10 ml sample. The U/S ratio is high (10:1). The majority of foraminifera belongs to the suborder Rotaliina (77%). The specimens of Miliolina are rare. This association is characterized by thin-walled species (sizes less than <250 µm): *Haynesina depressula*, *Asterigerinata mamilla*, *Valvulineria bradyana*. H index is the lowest of all samples (0.81), while the E index is 0.22. We refer to this association as the *Haynesina depressula* Assemblage (Table 5).

At 40 m depth in **Veliko Jezero** (Station #3), we found the *Asterigerinata mamilla* Assemblage (Table 5). This sample contains 18 species and 146 specimens, almost entirely belonging to the Rotaliina (91%): *A. mamilla*, *V. bradyana*, *H. depressula*, *Rosalina bradyi* and a large *Elphidium crispum* (Tables 3, 4). U/S ratio is low (5:1), and H and E indices are low (0.97 and 0.23 respecively).

In Malo More and in the Soline Channel we found a foraminiferal fauna different from that in Malo Jezero and Veliko Jezero. In **Malo More** (Station #2; 13 m depth), 32 species and 978 specimens were determined (U/S = 10:1, H = 0.91, E = 0.18), and in **Soline Channel** (Station #4; 1.5 m depth), 38 species with 1810 specimens were counted (U/S = 4:1, H = 1.23, E = 0.23) (Tables 3, 6). We assigned benthic foraminiferal assemblages in Malo More to the *Peneroplis planatus* Assemblage, whereas the *Peneroplis pertusus* Assemblage characterizes the station in Soline Channel (Table 5).

In Malo More, *P. pertusus* and *P. planatus* prevail and constitute about 60% of the foraminiferal assemblage, along with small Rotaliina: epifaunal *A. mamilla* and infaunal *H. depressula*. In the Soline Channel, the same species as in the "lakes" were found (*E. crispum*, *A. mamilla*, *H. depressula*), along with sessile and attached species (the later are sometimes mobile): *Cibicides refulgens*, *Cibicidella variabilis*, *Lobatula lobatula*, *Planorbulina mediterranensis*, *R. bradyi*, *Gavelinopsis lobatulus*.

The open sea **Križ** sample (Station #5; 38 m depth) was the only one in which *Textulariina* exceeded 1%. The *Rosalina bradyi* - *Cibicides refulgens* Assemblage contained 55 species with 876 specimens (H = 1.48, E = 0.26) (Tables 3, 5, 6). Biogenous fragments form an ideal substrate for such sessile species. Beside *R. bradyi* and *C. refulgens*, the sample contained *G. lobatulus*, *A.*

	STATIONS																			
	1. MALO JEZERO				2. MALO MORE				3. VELIKO JEZERO				4. SOLINE CHANNEL				5. KRIŽ (OPEN SEA)			
	unstained		stained		unstained		stained		unstained		stained		unstained		stained		unstained		stained	
FORAMINIFERA	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
Total	**120**	**100**	**12**	**100**	**887**	**100**	**91**	**100**	**122**	**100**	**24**	**100**	**1462**	**100**	**348**	**100**	**771**	**100**	**105**	**100**
TEXTULARIINA																				
Textularia sp.					1	0.11			1	0.9							11	1.4		
MILIOLINA																				
Vertebralina striata					21	2.4	1	1.1					8	0.6	1	3	3	0.4		
Adelosina mediterranensis					3	0.3											10	1.3		
Spiroloculina ornata					7	0.8	2	2.2					2	0.1	1	0.3	14	1.8	3	2.9
Siphonaperta aspera					9	1.0							72	4.9	18	5.2				
Cycloforina contorta													3	0.2			5	0.7		
C. juleana													10	0.7			4	0.5		
C. villafranca																	3	0.4	2	1.9
C. colomi																	1	0.1		
Lachlanella variolata					1	0.1							10	0.7	4	1.2	1	0.1		
Massilina secans																	1	0.1	1	1.0
M. gualtieriana													1	0.1						
Quinqueloculina nodulosa					4	0.5							2	0.1			23	3.0		
Q. laevigata	18	15	3	25	29	3.3	8	8.8	3	2.5			11	0.8			9	1.2	1	1.0
Q. limbata																	3	4		
Q. stelligera																	8	1.0		
Q. jugosa															2	0.6	24	3.1		
Q. parvula	3	2.5			25	2.8							188	13.0	9	2.6	17	2.2	3	2.9
Q. bidentata													36	2.5	6	1.7	8	1.0	2	2.0
Q. seminula													52	3.6	8	2.3	3	0.4	2	2.0
Q. ungeriana													6	0.4	3	0.9	6	0.8	1	1.0
Miliolinella subrotunda																	2	0.3	3	2.9
M. semicostata					2	0.2											3	0.4	1	1.0
M. grata													2	0.1	4	1.2				
M. webbiana																	1	0.1		
Pseudotriloculina laevigata					1	0.1							10	0.7			17	2.2	1	1.0
P. oblonga	4	3.3			2	0.2			2	1.6			8	0.6			4	0.5	1	1.0
Triloculina marioni					1	0.1	1	1.1					10	0.7			10	1.3	1	1.0
T. schreiberiana					1	0.1							41	3.0	9	2.6	13	1.7	1	1.0
Pyrgo sp.																	2	0.26		
Sigmoilinita costata					1	0.1											34	4.41		
Articulina carinata																	1	0.13		
Coscinospira hemprichii					1	0.1														
Wellmanelinella striata													2	0.1						
Laevipeneroplis inornatus													1	0.1						
Peneroplis pertusus	2	1.7			231	26.0	26	28.6	2	1.6	1	4.17	309	21.1	70	20.1	10	1.3	2	1.9
P. planatus					287	32.4	30	33	1	0.8	1	4.17	288	19.7	54	15.5	7	0.91		
P. arietinus													4	0.3						
Sorites orbiculus									2	1.6										
ROTALIINA																				
Lenticulina sp.																	3	0.4		
Polymorphina sp.7																	8	1.0	1	1.0
Sphaerogypsina globula																	9	1.2		
Bolivina sp.	6	5	1	8.3	1	0.1			1	0.8										
Elphidium crispum	4	3.3			22	2.5	1	1.1	18	14.8	7	29.2	93	6.4	80	23.0	46	6.0	10	9.5
E. aculeatum													3	0.2	1	0.3	16	2.1		
E. sp. 1					1	0.1	1	1.1	3	2.5							10	1.3		
E. sp. 4	2	1.7			3	0.3			2	1.6			29	2.0	5	1.4	32	4.2	1	1.0
E. cf. *depressulum*					4	0. 5							38	2.6	9	2.6				
E. cf. *maioricensis*													1	0.1			7	0.9		
Planorbulina mediterranensis					1	0.1							6	0.4	3	0.9	6	0. 8	3	2.9
Cibicides refulgens					1	0.1	2	2.2	2	1.6	2	8.3	45	3.1	12	3.6	77	10.0	6	5.7
Lobatula lobatula					3	0.3			3	2.5			29	2.0	3	0.9	13	1.7	5	4.7
Cibicidella variabilis													3	0.2	3	0.9			1	1.0
Asterigerinata mamilla	3	2.5			107	12.1	10	11	37	30.3	9	37.5	6	0.4	2	0.6	67	8.7	7	6. 7
Gavelinopsis lobatulus									3	2.5			93	6.4	31	8.9	42	5. 5	13	12.4
Rosalina bradyi	1	0.8			26	2.9	1	1.1	7	5.7			32	2.2	6	1.7	73	9.5	18	17.1
R. macropora																	3	0.4	3	2.9
R. vilardeboana																	27	3.5	2	1.9
Haynesina depressula	39	32.5	8	66.7	36	4.1	8	8	14	11.5	3	12.5			1	0.3				
Valvulineria bradyana	20	16.7			7	0.8			21	17.2	1	4.2							2	1.9
Eponides concameratus																	1	0.1		
Neoconorbina terquemi																	48	6.2	5	4.8
Astronion stelligerum													2	0.1			13	1.7	3	2.9
Ammonia parkinsoniana													6	0.4	3	0.9				
A. tepida	18	15			48	5.4											2	0.3		
Lagena sp.																	2	0.3		
Buccella sp. 1																	8	1.1		

STATIONS	UNSTAINED ASSEMBLAGES dominant species	secondary species	STAINED ASSEMBLAGES dominant species	secondary species
1. Malo Jezero	*Haynesina depressula*	*Valvulineria bradyana*, *Ammonia tepida*, *Quinqueloculina laevigata*	*Haynesina depressula*	*Quinqueloculina laevigata*
2. Malo More	*Peneroplis planatus*	*Peneroplis pertusus*, *Asterigerinata mamilla*	*Peneroplis planatus*	*Peneroplis pertusus*, *Asterigerinata mamilla*
3. Veliko Jezero	*Asterigerinata mamilla*	*Valvulineria bradyana*, *Elphidium crispum*, *Haynesina depressula*	*Asterigerinata mamilla*	*Elphidium crispum*
4. Soline Channel	*Peneroplis pertusus*, *Peneroplis planatus*	*Quinqueloculina parvula*	*Elphidium crispum*	*Peneroplis pertusus*, *Peneroplis planatus*
5. Križ (Open Sea)	*Cibicides refulgens*	*Asterigerinata mamilla*, *Gavelinopsis lobatulus*	*Rosalina bradyi*	*Elphidium crispum*, *Gavelinopsis lobatulus*

Table 5 Dominant and secondary species of benthic foraminifera in samples from each station. Surface sediment sample (0-2 cm), Mljet, May 1995.

mamilla, *E. crispum* and in much smaller amount spine specimens of *E. aculeatum*. Several different species of Miliolina were also present (Table 4).

Morphotype variations were only found in the *Elphidium crispum* species (Fig. 2). Two morphotypes have been distinguished based on the following features (after JORRISEN, 1988): (1) maximum diameter; (2) number of chambers per final whorl; (3) structure and ornamentation of the umbilical part of the tests (the presence or absence of defined umbilical boss); (4) degree of inflation of the chambers (their shape); (5) outline of the test. Morphotype #1 of *E. crispum* species is a thin-shelled, flattened form with the maximum size reaching 1.44 mm, with a high number of arcuate chambers (27-29) in the last whorl, and with 12-14 ponticuli with subelliptical fossettes in last chamber. The sutures are backward curved, with a pronounced umbilical knob with 7-9 large perforations, and with angular peripheral margin.

Morphotype #2 is characterized by thick-shelled, lenticular, inflated tests, the maximum size is up to 0.57 mm; low number of arcuate chambers (10-14) in the last whorl, 9-12 ponticuli in the last chamber, the fossettes between ponticuli are rectangular in shape, chambers gradually increasing in size. The sutures are backward curved, with a flat umbilical knob.

In Malo More and Veliko Jezero (samples #2 and #3 respectively), morphotype #1 prevails (in sample #2 morphotype #1 makes 90% of all elphidiids found at this station, and in sample #3 it participates with 67%). In sediment samples from the Soline Channel and Križ (#4 and 5), morphotype #2 strongly prevails (87% and 91% respectively) (Fig. 2).

Along with the distribution of morphotypes of *E. crispum*, the occurrence of *E. aculeatum* is shown in Fig. 2. It was found only in samples from Stations #4, and #5. Bottom sediment type at investigated locations is also presented in Fig. 2.

The percentage of specimens of attached species *Cibicides*, *Rosalina* and *Planorbulina* differs significantly from station to station (Fig. 3). In Malo Jezero, specimens of these species were not recorded, but toward the open sea their percentage significantly increases, up to 11.7% in the unstained assemblage and 14.7% in the stained assemblage at the station Križ. The percentage of sessile specimens in the stained

Table 4 Benthic foraminiferal abundance. Surface sediment sample (0-2 cm), Mljet, May 1995 (numbers of stained individuals are given in the right column and numbers of unstained are given in the left column for each station).

SAMPLE	SHANNON-WIENER INDEX (H)	EQUITA-BILITY INDEX (E)	TEXTULARIINA NUMBER	%	PERCENTAGE OF MILIOLINA NUMBER	%	ROTALIINA NUMBER	%
1. Malo Jezero	0.81	0.22	0	0	30	22.73	102	77.27
2. Malo More	0.91	0.18	1	0.1	694	71.27	283	28.94
3. Veliko Jezero	0.97	0.23	1	0.68	12	8.22	133	91.1
4. Soline Channel	1.12	0.23	0	0	1265	69.89	545	30.11
5. Križ (Open Sea)	1.48	0.26	11	1.26	272	31.05	593	67.7

Table 6 Shannon-Wiener index, equitability index, and percentage of Textulariina, Miliolina and Rotaliina, Mljet, May 1995.

assemblage is larger than the percentage of sessile specimens in the unstained association, contrary to the majority of vagile species.

5. DISCUSSION

As expected from physiographic and hydrographic data, the benthic foraminiferal assemblages show large differences. The ratio of Miliolina, Textulariina and Rotaliina (Table 6) indicates that the assemblages from stations located in the "lakes" (Stations #1 and 3) display characteristics of lagoon assemblages (MURRAY, 1991), whereas the assemblage at the marine nearshore station Križ (Station #5) indicates a normal marine environment with salinity over 30.

The smallest number of species and specimens in a standard 10 ml sample was found in Malo and Veliko Jezero (samples #1 and 3). Such assemblages are oligospecific (showing low species diversity and low abundance), but at the same time have high species dominance. Generally, they indicate a specific, restricted environment with stressed conditions (oxygen depletion, unusual temperatures, low or high salinity or their large variations). SEN GUPTA & MACHAIN-CASTILLO (1993) found that in dysoxic conditions typically 2-3 species constitute up to 80% of the total assemblage. We infer that the primary limiting factor for low species abundance, low species diversity, and high dominance in the Mljet Lakes is episodic low oxygen concentration (Table 1). The oxygen depletion of bottom water is produced by density stratification; in Malo Jezero the thermocline occurs between 5 and 12 m depth and in Veliko Jezero between 12 and 22 m depth. Both samples show that the fauna have three species making up to 64% of the total (unstained and stained) assemblage; *H. depressula*, *V. bradyana and A. tepida* represent 64% of total assemblage in sample #1; *A. mamilla*, *V. bradyana* and *E. crispum* make 63% of total assemblage in sample #3. In these samples the second dominant species is *V. bradyana* (making up to 15% of total assemblage at each station), an oxygen deficiency tolerant species (JORISSEN, 1987, p. 32). This species is absent in samples #4 and 5.

The species diversity index H for total (stained and unstained) assemblages increases from about 0.8 in sample #1 to 1.4 in sample #5. Lower values found in samples #1, 2 and 3 are the result of a high dominance of very few species (Table 5). The highest value (sample #5) implies that more favourable conditions for foraminiferal diversity exist in the open marine environment. The equitability index E is very low ranging from 0.18 in sample #2 to 0.26 in sample #5. This implies that all the samples are from somehow restricted environments.

Reoxygenation of bottom water after episodic deficiencies in the Mljet Lakes, as in other environments, is followed by colonization of benthic foraminifera. Shallow water foraminifera require only about three weeks to colonize the substrate and to stabilize their density (BUZAS, 1993, p. 158). Amongst many genera, representatives of *Quinqueloculina* and *Elphidium* are considered to be colonization pioneers. Their presence in all samples does not allow determination of whether foraminifera lived through the low oxygen/anoxia events, or if they recolonized after. However, in the Malo Jezero sample #1, the ratio between quinqueloculinids and elphidiids (0.18:0.05) is similar to that known from an assemblage found at 1 m depth in experimental conditions in Florida (0.35:0.07 - BUZAS, 1993, p. 159). The different ratio in the Veliko Jezero sample #3 (0.02:0.21) probably reflects somewhat different conditions (greater depth, diminished turbulence, no algal cover, lower temperature) which are favorable for elphidiids.

The tendency of changing shell shape with depth has been observed as intraspecific variation in operculinas (PECHEUX, 1995). The morphological changes have been described either as thinning of the walls, or as a change in chamber proportions (HOTTINGER, 1997). In lamellar-perforate foraminifera the thinning of the chamber walls has been shown to be the result of diminishing rates of turbulence in the water column (REISS & HOTTINGER, 1984).

The distribution of the morphotypes of *E. crispum* in the Mljet Lakes coincides with differences in the nature of substrate. Muddy sediments with a high food concentration (samples #2, 3) host prevalently large, flattened, morphotype #1, whereas in a sandy substrate (samples #4, 5) smaller, inflated, morphotype #2 (with diameters about 40% smaller than those of morpho-

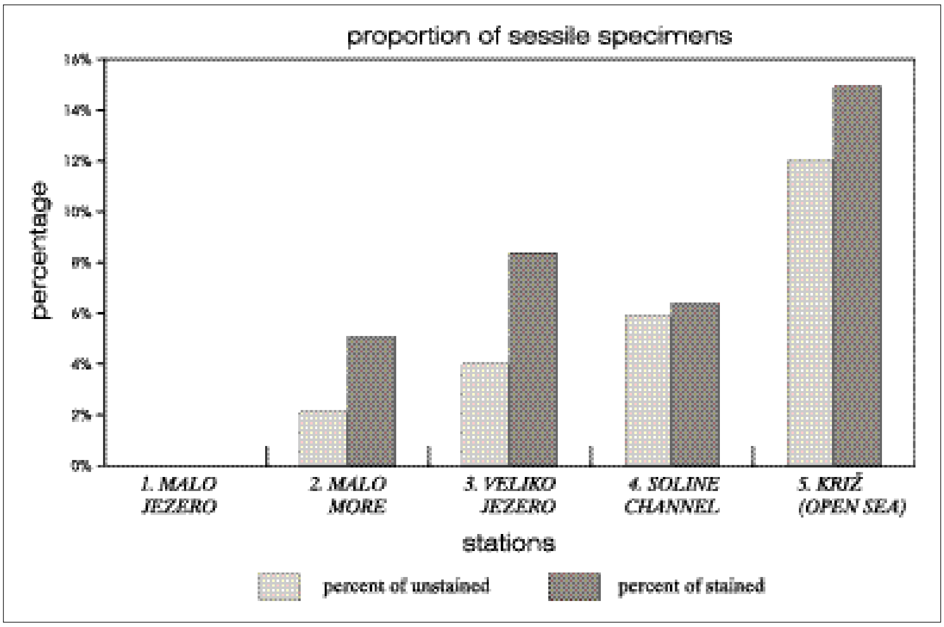

Fig. 3 Proportion of sessile specimens of *Cibicides*, *Planorbulina*, *Rosalina* in investigated samples.

types # 1) prevails. This contrasts JORISSEN's (1988) finding from the northern Adriatic Sea, where large, compact, morphotypes prevail in nutrient-poor conditions, and inflated morphotype in nutrient-rich conditions. On the other hand, this goes along with experimental evidence (TER KUILE & EREZ, 1988) that in lamellar perforate foraminifera the thinning of the chamber walls is a result of thinning of each lamella due to the diminishing rates of turbulence with increase in depth.

MURRAY (1991) suggested that elphidiids from a muddy substrate have infaunal preferences, while those from sand are more likely to have an epifaunal preference. LANGER (1988) and KITAZATO (1988) have described an epiphytic mode of life for *E. crispum* specimens, while MYERS (1943) noted that larger *E. crispum*, buried to a depth of about 1 cm, are able to escape in about 1 hour (calculation is made after Myers data, where active individuals spend about 12 hours traversing distance of 9 to 12 cm in vertical direction). It is expected that interstitial water in subsurface sediment (at one cm depth) has lower oxygen concentration than water at the water/sediment interface. Therefore, thinner, larger specimens (morphotype # 1) prefer muddy sediment with calm water above (Table 1; Fig. 2).

The relative sediment accumulation (relative sedimentation rate) can be estimated by using the percentage of sessile species, because attached species are incompatible with large sediment input (POAG et al., 1980). There is a net increase of the percent of specimens of sessile species from Malo Jezero (absent) toward the open sea (Station # 5, Križ) (Fig. 3). It suggests a greater sedimentation rate in the "lakes" than in open waters. The "lakes" most probably act as a trap for terrigenous and authigenous particles due to their topography.

Haynesina depressula is one of the most abundant species in bottom sediments of both Malo Jezero and Veliko Jezero. MURRAY (1991, p. 324), in an ecological overview of foraminifera, has representatives of genus *Haynesina* as brackish forams (living in salinity between 0 and 30), although (*ibid*, p. 141) some species can survive higher salinity (0-35). At the Malo Jezero, Malo More and Veliko Jezero stations stained specimens were noticed, indicating that those specimens were most probably authigenic. At the open-sea Križ station, *H. depressula* was not recorded, although hydrographic conditions, except for oxygen concentration, are similar to those in the "lakes". The percentage of *H. depressula*, similarly to *V. bradyana*, in the association decreases towards the open sea, whereas at the same time the biodiversity increases. Most probably, *H. depressula* tolerates stress conditions including a large range of oxygen concentrations, salinity and temperature, but is probably a bad competitor. The lack of *H. depressula* at the Križ station might therefore be a consequence of the increased competition there.

6. CONCLUSIONS

This study is based on five surface sediment samples collected in May, 1995, from the Mljet Lakes, and therefore can be considered only as a preliminary note. However, it is possible to put forward the following conclusions:

(1) Benthic foraminiferal assemblages from the Lakes area and from the nearshore indicate a transition from lagoonal towards open marine conditions, based on the ratio between Textulariina, Miliolina and Rotaliina.

(2) The "lakes" behave as temporary hypoxic lagoons, in which the main limiting factor for the benthic foraminifera is oxygen concentration. Episodic stagnant conditions in Malo and Veliko Jezero are

formed due to large temperature and salinity differences between bottom and surface water, which prevents water mixing. At the same time the "lakes" act as sediment traps with a higher sedimentation rate compared to the adjacent open sea. Episodic anoxia is reflected in a low foriminiferal species diversity, high abundance of specimens of two pioneer genera (*Quinqueloculina* and *Elphidium*), and presence of *Valvulineria* species tolerant to low oxygen conditions.

(3) The number of species and specimens in sediment foraminiferal assemblages increases with the influence of the open sea. In these peculiar marine lakes, unstable ecological conditions do not permit the accommodation of either a large number of species or of specimens, whereas in the nearshore, where ecological conditions are more stable ("normal"), the assemblage is much richer in species. The Shannon-Wiener index is rather low in all samples suggesting restricted environment (H=0.8-1.4), although its value increases continuously from the Malo Jezero towards the Križ Station.

(4) The distribution of morphotypes of *Elphidium crispum* in the Mljet Lakes may be correlated to substrate type, mode of life, water energy, and oxygen conditions. The larger flattened specimens of morphotype #1 occur more commonly in a muddy, oxygen depleted, and low energy environment.

(5) In the study area, *Haynesina depressula* tolerates a salinity range significantly higher than previously documented. It appears to be well adapted to stressed conditions, but probably cannot tolerate competition.

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