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HOLOCENE SEDIMENTATION IN THE SOLINE CHANNEL (MLJET LAKES, ADRIATIC SEA)

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A 103 cm long core from the Soline Channel (Mljet Island, Adriatic Sea), which is at present a surface connection between the peculiar marine Mljet Lakes and the open sea, indicates substantial changes of the sedimentary environment in the Holocene. In the layer dated to 4,600 B.P., 25–30 cm below the bottom (which is at 2.8 m depth), freshwater algae represented by species of *Chara/Nitella* were found along with the gastropod *Limnea stagnalis*. This dominantly brackish sediment extends from 10 to 60 cm below the bottom. Above that interval marine sediment was found and below it quartz dominated the subareal or freshwater sediment. This indicates that the surface marine connection between Mljet Lakes and the sea was established after deposition of freshwater/brackish sediments *i.e.* not earlier than ca. 4 kyr B.P.

Keywords: freshwater deposits; ostracods; gastropods; foraminifers; Characeae; Quaternary; Croatia

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Jezgra dugačka 103 cm izvađena iz kanala Soline (otok Mljet, Jadransko more), koji je danas površinska veza između jedinstvenih morskih Mljetskih jezera i otvorenog mora, ukazuje na bitne promijene taložnog okoliša u holocenu. U sloju čija je starost procijenjena na 4,600 godina, 25–30 cm ispod dna (koje se nalazi na dubini od 2.8 m), nađene su slatkovodne alge iz roda *Chara/Nitella* zajedno s puževima *Limmnea stagnalis.* Ti pretežno bočati sedimenti protežu se od 10 do 60 cm ispod dna. Iznad njih nalaze se marinski sedimenti a ispod kopneni ili slatkovodni sedimenti. To ukazuje da je površinska veza morem između Mljetskih jezera i otvorenog mora uspostavljena nakon taloženja slatkovodnih/bočatih sedimenata tj. ne prije oko 4 tisuće godina.

Ključne riječi: sedimenti; ostrakodi; puževi; foraminifere; haraceje; kvartar; Hrvatska

INTRODUCTION

During preparatory work for the construction of a protective dam at the entrance to the Mljet Lakes (Mljet Island, Adriatic Sea, Croatia, Fig. 1) a peculiar black-stained sediment layer was encountered in the shallow water of the Soline Channel. A 103 cm sediment core was taken from this layer in August 1997.

The Mljet Lakes (Veliko jezero and Malo jezero or *Large Lake* and *Small Lake*, respectively) are semi-enclosed, relatively deep depressions connected with the open sea by the narrow, shallow Soline Channel. Being connected with the sea, they contain marine water and, therefore, are not true lakes. However, due to their depth (46 and 29 m respectively) they can hardly be termed lagoons, which are usually defined as shallow semi-enclosed water bodies (PHLEGER, 1969) »having depths that seldom exceed a couple of meters« (KJERFVE & MAGILL, 1989). Therefore we propose that such isolated marine water bodies be called *marine lakes*. The Mljet lakes have peculiar sedimentological characteristics that have been previously investigated. Several interesting phenomena were found, including episodic sedimentation in anoxic con-

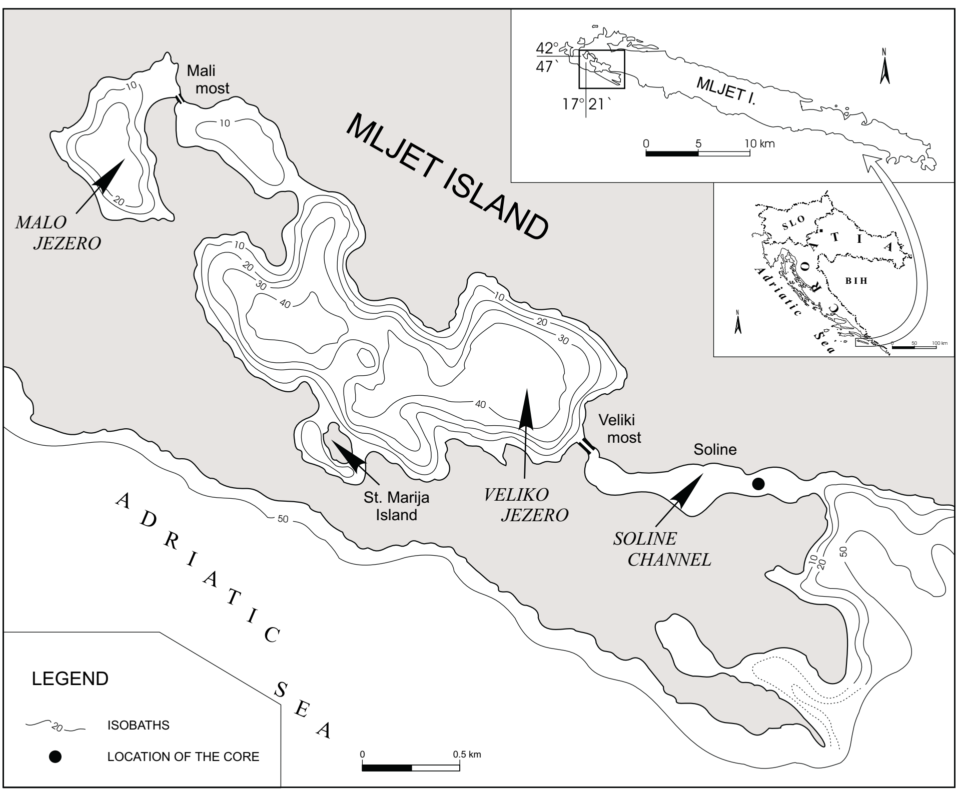

Fig. 1. Location and bathymetry of the Mljet Lakes and the Soline Channel with core location. Bathymetry of lakes after VULETIĆ (1953)

ditions and sedimentation of aragonite mud (VULETIĆ, 1953; SEIBOLD, 1958; JURAČIĆ *et al.*, 1995, 1998). Sediment cores from both lakes have been used for paleoclimatologic and paleoecologic research (BEUG, 1962; SCHMIDT, 1993; WUNSAM *et al.*, 1999).

The depressions in which the marine lakes are located are typically karstic (*dolinas* and *uvalas*) developed in Mesozoic limestones and dolomites. The formation of deep dolinas (sinkholes) occurred while their bottom was above sea level. It can be presumed that periods in recent geological history with a lowered sea level had an important role in their morphogenesis.

During the last glaciation (Würmian) 18 kyr B.P. the global sea level was approximately 120–125 m lower than at present (FAIRBANKS, 1989). Most probably, the dolinas encompassing Mljet Lakes were remodelled, if not formed, during this last glaciation. During Lower Holocene from 10 to 6 kyr B.P. conditions were favourable for the formation of Mljet freshwater lakes (similar to present-day Vrana lake on Cres Island, Adriatic Sea) (JURAČIĆ *et al.*, 1995; WUNSAM *et al.*, 1999). The sea level and the groundwater level (*i.e.* erosional base) rose above the bottom of dolinas during Holocene and hindered subsurface draining of rainwater. Depending on climatic conditions (humid/arid), percolation of freshwater towards the sea or seawater towards the lakes could occur. WUNSAM *et al*. (1999) indicated that marine ingression into Veliko jezero through the Soline Channel took place about 5 kyr B. P.

The Soline Channel is at present a surface connection between the open sea and the Veliko jezero. It is approximately 1 km long and 270 m wide. The entrance to the Veliko jezero is the *Veli most* strait, artificially enlarged to be 10 m wide and 2.5 deep. The maximum depth of the Soline Channel is only 3.8 m. The connection with the open sea (*Vratosolina*) used to be 0.5–1 m deep, but in 1960 was artificially deepened to 2.5 m (STRAŽIČIĆ, 1979).

The main objective of this paper is to add information on the sedimentation environment in the Soline Channel and to the development of the Mljet Lakes, *i.e.* to elucidate the possible time of the opening of the surface connection between the lakes and the open sea.

SAMPLING AND METHODS

The 103 cm sediment core in a plastic tube was taken by SCUBA diving in Soline Channel at a water depth of 2.8 m (Fig. 1). A subsampling of the core was done at uneven intervals, and the following subsamples were subsequently analysed: 0–3, 3–5, 10–20, 25–30, 45–47, 55–57, 70–72, 86–88 and 98–100 cm from the top of the core (Fig. 2).

Granulometric analysis was done by combining wet sieving through standard ASTM sieves (>32 mm) on Analiysette II (Fritsch, Germany), and particle counting on a Coulter Counter TA II (Coulter Electronics, UK). Sediment type was determined after FOLK (1954) for the top subsample, and after SHEPARD (1954) for the remaining subsamples. Granulometric parameters were determined after FOLK & WARD (1957).

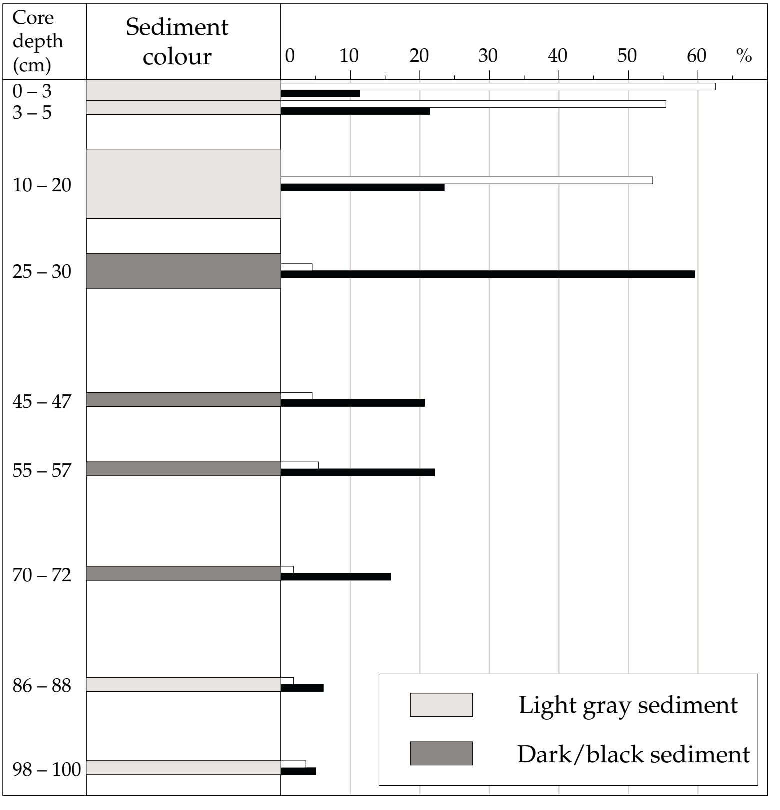

Fig. 2. Schematic presentation of the Soline Channel core: left – subsample colour; right – percent of carbonate (white bars) and of organic matter (black bars).

The total organic matter (TOM) was determined as weight loss after the samples had been treated with 15% H_2O_2 and heated at 450 °C for 6 h (VDOVIĆ *et al.*, 1991).

Carbonate content was determined gas-volumetrically (JOBSTRAIBIZER, 1970).

Semiquantitative mineralogical composition of some samples was performed using a Philips X-ray diffractometer equipped with a graphite crystal monochromator.

A sediment fraction larger than 125 µm from the bulk of the sample was extracted to identify particles present. Foraminifers were identified after CIMERMAN & LANGER (1991), plant remnants after BEIJERINCK (1976) and MÄGDEFRAU & EHRENDORFER (1988), gastropods after RADOMAN (1983) and BOLE (1969) and ostracods after ASCOLI (1964). The degree of preservation/fragmentation of biogenous remnants was used to indicate also a degree of autochthony/allochthony.

^{14}C activity of the organic fraction from the 25–30 cm sample was measured on a gas proportional counter (SRDOČ *et al.*, 1971) in order to determine the age of the sample. The sample was measured twice and the mean radiocarbon age was dendrochronologically corrected after STUVIER *et al.* (1998).

RESULTS

The granulometric parameters of the samples investigated are presented in Tab. 1. They indicate that only the surface sample (0–3 cm) has coarse-grained particles, whereas in the rest of the core, fine-grained (silt and clay) particles prevail.

The mineralogical composition (Tab. 2) indicates a large share of carbonates in the upper part of the core (0–20 cm) (Fig. 2), whereas quartz is the only abundant mineral in the bottom part of the core (86–88 and 98–100 cm). Pyrite was detected in the 25–30 and 98–100 cm samples. The TOM content is rather high through the core (>5.0%) but is extremely high in the central part (10–60 cm) with the maximum (59.5%) in the sample from 25–30 cm (Fig. 2). The identified fossils (foraminifers, ostracods and gastropods) and plant remnants found in the >125 μm fraction are shown in Tab. 3.

Samples description

The samples are divided in four groups according to their granulometric, biogenous and mineralogical characteristics.

Surface sample (0–3 cm)

This sample is a gravelly, muddy sand (FOLK, 1954), with 62.5% of carbonates and TOM content of 11.3%. The dominating minerals are calcite, 5% Mg-calcite, aragonite, and quartz. The sample is characterized by a high content of biogenic car-

Tab. 1. Granulometric parameters and sediment type

Core depth (cm)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mean size, Mz (μm)	Sorting, S_0 (FOLK & WARD, 1957)		Skewness, S_k, < or > then Mz		Sediment type (SHEPARD, 1954)
0–3	17.4	62.3	18.8	3.5	238.2	2.99	very poorly	0.15	finer	gravelly muddy sand*
3–5	0	7.6	74.8	17.9	10.5	1.66	poorly	5.56	finer	clayey silt
10–20	0	27.2	48.2	24.6	17.9	3.00	very poorly	–0.33	coarser	clay-sand-silt
25–30	0	27.7	65.3	7.0	27.8	1.95	poorly	–0.177	coarser	sandy silt
45–47	0	5.1	54.0	40.8	5.8	1.77	poorly	–0.094	coarser	clayey silt
55–57	0	4.9	74.4	20.7	9.2	1.58	poorly	0.11	finer	clayey silt
70–72	0	6.7	72.9	20.4	8.8	1.75	poorly	0.044	finer	clayey silt
86–88	0	12.3	39.9	47.7	6.4	2.36	very poorly	–0.42	coarser	silty clay
98–100	0	8.1	67.6	24.3	8.4	1.91	very poorly	0.084	finer	clayey silt

* FOLK (1954)

Tab. 2. Mineralogical and chemical composition of sediments.

	Core depth in cm	0–3	3–5	10–20	25–30	45–47	55–57	70–72	86–88	98–100
Minerals	Calcite	+++	n.a.	+++	+	n.a.	n.a.	n.a.	–	–
	Mg calcite	+++	n.a.	–	–	n.a.	n.a.	n.a.	–	–
	Dolomite	+	n.a.	+	–	n.a.	n.a.	n.a.	–	–
	Aragonite	+++	n.a.	++	–	n.a.	n.a.	n.a.	–	–
	Quartz	+++	n.a.	++	+	n.a.	n.a.	n.a.	+++	+++
	Muscovite	–	n.a.	+	–	n.a.	n.a.	n.a.	–	–
	Kaolinite	–	n.a.	–	–	n.a.	n.a.	n.a.	–	+
	Illite	++	n.a.	+	+	n.a.	n.a.	n.a.	++	++
	Smectite	–	n.a.	–	–	n.a.	n.a.	n.a.	++	–
	Plagioclase	–	n.a.	–	++	n.a.	n.a.	n.a.	++	++
	Pyrite	–	n.a.	+	++	n.a.	n.a.	n.a.	+	+++
Amorphous substance		–	n.a.	–	+++	n.a.	n.a.	n.a.	–	–
Carbonates (%)		62.5	55.4	53.5	4.5	4.5	5.4	1.8	1.8	3.6
Organic matter (%)		11.3	12.4	23.5	59.5	20.7	22.1	15.8	6.1	5.0

Estimation from X-ray diffractograms: +++ very abundant (>25 %); ++ fairly abundant (10–25 %); + detected (>2 %); – not detected; n.a. not analysed.

bonate detritus. In the coarser fraction (250–500 µm) gastropods and bivalves fragments and sponge spicules are very abundant. Ostracod valves belonging to species of *Loxoconcha affinis* (BAIRD), *Aurila convexa* (BAIRD, 1850), *Semythereis aff. inversa* (MÜLLER, 1894), *Procytherideis complicata* (RUGGIERI, 1953), *Xestoleberis communis* (MÜLLER, 1894), *Xestoleberis gr. dispar* (MÜLLER, 1894) and genera of *Urocythereis* are also abundant, whereas *Cyprideis torosa* (JONES, 1850) valves are less abundant. The ostracod assemblage confirms normal marine salinity, except *C. torosa,* which could indicate freshwater influence. All the foraminifers present (Tab. 3) also confirm normal marine conditions, although some of species detected can tolerate large salinity variations (MURRAY, 1991).

Subsurface sample (3–5 cm)

This sample is a clayey silt (SHEPARD, 1954) with 55.4% carbonates and 12.4% TOM content. Biogenic carbonate remnants are mostly fragmented, although intact shells are also found. Foraminifers, such as *Quinqueloculina, Peneroplis, Elphidium*, gastropods, such as Trochidae, Ceritoidae, Rissoidae and *Ventrosia cissana* (RADOMAN, 1973), and ostracods such as *Aurila convexa*, *Urocythereis* sp., *Semythereis aff. inversa* and *Procytherideis complicata* were detected. Organic plant remnants were also found in this sample (*Ceratophyllum/Potamogeton/Ranunculus* sp. fruits, and oogonia fragments of *Chara/Nitella* sp.).

Tab. 3. Animals and plants determined in fraction >125 µm

Core depth, cm		0–3	3–5	10–20	25–30	45–47	55–57	70–72	86–88	98–100
Ostracods	*Aurila convexa*	+	+							
	Cyprideis torosa	+	+	+	+	+	+			
	Loxoconcha affinis	+								
	Potamocypris lucicola	+	+							
	Semitherura aff. inversa	+								
	Xestoleberis communis	+								
	Xestoleberis gr. dispar	+								
	Urocithereis sp.	+								
Gastropods	*Lymnea stagnalis*				+					
	Ventrosia cissana	+	+	+						
	Trochidae	+	+	+						
	Rissoidae		+	+	+					
	Ceritoidae	+	+	+		+				
	Hydrobiidae	+			+	+				
Foraminifers	*Triloculina schreiberiana*	+		+	+					+
	Rosalina bradyi	+	+	+		+				
	Quinqueloculina nodulosa	+				+				
	Quinqueloculina laevigata	+	+		+					
	Peneroplis pertusus	+	+	+	+	+				+
	Elphidium crispum	+	+	+	+	+	+	+		+
	Cibicides refulgens	+	+	+	+	+	+			
	Asterigerinata mamilla	+	+	+	+	+	+			+
Plants	*Chara/Nitella* sp.		+	+	+	+	+	+		
	Ceratophyllum/Potamogeton/Ranunculus		+	+	+		+	+		
	Potentilla sp.						+	+		

Sediment from 10 to 60 cm depth (samples 10–20, 25–30, 45–47 and 55–57 cm)

These sediment samples are mostly silty. The top is still carbonate-rich (53.5%), whereas below 20 cm the carbonate content is low (4–6%). This part of the core is characterized by a very high TOM content (over 20%) with a maximum of 59.5% in the dark (black) layer at 25–30 cm.

In all samples, in this interval, fruit fragments of *Ceratophyllum/Potamogeton/Ranunculus* sp. and oogonia of *Chara/Nitella* sp. were found.

In the 10–20 cm sample well-preserved remnants of species *Cyprideis torosa* were abundant. This is a euryhaline genus that can also be found in fresh water (ASCOLI, 1964). A gastropod *Ventrosia cissana* (RADOMAN, 1973) characteristic of brackish water was abundant in this layer.

The 25–30 cm sample, containing the 2 cm long gastropod *Lymnea stagnalis* (L), also presents very scarce biogenic remnants in fraction 125–500 μm, but a very high TOM content. The radiocarbon age of this sample (Sample No. Z-2749) with 1 σ error is 4055 ± 111 yr B.P. The conversion of ^{14}C age to calibrated (cal) age using a calibration curve after STUIVER *et al.* (1998) gave the age interval of 2860–2460 cal yr B.C. with a confidence of 68.2%. Deeper samples (45–47 cm and 55–57 cm) show an increased share of carbonised plant remnants (black ones that resemble wood fragments, and brown ones that look like grass blades).

Sediment from 60 to 100 cm depth (samples 70–72, 86–88 and 98–100 cm)

Sediments in this interval are also fine-grained (silty clay and clayey silt). Carbonate content is low (1.8–3.6%), and TOM content is diminishing towards the bottom (from 15.8 to 5.0%). The main mineral encountered is quartz, with some minor proportions of plagioclase, pyrite and illite. The main characteristic of these samples is a dominance of quartz grains in 125–500 mm fraction, and very low incidence or absence of biogenic detritus. There are very rare foraminifers of the genera *Elphidium* and *Peneroplis* that are mostly fragmented, and very rare plant remnants (wood and branch fragments, and grass blades).

DISCUSSION

The Holocene evolution of the Soline Channel is quite interesting. Today it is a shallow (2.5 m) surface connection between the open sea and the Mljet Lakes (Veliko jezero). The lower part of the investigated core, 60 to 100 cm below the bottom (older than ~ 4.8 cal kyr B.P.), is poor in biogenic remnants. The predominance of quartz associated with clay minerals indicates that in this period, the Soline Channel area was either the dry bottom of a shallow *dolina* accumulating red soil (*terra rossa*), or a swampy depression probably similar to *blatine* (depressions in carbonate rock with bottom near to, or below sea level filled with fresh/brackish water, and characterized by the accumulation of mud) (BOGNAR & CURIĆ, 1995). Such *blatine* are quite common on Mljet Island. Sporadic marine biota remnants (mostly fragmented foraminifers and gastropods) may have found their way into the sediment either by bioturbation or during storms from the nearby sea. According to WUNSAM *et al.* (1999), between 6.3. and 5.5 kyr B.P., the climate was changing from more humid conditions towards a Mediterranean climate (with prevalent precipitation during winter). In this period, quartz sand grains might have been brought from surrounding hillsides. Their genesis might be similar to the quartz sand deposits found on the opposite, eastern side of the Mljet Island. These quartz sands were probably brought by wind in the Pleistocene (KRKALO & PENCINGER, 1995).

The main, most interesting part of the core is the interval between 60 and 10 cm, characterized by high TOM content. The remnants of freshwater plants (*Chara*/

Nitella sp., Tab. 3) indicate a depositional environment such as a freshwater lake/ swamp. The preservation of the plant remnants was enhanced by the existence of anoxic conditions at and below the water/sediment interface (as evidenced by high TOM content, black color, pyrite). The freshwater/brackish character of the environment is supported by findings of gastropods *Ventrosia cissana* and *Lymnea stagnalis*. Moreover, only ostracod species *Cyprideis torosa* was found in this interval, and it is a brackish water species. Plant remnants from the layer 25–30 cm with ^{14}C calibrated age of 4810–4410 cal yr B.P. indicate that during that period in the Soline Channel there was a brackish water environment. Therefore this channel could not have acted as a marine ingression path to Veliko jezero as stated in WUNSAM *et al.* (1999). The observed changes towards sea conditions of Veliko jezero must thus have occurred underground, through the karstified flanks.

The surface sediment layer in the Soline Channel is rather distinct. It is predominantly biogenic carbonate sand, mainly originating from fragmentation of skeletons and shells of gastropods, foraminifers and bivalves. The sediment type is in accordance with present hydrographic and environmental conditions in the Channel. The transition into lower TOM sediment is gradual. There is a decrease in carbonate content, in share of marine species remnants, and there is a gradual increase of freshwater/brackish remnants. Especially, the 3–5 cm layer shows mixed characteristics. Most probably such a gradual change is due to the bioturbation of sediments. However, the opening of the Channel and the establishment of a tidal current system could have influenced the formerly sedimented material, and an erosional phase between the lower freshwater/brackish and the normal upper marine sedimentation might have occurred.

The human influence on the opening of the Channel remains open. However, the anthropogenic changes (deepening and enlargements of straits) are well documented.

CONCLUSION

A sediment core from the Soline Channel indicates a succession of three different paleoenvironments in the Holocene. The lower part of the core (60–100 cm) indicates a subareal or freshwater accumulation of a quartz-dominated sediment in the bottom of a karst dolina. The central part (10–60 cm) of the core is dominated by organic remnants deposited in freshwater/brackish environment, whereas only the surface sediment (0–3 cm) is in accordance with present hydrographical conditions (sheltered shallow marine channel with tidal currents).

The freshwater character of sediments dated to between 4810–4410 cal yr B.P. in the Soline Channel indicates that the surface connection between Mljet Lakes and the open sea was established later than formerly presumed (WUNSAM *et al.*, 1999).

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SAŽETAK

Holocenska sedimentacija u solinskom kanalu (Mljetska jezera, Jadransko more)

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Analizom sedimenata iz jezgre dužine 103 cm pokušalo se objasniti promjene u sedimentacijskom okolišu Solinskog kanala tijekom holocena. Danas je Solinski kanal vodena veza Mljetskih jezera s otvorenim morem. Na dnu jezgre u uzorcima s dubine 98–100 i 86–88 cm nađeni su sedimenti gotovo bez i jednog biljnog ili životinjskog ostatka ali s kvarcnim zrnima (frakcije 125–250 µm i 250–500 µm). Moglo bi se pretpostaviti da su taloženi u kopnenim ili/i slatkovodnim uvjetima. Njihova starost je veća od 4600 godina. U uzorku 70–72 cm pojavljuju se ostaci *Chara/Nitella* koji ukazuju na slatkovodne uvjete. U grupi uzoraka (55–57, 45–47 i 25–30 cm) očituje se povećanje udjela organske tvari što upućuje na anoksične uvjete, a ostaci bilja i životinja ukazuju na bočatu sredinu. Starost uzorka 25–30 cm određena je pomoću ^{14}C metode na 4600 godina, a udio organske tvari u uzorku je veći od 50%. U vrijeme taloženja sedimenta u uzorku 25–30 cm u Solinskom kanalu su vladali slatkovodni/močvarni uvjeti u kojima je raslo slatkovodno bilje. To dovodi u pitanje pretpostavku da je u vremenu između 4000 i 5000 godina prije sadašnjosti postojala veza između Velikog jezera i otvorenog mora kroz Solinski kanal (WUNSAM *et al.*, 1999). Velika je razlika u tipu sedimenata koji se nalaze danas na dnu Solinskog kanala i onih koji im prethode. Ta razlika je uočljiva već u uzorku s dubine 3–5 cm u kojem prevladava glinoviti silt, dok na površini prevladava sitnozrni pijesak. Razlika je i u udjelu nađenih marinskih životinjskih ostataka kojih u površinskom sedimentu ima znatno više no u svim ostalim ispitivanim uzorcima jezgre.