

# Late Pleistocene and Holocene paleoenvironmental reconstruction of a drowned karst isolation basin (Lošinj Channel, NE Adriatic Sea)

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1 **Late Pleistocene and Holocene paleoenvironmental reconstruction of a drowned karst isolation**  
2 **basin (Lošinj Channel, NE Adriatic Sea)**

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10 **Abstract**

11 The results of a comprehensive study of submerged paleoenvironments developed along the  
12 karstified eastern Adriatic coast during the Late Quaternary are presented in this study. The Lošinj  
13 Channel is a drowned karst basin filled with sediments. A multi-proxy analysis of two sediment cores  
14 (LK-12 and LK-15) recovered from water depths of 62 and 64 m was conducted. We used magnetic  
15 susceptibility, grain size, mineralogy, XRF core scanning, organic and inorganic carbon, total nitrogen,  
16 and paleontological data, supplemented with AMS <sup>14</sup>C dating results and high-resolution seismic data,  
17 to reconstruct the infill history of the Lošinj basin during the Late Pleistocene and Holocene. Our  
18 findings include the first detailed description of the presumed Marine Isotope Stage (MIS) 5a marine  
19 sediment succession along the eastern Adriatic coast. Deposition in the brackish-to-freshwater  
20 lacustrine body (Lošinj paleolake) occurred during MIS 3. Sea level lowstand that followed caused the  
21 formation of environmental conditions typical of a karst polje. The post-Last Glacial Maximum (LGM)  
22 sea level rise led to the establishment of a brackish marine lake with seawater seepage through the  
23 karstified sill at 13.7 cal kyr B.P. The transition to the present-day marine conditions commenced at  
24 10.5 cal kyr B.P. Paleoenvironmental changes in the investigated area can be linked to the presence of

25 a sill at -50 m depth that separates the Lošinj basin from the Kvarnerić Bay. The sill depth determines  
26 the isolation or inundation of the investigated basin in response to the changes in sea level.  
27 Paleoenvironments reacted sensitively to these changes, and therefore, the study area represents an  
28 ideal setting to track regional sea level and climate variability.

## 29 **1. Introduction**

30 Submerged paleoenvironments formed during the Late Quaternary have been the focus of  
31 many recent geological and archaeological studies in the Mediterranean region (e.g., Micallef et al.,  
32 2013; Foglini et al., 2015; Geraga et al., 2017; Flemming et al., 2017). This type of research is essential  
33 in estimating the response of present-day coastal areas to future sea level and climate changes  
34 (Lambeck et al., 2011; Wahl et al., 2017; Antonioli et al., 2017). The Quaternary period is characterized  
35 by significant sea level fluctuations primarily resulting from the waxing and waning of large high-  
36 latitude ice sheets (Shackleton, 1987; Lambeck and Chappell, 2001). At regional and local scales, the  
37 impact of glacio-hydro-isostasy and vertical tectonic movements is also relevant when assessing sea  
38 level changes (Lambeck et al., 2004; Antonioli et al., 2009; Rovere et al., 2016). An exhaustive studies  
39 of relative sea level (RSL) changes in the Mediterranean Sea were published by Sivan et al. (2001),  
40 Lambeck et al. (2011), Vacchi et al. (2014, 2016), Benjamin et al. (2017) and references therein. It is  
41 considered that during MIS 5a RSL was approximately 1 m higher than at present (Dorale et al., 2010).  
42 However, there is a lack of Mediterranean MIS 4 and MIS 3 RSL records (Caruso et al., 2011; Benjamin  
43 et al., 2017). Global data suggests that during MIS 3 sea level was between -60 and -90 m (Siddall et  
44 al., 2003; Rohling et al., 2008). During the LGM sea level fell rapidly to reach a lowstand of -120 to -134  
45 m (Fairbanks, 1989; Lambeck and Purcell, 2005; Lambeck et al., 2014). The post-LGM melting of the  
46 ice sheets caused inundation of the coastal areas in the Mediterranean region and led to the  
47 development of numerous present-day embayments, channels and indentations (Flemming et al.,  
48 2017; Benjamin et al., 2017).

49           Considering the fact that the vast areas of the Adriatic Sea are very shallow (<100 m depth),  
50 paleoenvironmental evolution was substantially influenced by the Late Quaternary sea level changes  
51 (Bailey and Flemming, 2008). Paleoenvironments developed along the western and northern coast of  
52 the Adriatic Sea have been thoroughly investigated, but there is an obvious scarcity of data regarding  
53 the eastern Adriatic coast (Alberico et al., 2017).

54           The development of a large alluvial plain cut only by the Po River and its tributaries during the  
55 sea level lowstands is well-documented in sedimentary and seismic records in the western and  
56 northern part of the Adriatic Sea (e.g., Correggiari et al., 1996; Galassi and Marocco, 1999; Correggiari  
57 et al., 2001; Kent et al., 2002; Amorosi et al., 2003; Amorosi et al., 2004; Amorosi et al., 2008; Moscon  
58 et al., 2015; Campo et al., 2017; Trobec et al., 2017; Pellegrini et al., 2018; Ronchi et al., 2018). At times  
59 of sea level rise, the alluvial plain was inundated, with the development of barrier-lagoon systems,  
60 which allow tracking of the sea level rise in the region (e.g., Correggiari et al., 1996; Amorosi et al.,  
61 2003; Moscon et al., 2015).

62           The research conducted so far along the eastern coast of the Adriatic Sea has indicated  
63 different paleoenvironmental evolution of this area. The existence of submerged lacustrine  
64 environments (paleolakes) along the eastern coast of the Adriatic Sea was suggested by Juračić et al.  
65 (1999), who proposed the development of brackish or freshwater lacustrine environments during the  
66 glacial sea level lowstands. Schmidt et al. (2001) and Wunsam et al. (1999) described the Last Glacial  
67 and Holocene lacustrine deposits that preceded the onset of the marine deposition in the Valun Bay  
68 in the Kvarner region and Mljet Lakes in the southern Dalmatia. Recent studies based on marine  
69 sediment cores are mostly limited to the Holocene (Faivre et al., 2011; Marriner et al., 2014; Felja et  
70 al., 2015; Shaw et al., 2016; Brunović et al., 2019). Research that encompasses a long-term high-  
71 resolution Pleistocene sedimentary record is still missing. Data regarding RSL and climate variations in  
72 the eastern Adriatic during the Pleistocene have been mostly derived from analysis of submerged

73 speleothems. Evidence of these changes is presented in the research published by Surić et al. (2005,  
74 2009) and Surić and Juračić (2010).

75         The main aim of this study is to investigate how depositional environments along the eastern  
76 Adriatic coast responded to the Late Pleistocene and Holocene sea level and climate changes. We  
77 provide a sedimentological record based on two piston cores (LK-12 and LK-15), combined with high  
78 resolution seismic data, from the submerged silled karst basin in the Lošinj Channel. It is considered  
79 that sediments deposited in silled and partly isolated basins are valuable records of past environmental  
80 and sea level changes (Lambeck and Purcell, 2005; Long et al., 2011). Prolific paleoenvironmental  
81 studies of silled basins have been conducted in Canada and Greenland (Long et al., 2011; Normandeau  
82 et al., 2017; Fedje et al., 2018), Scotland (Lloyd, 2000; Lloyd & Evans, 2002), Scandinavia (Balascio et  
83 al., 2011; Narančić et al., 2016), and Black and Marmara Sea (Çağatay et al., 2003; Bahr et al., 2005;  
84 Taviani et al., 2014; Filikci et al., 2017). There is, however, a lack of such studies in the Adriatic Sea.  
85 Here, we evaluate the suitability of the submerged silled karst basin in the Lošinj Channel to improve  
86 and fill the gaps in the Late Quaternary paleoenvironmental reconstructions along the eastern Adriatic  
87 coast.

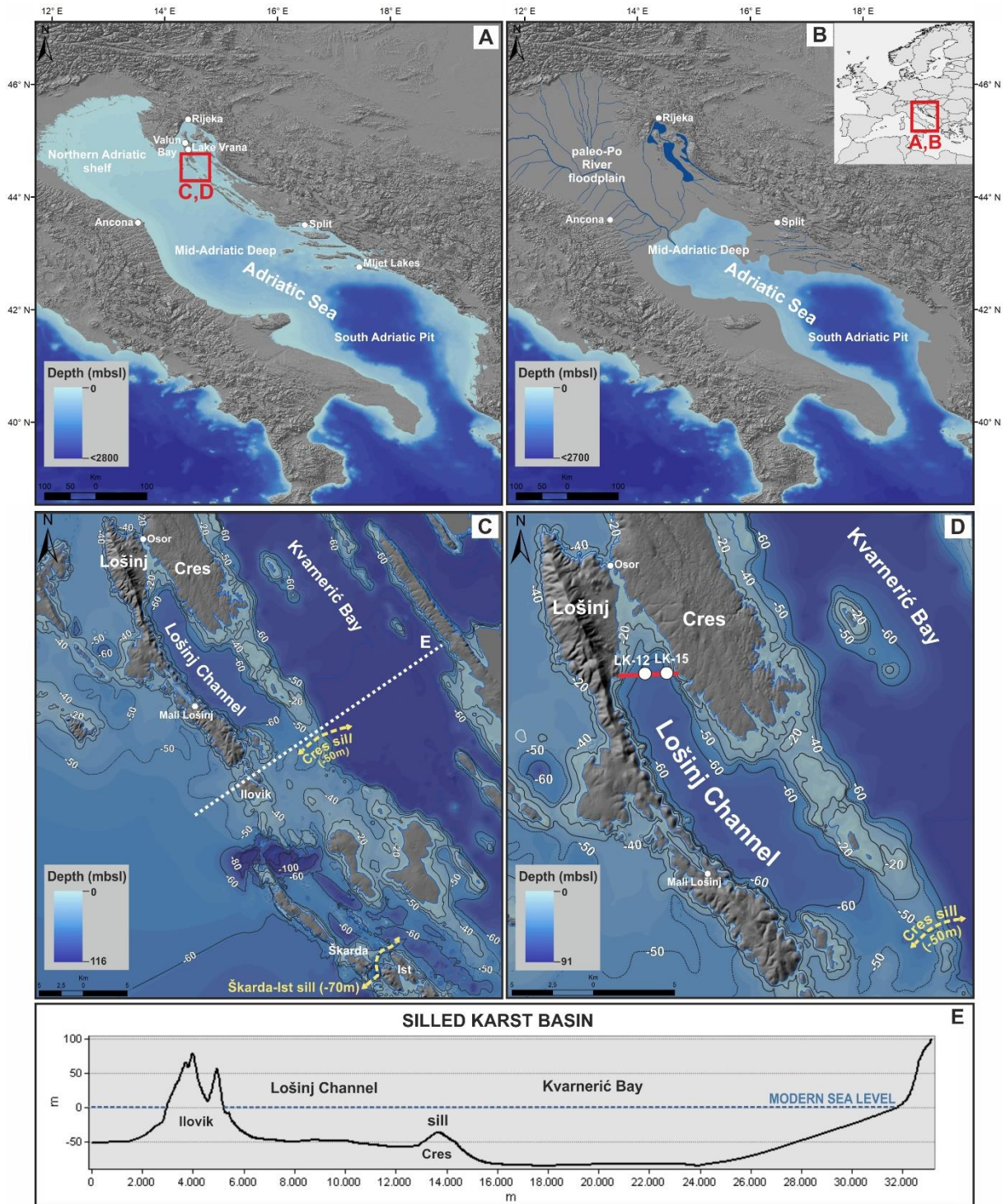
## 88 **2. Regional setting**

89         The Lošinj Channel encompasses a 35-km-long and 6-km-wide area between the shore-parallel  
90 islands Lošinj and Cres on the eastern coast of the Adriatic Sea, in the Kvarner region (Fig. 1). The  
91 Adriatic Sea is a part of the Mediterranean Sea and is characterized by its semi-enclosed nature. The  
92 eastern and western coasts of the Adriatic Sea differ significantly (Pikelj and Juračić, 2013). Whereas  
93 the eastern coast is described in the literature as a Dalmatian-type coast with chains of islands parallel  
94 to the coastline and channels in between them (Kelletat, 2005), the western side is a typical low-lying  
95 coast with dominant riverine sediment input (Frignani et al., 2005).

96 Carbonate deposits ranging in age from Carboniferous to Eocene predominantly build the  
97 eastern Adriatic coast and islands (Vlahović et al., 2005). Prevalent strata on the islands Lošinj and Cres  
98 are carbonate deposits of Cretaceous age (Korbar et al., 2001; Korbar and Husinec, 2003). Paleogene  
99 carbonate deposits and Quaternary loess deposits are also present (Mamužić, 1968; Magaš, 1968;  
100 Fuček et al., 2012; Fuček et al., 2014). Several reverse faults were recognized on geological maps of  
101 islands Lošinj and Cres (Mamužić, 1968; Magaš, 1968). The reader is referred to Korbar (2009) and  
102 references therein for a comprehensive overview of the eastern Adriatic tectonic setting. Neotectonic  
103 history of the coast is complex and still a matter of debate, with different studies arguing subsidence  
104 (Antonioli et al., 2009; Faivre et al., 2011; Marriner et al., 2014; Shaw et al., 2018; Faivre et al., 2019),  
105 uplift (Surić et al., 2009, 2014) and tectonic stability (Faivre et al., 2013).

106 Because carbonate rocks are prone to karstification, different features typical for karst were  
107 formed (dolines, poljes, caves, etc.). There were two major stages of karst development in the  
108 Mediterranean, the Messinian Salinity Crisis and the Pliocene/Quaternary (Mocochain et al., 2006;  
109 Roveri et al., 2014). Some of the karst features developed along the eastern Adriatic coast were  
110 submerged due to the rising sea level during the Late Pleistocene-Holocene marine transgression that  
111 shaped the present-day coast (Surić, 2002; Kelletat, 2005; Paskoff, 2005). The hydrogeology of the  
112 karstified coastal environments is highly dependent on sea level oscillations considering that a rise in  
113 sea level causes a rise in the groundwater level and seawater seepage through karstified and porous  
114 rocks (Shinn et al., 1996; van Hengstum et al., 2011; van Hengstum and Scott, 2011).

115 The study area of the Lošinj Channel is a drowned silled karst basin (Fig. 1). Submerged  
116 prolongation of the Island of Cres forms a sill (Cres sill), with the deepest point at -50 m, that separates  
117 the Lošinj Channel from the Kvarnerić Bay (Fig. 1). The Cres sill depth determines the isolation or  
118 flooding of the Lošinj Channel in relation to the Quaternary sea level changes. Seawater flooding of the  
119 adjacent Kvarnerić Bay probably occurred through a narrow channel/sill at a depth of approximately  
120 70 m located between the islands Škarda and Ist (Škarda-Ist sill) (Fig. 1C).



121

122 Fig. 1. Maps and cross-section of the investigated area. A) Map of the present-day Adriatic Sea. B)  
 123 Schematic map of the Adriatic Sea during the LGM (western Adriatic coast is modified from Maselli et  
 124 al., 2011 and Maselli and Trincardi, 2013; eastern Adriatic coast is reconstructed using bathymetry data  
 125 (Becker et al., 2009) and data from Miko et al., 2016). C) Map of the Lošinj Channel and Kvarnerić Bay

126 with sill locations (yellow lines). D) Coring locations (white circles) and interpreted Seismic line 1 (red  
127 line). E) Cross-section of the Lošinj Channel. The location of the cross-section is marked on map C.

### 128 **3. Materials and methods**

#### 129 **3.1. High-resolution seismic survey**

130 High-resolution seismic data were obtained in April 2015 using a 3.5-kHz sub-bottom profiling  
131 system with Geopulse transmitter and a 4 array transducer, mounted on the vessel *Zlatica dva*. A pulse  
132 duration of 1 ms and a pulse rate of 10 s<sup>-1</sup> were used. The vertical resolution of the system was about  
133 0.5 m which is the minimum distance between the distinguishable reflectors. The average survey speed  
134 was 4 knots, and the positional data was provided by a Differential Global Positioning System (DGPS)  
135 with an accuracy of ±1-2 m. Overall, almost 204 km of seismic lines were recorded during the seismic  
136 survey in the Lošinj Channel. For this study, only the high-resolution seismic reflection profile (Seismic  
137 line 1) along the coring sites was interpreted (Fig. 1).

#### 138 **3.2. Sediment cores**

139 Two sediment cores (LK-12 and LK-15) were retrieved from the northern part of the Lošinj  
140 Channel in September 2015 (Fig. 1). A coring platform equipped with a Niederreiter piston corer  
141 (UWITEC®) was used for core extraction. Core LK-12 (422 cm) was extracted adjacent to the Island of  
142 Lošinj (44°38'16" N, 14°25'10" E), whereas core LK-15 (480 cm) was retrieved in the vicinity of the  
143 Island of Cres (44°38'16" N, 14°26'11" E). The cores were taken at water depths of 62 and 64 m,  
144 respectively (Fig. 1).

#### 145 **3.3. Sediment core analysis**

146 Sediment cores LK-12 and LK-15 were analyzed through a multi-proxy approach. In the  
147 laboratory, cores were cut into approximately 1.5-m-long segments, split lengthwise, photographed  
148 and stored at +4°C until further analysis.



### 149 **3.3.1. Magnetic susceptibility**

150 Manual measurements of magnetic susceptibility (MS) with a Bartington MS2E surface sensor  
151 at 1-cm resolution were conducted on the working halves of the cores.

### 152 **3.3.2. Grain size**

153 The grain size analyses were carried out on 148 samples using a Shimadzu SALD-2300 laser  
154 diffraction particle size analyzer. To analyze the grain size distribution of the siliciclastic component in  
155 the carbonate-rich environment, it was necessary to remove both organic material with hydrogen  
156 peroxide (H<sub>2</sub>O<sub>2</sub>) and carbonates with hydrochloric acid (HCl) (Murray, 2002). Furthermore, sodium  
157 hexametaphosphate ((NaPO<sub>3</sub>)<sub>6</sub>) was added to the samples to prevent particle aggregation, whereas  
158 larger mollusk shells were removed manually from the sediment prior to the pretreatment. Using the  
159 GRADISTAT software package (Blott and Pye, 2001), main statistical parameters were determined  
160 following the Folk and Ward (1957) method.

### 161 **3.3.3. Mineralogy**

162 Bulk mineralogical analyses were performed on selected powder samples taken throughout  
163 the cores using an X'Pert Powder diffractometer (XRD) equipped with Ni-filter CuK $\alpha$  radiation, a vertical  
164 goniometer with a  $\theta/\theta$  geometry, and a PIXcel detector. The scan conditions were set to 45 kV and 40  
165 mA, alongside  $\frac{1}{4}$  divergence and antiscatter slits, and with a step size of 0.02° 2 $\theta$  and a 4 s time per  
166 step within a range between 4° 2 $\theta$  and 66° 2 $\theta$ .

### 167 **3.3.4. XRF core scanning**

168 The downcore relative elemental composition of sediment cores in 1 cm resolution was  
169 analyzed at the Institute of Marine Science (CNR-ISMAR) in Bologna using an AVAATECH  $\mu$ XRF core  
170 scanner. Analysis of the elemental composition was performed using an X-ray source with the voltage

171 set to 10 and 30 kV, which enabled measurements of major and minor elements. The acquired XRF  
172 scanning data are semi-quantitative and reported as elemental ratios (Croudace et al., 2006).

### 173 **3.3.5. Total organic and inorganic carbon and total nitrogen**

174 Total organic (TOC) and inorganic carbon (TIC) and nitrogen (TN) abundances in 157 samples  
175 were determined using a Thermo Fisher Scientific Flash 2000 NC Analyzer. This method allows direct  
176 measurements of the total carbon (TC) and TN. The addition of HCl removes the carbonate component  
177 and allows the determination of TOC (Tung and Tanner, 2003). The difference between TC and TOC  
178 was used for calculation of TIC, whereas the calcium carbonate (CaCO<sub>3</sub>) content was calculated from  
179 the obtained TIC values. The C/N ratio was calculated by dividing the TOC and TN.

### 180 **3.3.6. Paleontology**

181 To further strengthen the reconstruction of the past environments and to establish with  
182 certainty the timing of marine intrusion into the Lošinj Channel, foraminiferal assemblages were  
183 determined. Foraminifera are considered to be a useful tool for the reconstruction of  
184 paleoenvironmental changes (e.g., Lloyd, 2000; Cosentino et al., 2017). In total, 32 samples in core LK-  
185 12 were chosen for analysis. The benthic foraminifera specimens were observed under a binocular  
186 microscope in the fraction >63 µm. Approximately 300 specimens were counted in each sample.  
187 Samples with total number of foraminifera specimens <300 were also examined and specimens  
188 counted. Identification of the genera and species is primarily based on the classifications given by  
189 Cimerman and Langer (1991) and Loeblich and Tappan (1987). The purpose of this paper is not to  
190 perform a detailed statistical analysis of foraminifera assemblages but rather to determine their  
191 presence or absence. Determination of mollusk genera present in the sediment cores will further  
192 improve the paleoenvironmental reconstruction.

### 193 **3.3.7. Core chronology**

194 Core chronologies were established using the accelerator mass spectrometry (AMS)  
195 radiocarbon dating method ( $^{14}\text{C}$ ) at Beta Analytics Laboratory. For dating purposes, 10 mollusk shells  
196 were selected from sediment cores LK-12 and LK-15. Terrestrial plant macrofossils and charcoal were  
197 not present in the analyzed cores. The basal part of core LK-15 (from 135 cm downcore) was also  
198 devoid of mollusk shells suitable for dating.

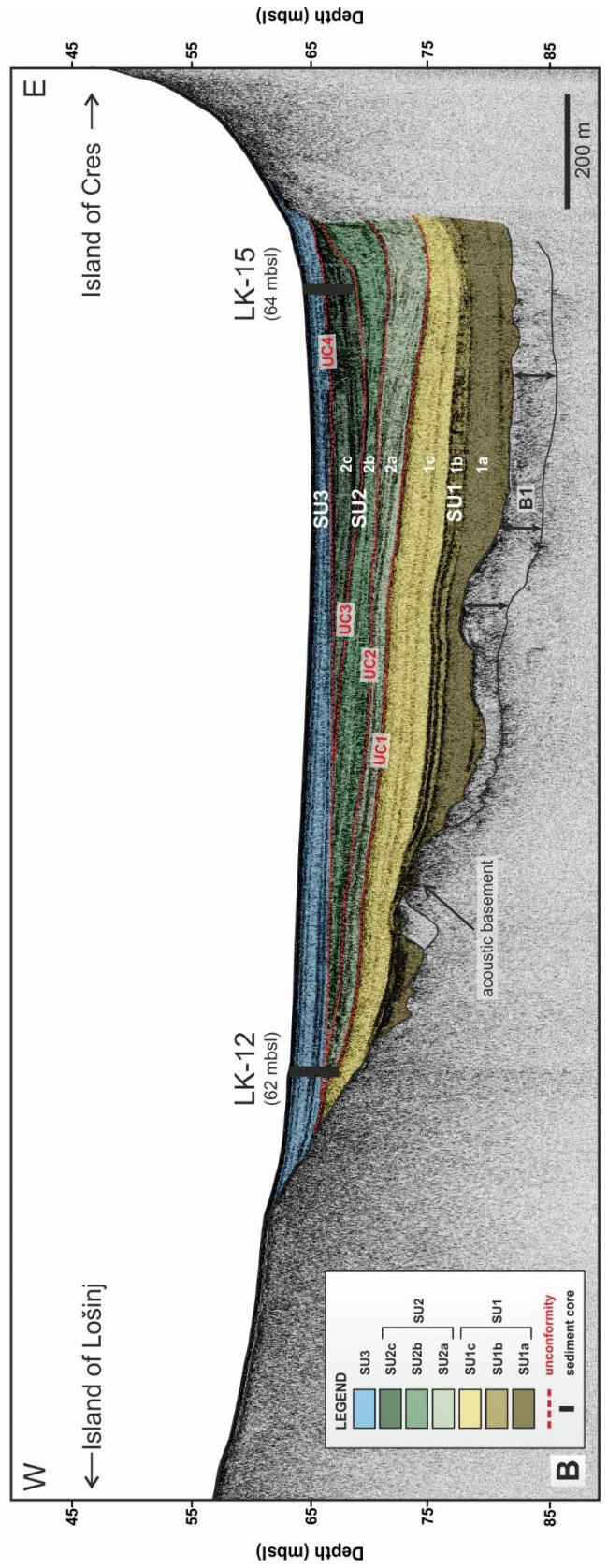
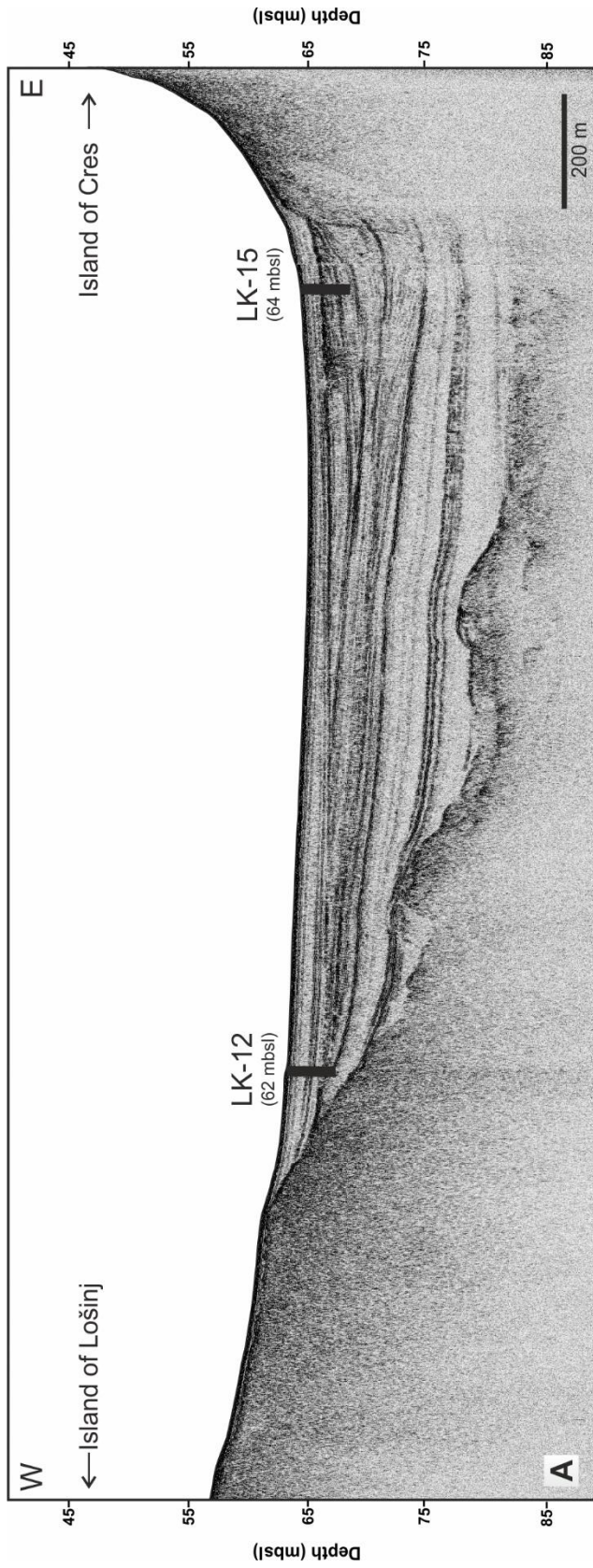
199 The radiocarbon data were further analyzed using Clam software package (Blaauw, 2010) to  
200 obtain reliable age-depth models for each core. The marine reservoir age correction of  $456\pm 46$   
201 ( $\Delta R=100\pm 20$   $^{14}\text{C}$  yr) was adopted (Faivre et al., 2015). The ages obtained from the specimens of the  
202 freshwater mollusk species *Bithynia tentaculata* were also corrected for marine reservoir effects due  
203 to their stable isotopes shell values ( $\delta^{13}\text{C}=-1.6\text{--}2.8$ ), which are typical for growth in the water with  
204 marine influence (Stuiver and Polach, 1977). The Marine13 calibration curve was used for calibration  
205 of the obtained data into calendar years (Reimer et al., 2013).

## 206 **4. Results**

### 207 **4.1. High-resolution seismic data**

208           The interpreted seismic profile (Seismic line 1) indicates the existence of a 22-m-thick  
209 sedimentary succession at the coring sites (Fig. 2). Three main units (SU1-SU3) and six subunits (SU2a-  
210 SU2c and SU3a-SU3c), bounded by unconformities (UC1-UC4), have been determined based on the  
211 seismic unit definition proposed by Mitchum et al. (1977). The acoustic basement has a prolonged  
212 acoustic character, whereas its upper part (B1) exhibits amorphous acoustic facies (Fig. 2). Directly  
213 above the acoustic basement, unit SU1 has been recognized. Reflector characteristics within SU1 led  
214 to the subdivision of seismic subunits SU1a to SU1c. Subunits SU1a and SU1c show a semi-transparent  
215 acoustic character with a few parallel weak internal reflectors. SU1b consists of moderate-to-high  
216 amplitude and laterally continuous reflectors (Fig.2). The lowermost unit SU1 is distinguished from unit  
217 SU2 by a distinct unconformity (UC1). Unit SU2 consists of bands of sub-parallel inclined reflectors with  
218 limited lateral continuity featuring high frequencies with moderate amplitudes. SU2 can be subdivided  
219 into three subunits (SU2a, SU2b and SU2c) that are well defined by their internal seismic characteristics  
220 and stratigraphic contacts. High amplitude stratigraphic unconformities (UC2, UC3 and UC4) mark the  
221 boundary between these subunits and between the SU2 and the overlying unit. The uppermost unit  
222 SU3 appears acoustically semi-transparent with weak parallel reflectors. Sub-bottom data revealed  
223 variable thickness of seismic units in the western and eastern side of the Lošinj Channel, where the  
224 sediment cores were extracted. Cores LK-12 and LK-15 penetrated through 3 previously described units  
225 (SU3 and subunits SU2c and SU1c) (Fig. 2).

226



227 Fig. 2. (A) Seismic profile of Seismic line 1 and (B) its stratigraphic interpretation.

## 228 4.2. Sediment core data

### 229 4.2.1. Core chronology

230 Radiocarbon measurements on 8 mollusk shells revealed that sediment core LK-12 spans the  
231 Late Pleistocene to Holocene time interval (Table 1).  $^{14}\text{C}$  analysis of the mollusk shells from the lower  
232 part of the core (329 and 259 cm) yielded ages of approximately 46.5 and 45 cal kyr B.P. The LK-15  
233 sediment core chronology is less constrained with 2 dates that indicate Holocene age of the upper core  
234 section (10.3 cal kyr B.P. and 9.6 cal kyr B.P.) (Table 1).

235 Table 1. AMS  $^{14}\text{C}$  dating results of samples from sediment cores LK-12 and LK-15.

Sediment core	Depth (cm)	Sample ID	Material	$\delta^{13}\text{C}$ (‰)	Conventional radiocarbon age ( $^{14}\text{C}$ B.P.)	Probability (%)	Calibrated age (cal B.P.)
LK-12	37	Beta - 475881	gastropod shell	+3.0	5550 ± 30	94.2	5725-5909
LK-12	201	Beta - 475882	bivalve shell	+0.8	9680 ± 30	95	10272-10486
LK-12	204	Beta - 459905	gastropod shell	+2.0	9750±30	95	10411-10572
LK-12	211	Beta - 459907	gastropod shell	+0.1	11750± 30	95	13079-13225
LK-12	223	Beta - 468184	gastropod shell	-0.6	12210±40	95	13469-13689
LK-12	233	Beta - 475880	gastropod shell	-1.6	12310±40	95	13577-13758
LK-12	259	Beta - 468185	gastropod shell	+2.8	42110±630	95	44040-45980
LK-12	329	Beta - 459906	gastropod shell	0.0	43050±830	95	45032-47982
LK-15	83	Beta - 468186	bivalve shell	+1.8	9040 ± 30	95	9484-9672
LK-15	134	Beta - 468187	gastropod shell	+3.0	9590 ± 30	92.7	10205-10429

236

### 237 4.2.2. Core lithology and multi-proxy analysis

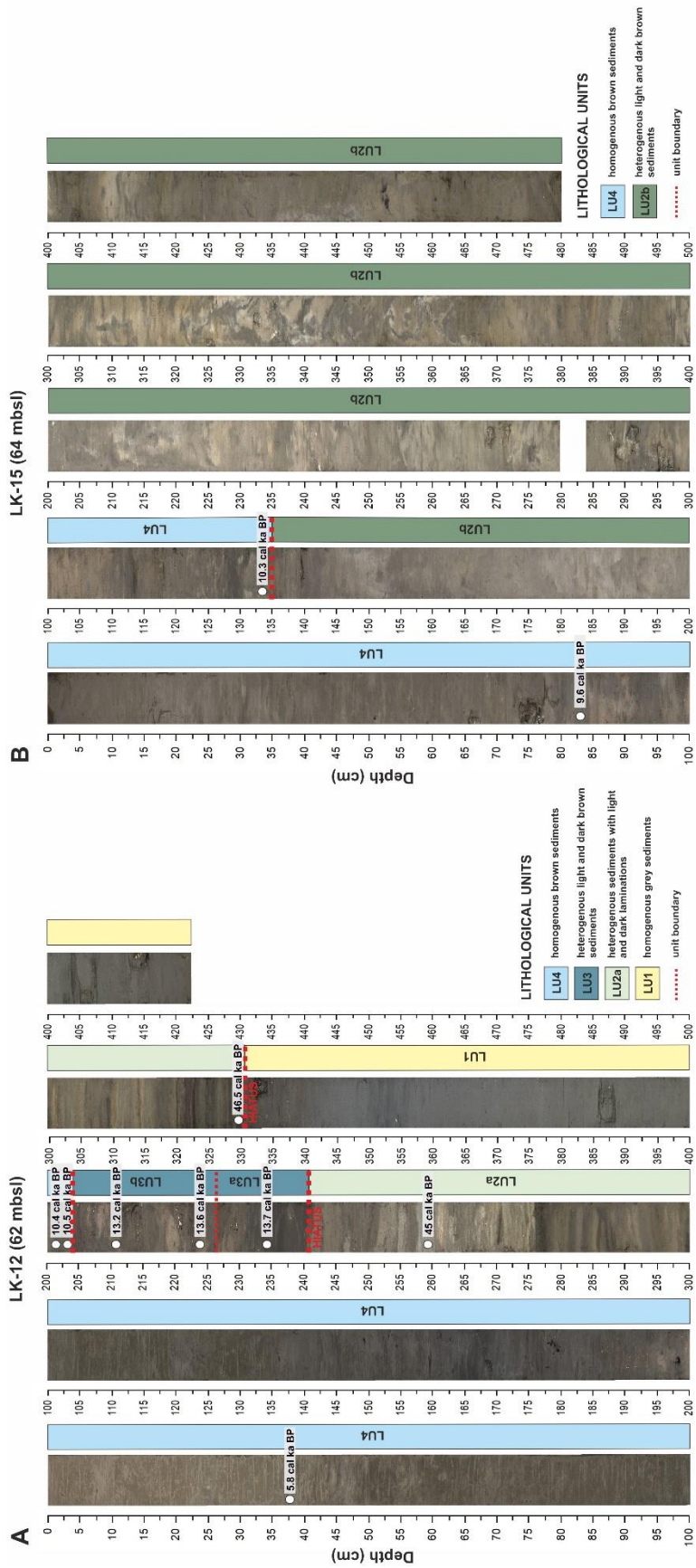
238 Sedimentological, geochemical, mineralogical, and paleontological data used in this study  
239 enabled the division of cores LK-12 and LK-15 into distinct lithological units (Fig. 3).

240 Sediment core LK-12 was subdivided into four lithological units (Fig. 3). Homogenous grey  
241 sediments of the lowermost lithological unit LU1 (>46.5 cal kyr B.P.), recognized in the interval from  
242 422 to 329 cm, are predominantly constituted of high percentages of silt-sized particles (77-84%) (Fig.  
243 4; Supplement 1). Magnetic susceptibility is low in this unit ( $2.9\text{-}13.7 \times 10^{-5}$  SI), whereas the main  
244 mineralogical constituents of the bulk samples are quartz, dolomite, calcite and aragonite. The  
245 lowermost part of core LK-12 is characterized by high Sr/Ca and Ti/Ca ratios (Fig. 4). The TOC content  
246 (0.42-0.97%) and C/N ratios (7.95-13.57) are low. The CaCO<sub>3</sub> content vary between 41.61-56.43% (Fig.  
247 4; Supplement 2). Benthic foraminiferal assemblages are dominated by species *Aubignyna planidorso*,  
248 *Elphidium translucens* and *Ammonia tepida*. The relative abundances of foraminifera specimens are  
249 provided in Supplement 3. Recognized mollusks include *Cerastoderma* sp., *Turritella* sp. and *Cerithium*  
250 sp. Significant number of fragmented shells was observed.

251 Sediments of the overlying unit LU2a in core LK-12 (329-240 cm; 46.5-44.7 cal kyr B.P) are  
252 distinguished by light and dark brown laminations (Fig. 3). This unit is characterized by a slightly coarser  
253 grain size and low MS ( $0.2\text{-}13.6 \times 10^{-5}$  SI) (Fig. 4). Calcite predominantly builds sediments from LU2a,  
254 whereas quartz and dolomite are less abundant. The acquired XRF data exhibit an increase in Ca/Ti  
255 and a decrease in Sr/Ca ratios in LU2a. The Mn/Fe ratios abruptly increase in the interval from 277 to  
256 240 cm. The Zr/Rb ratios reached maximum in the core interval from 286 to 254 cm (Fig. 4). The lower  
257 part of unit LU2a (329-281 cm) is composed of organic-rich sediments, with TOC content of up to 6.18%  
258 (Fig. 4). The upper part of this unit (281-240 cm) has a lighter color and is dominated by high CaCO<sub>3</sub>  
259 content (up to 77.7%). The C/N ratios vary between 11.36-22.19 (Fig. 4; Supplement 2). Foraminiferal  
260 analysis of 9 samples revealed poor preservation of foraminifera specimens and their low abundances.  
261 The exception is the sample from the core depth of 260-261 cm, in which a low number of well-  
262 preserved foraminifera specimens was observed. The mollusk fauna are dominated by *Bithynia*  
263 *tentaculata*. In the basal part of this unit, Chara oogonia are especially abundant.

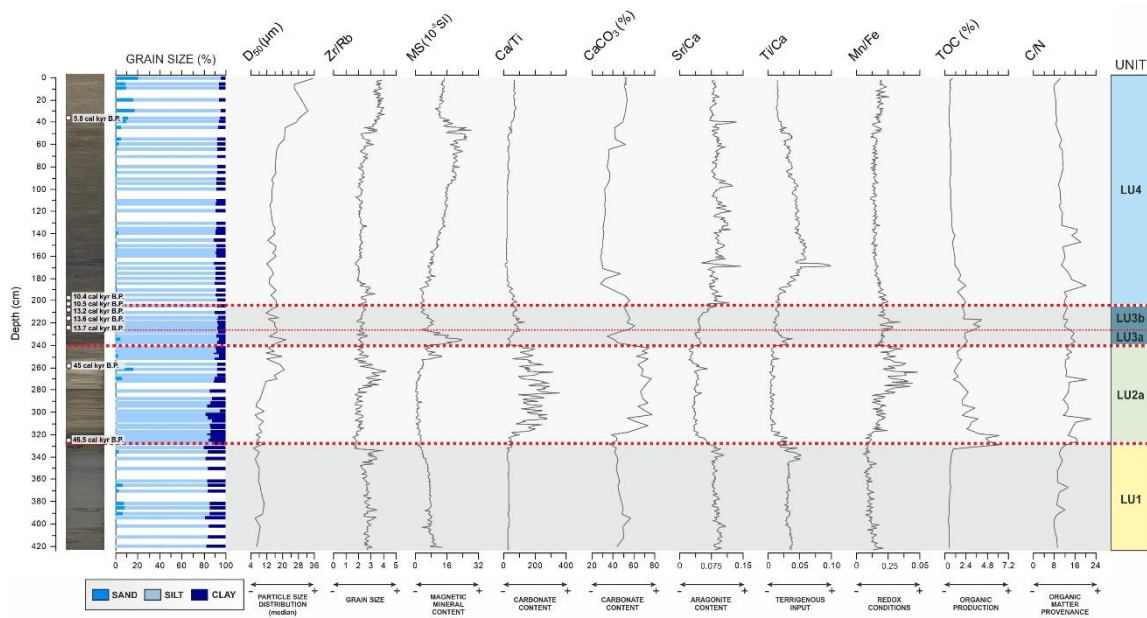
264

265 Fig. 3. Recognized lithological units in: A) sediment core LK-12, B) sediment core LK-15.

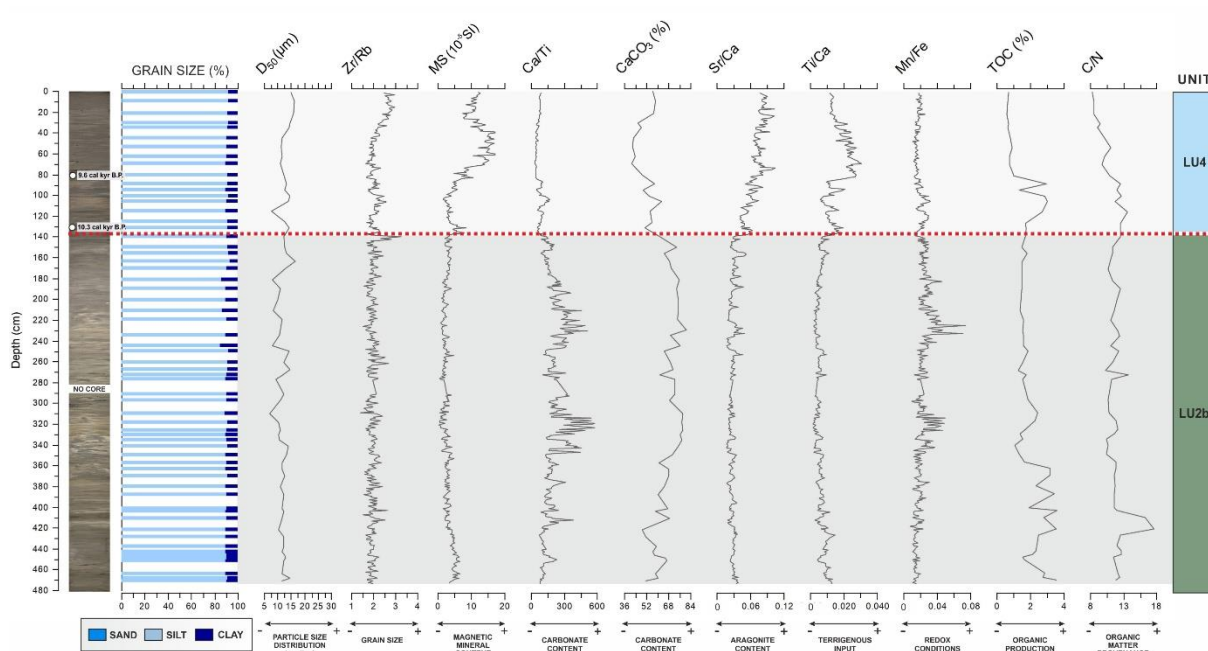




266 The third lithological unit LU3 is recognized in the core interval from 240-204 cm. Sediments  
 267 from LU3 were deposited from 13.7 cal kyr B.P. to 10.5 cal kyr B.P. In the dark brown faintly-laminated  
 268 sediments, silt-sized particles predominate (89-93%) (Fig. 4; Supplement 1). Quartz is the dominant  
 269 mineral phase in all analyzed samples. Aragonite, calcite and dolomite were also determined.  
 270 Significant variations in the obtained data enabled the differentiation of subunits LU3a and LU3b. High  
 271 MS (up to  $23.6 \times 10^{-5}$  SI) was measured in the basal part of the unit (LU3a), whereas Ti/Ca ratios were  
 272 also high. Fig. 4 demonstrates that after peaking in LU3a, C/N ratios decreased in LU3b (11.49-16.08).  
 273 Towards the upper subunit, Ca/Ti, Sr/Ca and Mn/Fe ratios increased (Fig. 4). Subunit LU3b is  
 274 characterized by CaCO<sub>3</sub> content of up to 60.9%, and higher TOC (2-4.2%) (Fig. 4; Supplement 2). A low  
 275 number of foraminifera specimens -but in a good preservational state- were observed throughout unit  
 276 LU3. Subunit LU3b is dominated by almost-monospecific foraminifera assemblages, composed of  
 277 *Ammonia tepida* and *Criboelphidium gunteri* (Supplement 3). Mollusks *Theodoxus* sp., *Bithynia*  
 278 *tentaculata*, *Turritella* sp. were recognized.



279  
 280 Fig. 4. Downcore variability of grain size, MS, elemental ratios obtained using XRF core scanner, TOC  
 281 and CaCO<sub>3</sub> content, and C/N ratios in sediment core LK-12.



282  
 283 Fig. 5. Downcore variability of grain size, MS, elemental ratios obtained using XRF core scanner, TOC  
 284 and CaCO<sub>3</sub> content, and C/N ratios in sediment core LK-15.

285 Sediments of the topmost unit LU4 in core LK-12 (204-0 cm), deposited from 10.5 cal kyr B.P.  
 286 to the present, were distinguished by its brown color and coarsening-upwards succession (Fig. 4).  
 287 Significant percentages of sand fraction were measured (up to 20%), in comparison with the previously  
 288 described units. Lithological unit LU4 is characterized by an evident increase in MS ( $2.5\text{--}28.3 \times 10^{-5}$  SI),  
 289 as shown in Fig. 4. The dominant mineral phase is quartz, whereas calcite, aragonite and dolomite are  
 290 also abundant. The Sr/Ca ratios exhibit an abrupt transition from unit LU3 into LU4 (Fig. 4). A peak in  
 291 Ti/Ca ratio was observed at 168 cm, followed by a decrease towards the top of the core. A significant  
 292 variations of C/N ratios were detected (7.95-23.57), whereas TOC content was generally low  
 293 throughout the unit (0.49-2.4%). From 206 cm (transition LU3/LU4) foraminifera abundances increase.  
 294 The assemblages are composed of *Elphidium translucens*, *Epistominella exuiga*, *Asterigerinata*  
 295 *adriatica* and *Textularia conica* specimens (Supplement 3). Mollusks *Mytilus* sp. and *Cerastoderma* sp.  
 296 were recognized.

297 Sediment core LK-15 was subdivided into two lithological units (Figs. 3 and 4). Differentiated  
 298 units in sediment cores LK-12 and LK-15 are challenging to correlate, with the exception of the topmost

299 unit, because they have been deposited in different settings as evidenced by seismic data (Fig. 2). The  
300 similarities in the sediment composition of the topmost unit LU4, in cores LK-12 and LK-15, can be  
301 observed in Figs. 4 and 5. However, LU4 is less thick in core LK-15 (135-0 cm), and encompasses a  
302 shorter time interval (10.3 cal kyr B.P.-present). Sediments of units LU1 and LU3, recognized in core  
303 LK-12, are missing in core LK-15. However, additional lithological unit (LU2b) was distinguished in core  
304 LK-15. There are certain similarities in the geochemical composition of this unit and lithological unit  
305 LU2a from sediment core LK-12.

306 Faint laminations and possible dewatering structures were recognized in sediments from the  
307 lowermost unit LU2b in core LK-15 (480-135 cm). Generally, silty sediments are characterized by high  
308 Ca/Ti ratios and CaCO<sub>3</sub> content (up to 80.52%). Occasionally, pebble-sized carbonate clasts were  
309 embedded in a matrix. The main mineralogical constituent of LU2b sediments is calcite. Both TOC  
310 content (1.06-3.6%) and C/N ratios (10.32-17.55) are relatively high (Fig. 5). This unit is devoid of  
311 macrofossils, apart from the poorly preserved gastropod shell at a core depth of 392 cm.

## 312 **5. Discussion**

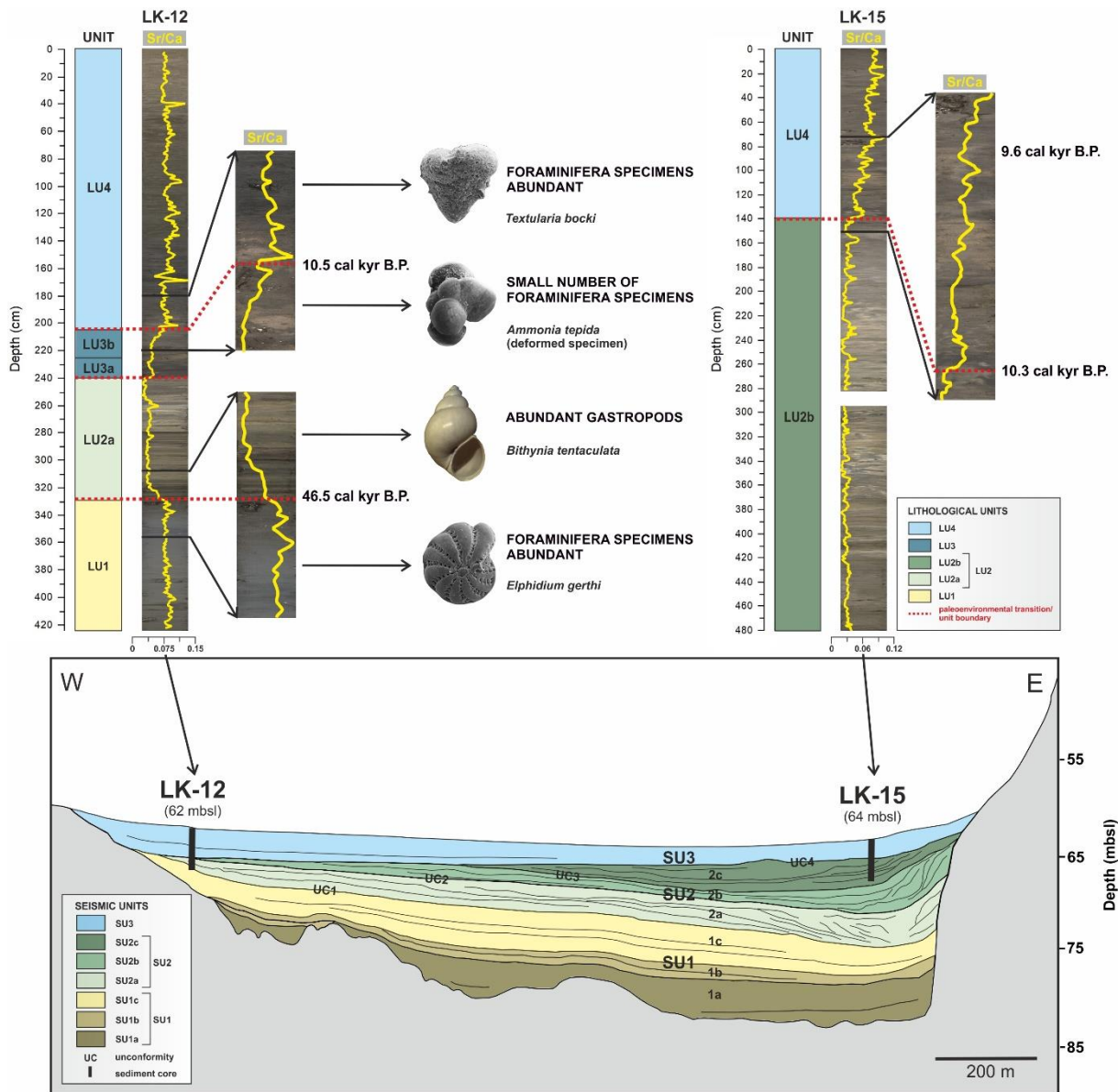
313           The sediment infill preserved in the Lošinj Channel karst basin reveals a dynamic depositional  
314 history of the study area during the Late Pleistocene and Holocene. The comparison of all results  
315 obtained via multi-proxy analysis of sediment cores LK-12 and LK-15 and correlation with seismic data  
316 enabled the unravelling of this history. The dated sediment succession can be divided into several  
317 paleoenvironmental phases primarily governed by climate changes, sea level oscillations, and basin  
318 geomorphology of the study area. Each paleoenvironmental phase will be discussed below considering  
319 (i) conditions in the depositional environment inferred from seismic and sediment core data (ii) global  
320 and RSL changes in relation to the depth of the Cres sill.

### 321 **5.1. Marine phase (>46.5 cal kyr B.P.)**

#### 322 **5.1.1. Paleoenvironmental reconstruction based on seismic and core data**

323           Sediments that were deposited at the bottom of the silled basin were not penetrated by  
324 sediment cores (Fig. 2). Therefore, in this paper, we will not discuss the paleoenvironmental history of  
325 the Lošinj Channel during the deposition of sediments from seismic subunits SU1a and SU1b. The  
326 overlying acoustically semi-transparent seismic subunit SU1c onlaps (marine onlap) onto the acoustic  
327 basement in the western part of the basin. Carbonate rocks that occur on the surrounding islands  
328 constitute the acoustic basement, whereas the upper part of the acoustic basement (B1) exhibits  
329 amorphous acoustic facies representing karstified carbonates (Fig. 2). As evidenced by the core-to-  
330 seismic correlation, subunit SU1c corresponds to the basal part of the sediment core LK-12 (LU1) (Fig.  
331 6 and Table 2). Several analyzed parameters in lithological unit LU1 show distinctive patterns, based  
332 on which we were able to interpret the paleoenvironmental conditions in the Lošinj karst basin during  
333 the deposition of sediments from this unit. The carbonate content is moderate to high throughout the  
334 succession, emphasizing both marine and karst influence. However, the most important geochemical  
335 feature of LU1 is the high Sr/Ca ratio, which can be used as a proxy of shallow marine environmental

336 conditions in the study area (Figs. 6 and 7A). The Sr-enriched seawater enables the precipitation of  
337 aragonite in marine environment, contributing to the high Sr/Ca ratios (Croudace et al., 2006; Goudeau  
338 et al., 2014; Filikci et al., 2017; Çağatay et al., 2019). The presence of aragonite in this interval is also  
339 supported by XRD. Indicators for terrestrially sourced lithogenic material (e.g., Ti/Ca) (Bahr et al., 2005;  
340 Blanchet et al., 2013; Croudace and Rothwell, 2015) show significant input of siliciclastics from soil  
341 erosion from the catchment into the Lošinj basin (Figs. 4 and 7B). This is also evidenced by relatively  
342 high MS (Fig. 4). The obtained data suggest that despite the prevalence of marine conditions, input of  
343 terrestrially sourced material, possibly as a result of humid climate conditions and/or proximity of the  
344 coring location to the coast, was important. The Mn/Fe ratio is frequently used as a proxy of redox  
345 conditions (Haenssler et al., 2014; Croudace and Rothwell, 2015). The low values of Mn/Fe in LU1 likely  
346 indicate that the Lošinj basin was not a fully oxygenated environment. We believe that in this unit,  
347 Mn/Fe could be used as a proxy of redox conditions due to the poor correlation of Mn and terrestrial  
348 elements (e.g., Ti) and Mn and trace metals (e.g., Zn) (Fig. 7C,D). Therefore, the existence of an  
349 enclosed marine environment with limited water circulation due to the presence of the submerged sill  
350 is postulated (Figs. 8A and 9A). Density stratification, and resulting anoxic conditions, in silled marine  
351 basins has been reported and described in environmental studies of the enclosed Black Sea (Major et  
352 al., 2002; Aksu et al., 2002). In the established marine environment in the Lošinj basin productivity was  
353 low (<TOC), whereas preserved organic matter was aquatically sourced (<C/N; Meyers, 1994; Meyers,  
354 2003; Lamb et al., 2006). Diverse foraminiferal assemblages and rich marine molluscan fauna support  
355 the existence of marine environmental conditions (Fig. 6). The dominant foraminifera species  
356 *Aubignyna planidorso*, *Elphidium translucens* and *Ammonia tepida* usually inhabit shallow marine-to-  
357 brackish water environments (Murray et al., 2000; Debenay and Guillou, 2002; Murray, 2006).



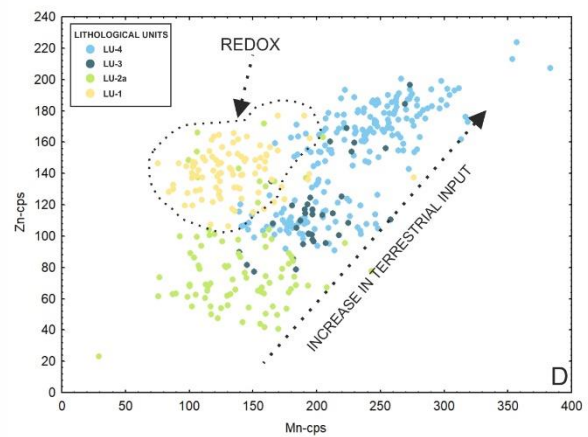
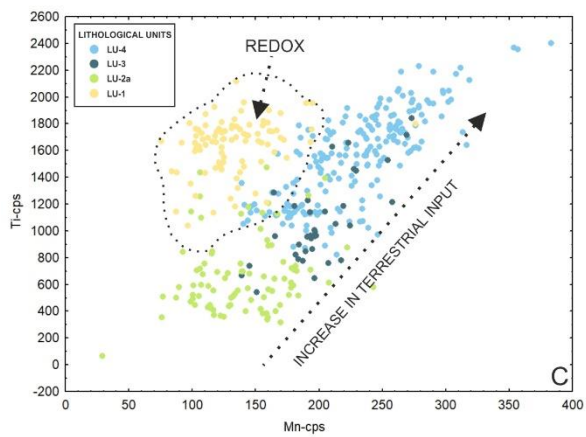
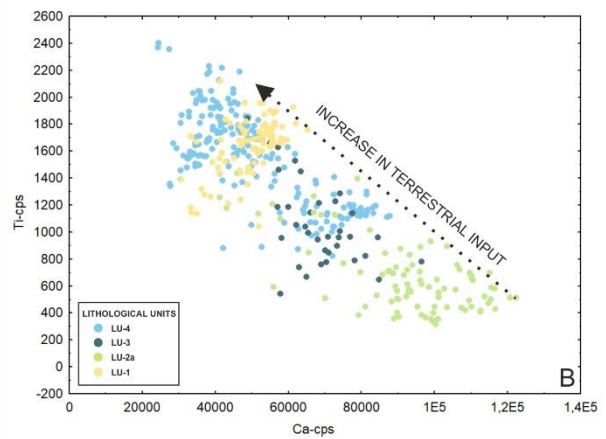
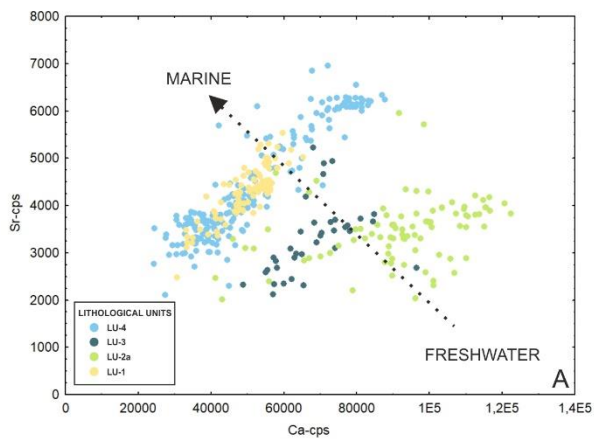
358

359 Fig. 6. Illustration of seismic and lithological units. Variations in Sr/Ca ratios in sediment cores LK-12  
 360 and LK-15 are plotted and main paleontological components of differentiated units are shown.

361 Table 2. Correlation of recognized seismic and lithological units.

Seismic unit and unconformity	Seismic subunit	Lithological unit	Lithological subunit	Core depth	Stage/Epoch	Depositional environment	Figs. 8,9
SU1	a				Pleistocene		
	b				Pleistocene		
	c	LU1		LK-12 (422-329 cm)	MIS 5a	MARINE ENVIRONMENT	A
UC1		HIATUS			MIS 4	KARST POLJE	B
SU2	a	LU2	a	LK-12 (329-240 cm)	MIS 3	LACUSTRINE ENVIRONMENT	C
UC2		HIATUS					
SU2	b						
UC3		HIATUS			MIS 3/MIS 2	KARST POLJE	D
SU2	c	LU2	b	LK-15 (480-135 cm)			
UC4		HIATUS					
SU3		LU3	a	LK-12 (240-226 cm)	MIS 2	MARSH OR SHALLOW LAKE	E
			b	LK-12 (226-204 cm)		MARINE LAKE	E
		LU4		LK-12 (204-0 cm)	MIS 1	MARINE ENVIRONMENT	F, G
				LK-15 (135-0 cm)			

362



363

364 Fig. 7. Scatterplots of A) Ca (cps) against Sr (cps), B) Ca (cps) against Ti (cps), C) Mn (cps) against Ti (cps),  
365 D) Mn (cps) against Zn (cps). Sediment core LK-12 was subdivided into units representing different  
366 depositional environments: LU1- marine; LU2a- lacustrine; LU3- marine lake; LU4-marine.

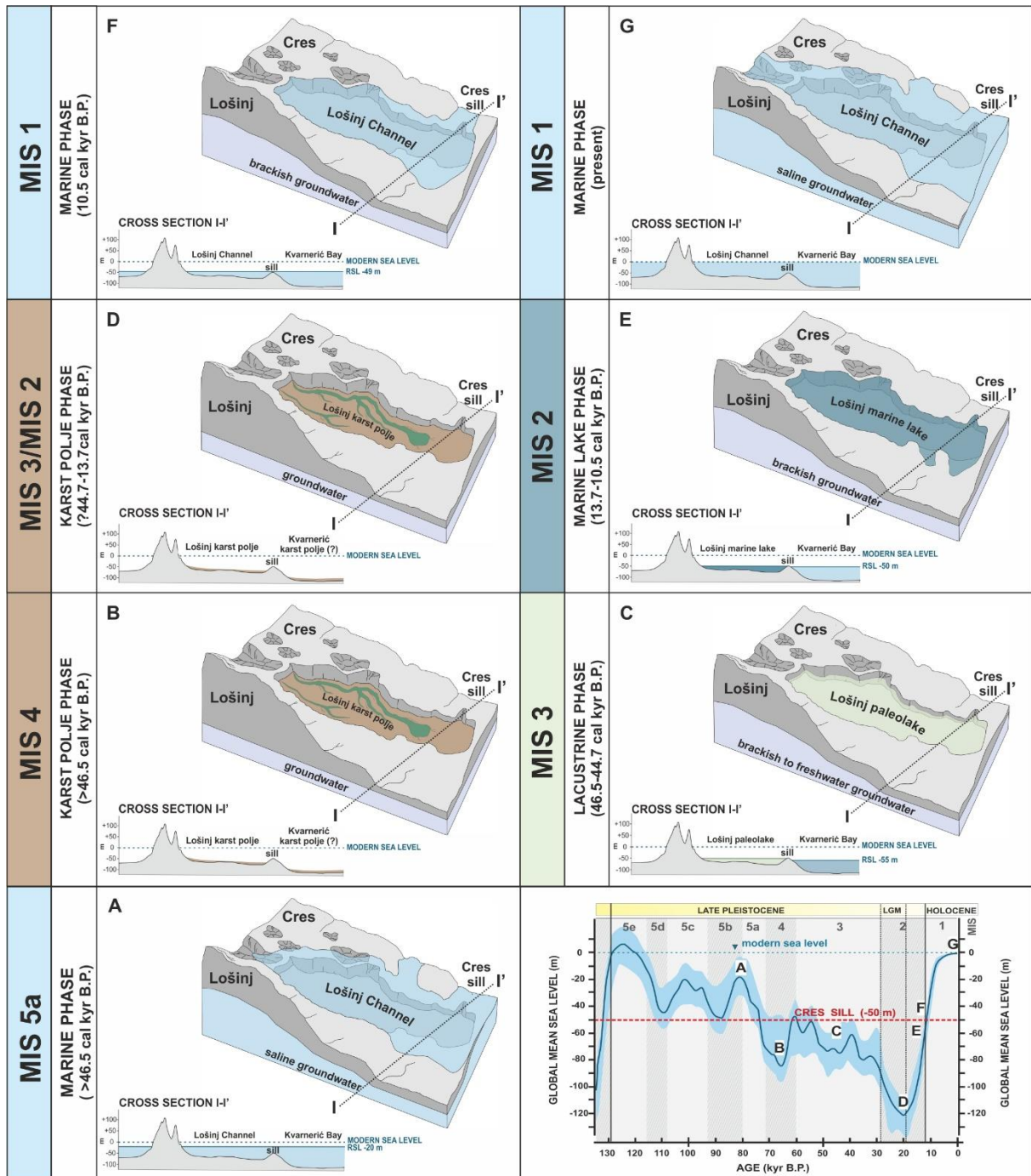
### 367 **5.1.2 Paleoenvironmental reconstruction considering sea level fluctuations and sill depth**

368 The age of the described marine succession can only be hypothesized. The base of the  
369 overlying unit LU2a in sediment core LK-12 has been dated at 46.5 cal kyr B.P. (MIS 3). Therefore, the  
370 deposition of marine sediments corresponding to seismic subunit SU1c and lithological unit LU1  
371 occurred before that time. It is possible that sediments were deposited during the older MIS 3, MIS 4  
372 or MIS 5. However, for marine environmental conditions to develop in the Lošinj Channel, RSL needs  
373 to be > -50 m, which corresponds to the deepest point of the present-day Cres sill that separates the  
374 Lošinj Channel from the Kvarnerić Bay. It is considered that sea level was > -50 m only during MIS 5,  
375 based on global and regional sea level data for this period (Waelbroeck et al., 2002; Dorale et al., 2010).  
376 Previously conducted research in the Kvarner region by Surić et al. (2009) reported 2 sea level  
377 highstands during MIS 5a. The sea level was higher than -14.5 m from 87-82 kyr, whereas from 90-82  
378 kyr and from 77-64 kyr RSL was higher than -18.8 m. Therefore, we propose the deposition of the  
379 described marine succession during the youngest part of MIS 5 (MIS 5a) (Figs. 8A and 9A). Surić et al.  
380 (2009, 2014) also stressed possible tectonic activity in the region. In the case in which the Kvarner area  
381 was indeed affected by tectonic uplift since MIS 5a, the Cres sill was possibly also uplifted. However,  
382 the study area where uplift rates were estimated (Island of Krk) has a different tectonic setting  
383 compared to the area investigated in the present study (Korbar, 2009). Therefore, uplift rates have not  
384 been applied and further research regarding the tectonic setting of the Kvarner region must be  
385 conducted to fully comprehend possible tectonically triggered variations in the Cres sill depth that had  
386 a fundamental impact on the flooding or isolation of the Lošinj basin during the Quaternary. We  
387 emphasize our uncertainty in the estimation of the age of the marine succession due to the inability



388 to date material, and the proposed MIS 5a age should be interpreted cautiously until substantiated  
389 with additional evidence.

390           Whereas MIS 5a deposits have been investigated in the western and central Adriatic (Amorosi  
391 et al., 2004; Ridente et al., 2008; Piva et al., 2008), marine deposits attributed to the MIS 5a have not  
392 been found along the eastern coast of the Adriatic Sea so far. It appears that the possible deposition  
393 of MIS 5a sediments deep in the subsurface of the Lošinj Channel is not necessarily a consequence of  
394 subsidence but rather a peculiar geomorphological setting, with a generally steep coast and deep karst  
395 depressions that accumulate sediments. The same can be hypothesized for MIS 5e marine deposits,  
396 which have not yet been recorded with certainty along the eastern Adriatic coast (Babić et al., 2012).  
397 If during this time period sea level was above the present level in the study area, MIS 5e deposits were  
398 accumulated at the bottom of the deep karst depressions and potentially in the coastal area. However,  
399 subsequent erosion events could have eroded coastal MIS 5e deposits during the latter lowstand  
400 periods.



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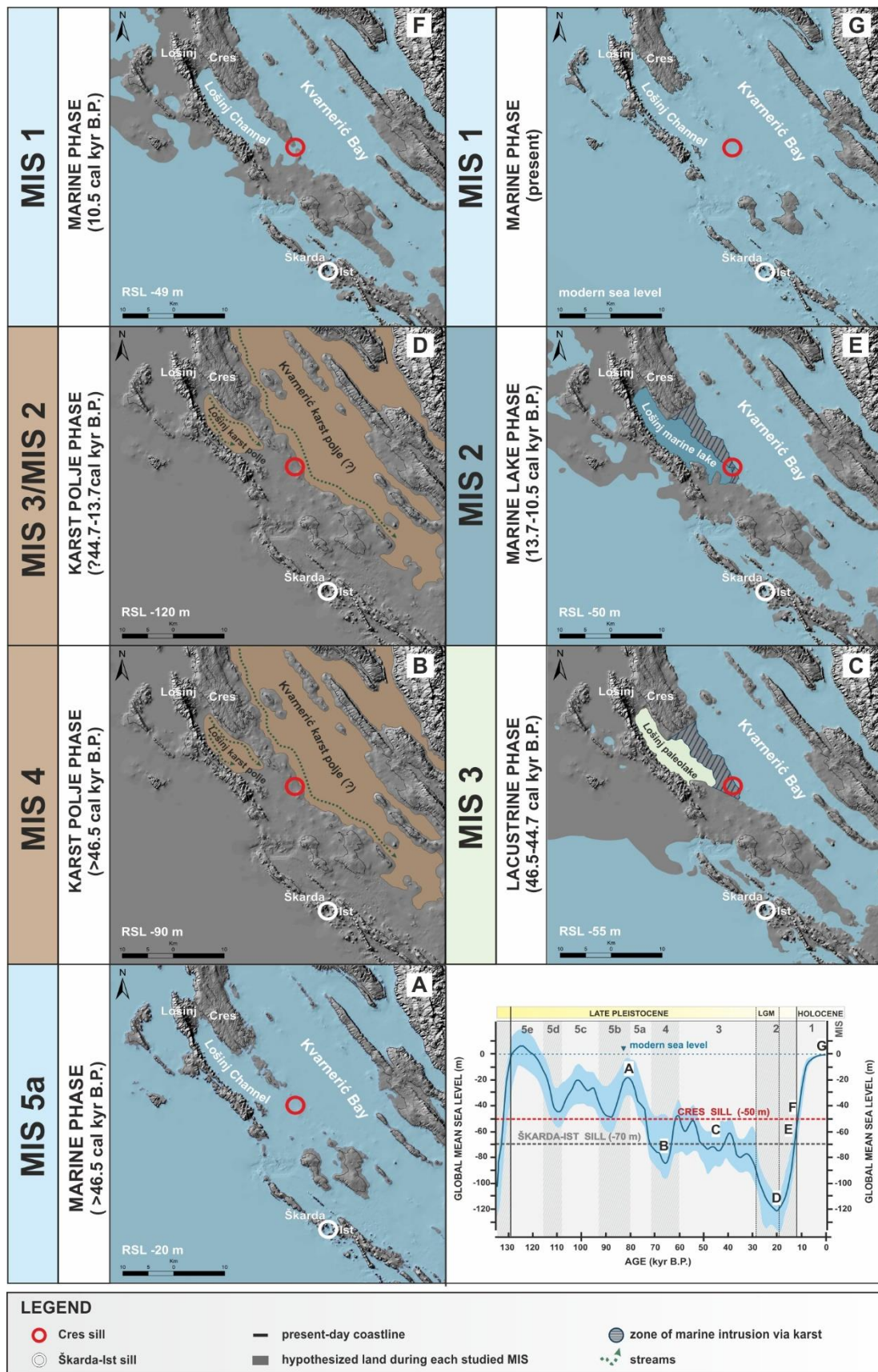
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Fig. 8. Schematic paleoenvironmental reconstructions of the Lošinj Channel karst basin during the Late Pleistocene and Holocene and schematic cross-sections of the Lošinj basin with a marked connection to the Kvarnerić Bay RSL. A) MIS 5a marine environment. B) MIS 4 karst polje. C) MIS 3 Lošinj paleolake. D) MIS 3/MIS 2 karst polje phase with periodical streams. E) Lošinj marine lake during MIS 2 (Allerød interstadial). F) Seawater flooding of the Lošinj marine lake at 10.5 cal kyr B.P. G) Holocene marine environment. Each environmental phase is marked with corresponding letter on the Middle

408 Pleistocene-Holocene eustatic sea level curve (Waelbroeck et al., 2002; modified from Benjamin et al.,  
409 2017).



410

411 Fig 9. Schematic Late Pleistocene and Holocene palaeogeographic maps of the Lošinj Channel karst

412 basin, based on bathymetric data (Tk25 topographic map to the scale 1:25 000, State Geodetic

413 Administration-Croatia), global sea level curve (Waelbroeck et al., 2002) and data from this study. A)  
414 MIS 5a marine environment (with hypothesized RSL at -20 m). B) MIS 4 karst polje (with hypothesized  
415 RSL at -90 m). C) MIS 3 Lošinj palaeolake (with hypothesized RSL at -55 m). D) MIS 3/MIS 2 karst polje  
416 with periodical streams (with hypothesized RSL at -120 m). E) Lošinj marine lake during MIS 2 (Allerød  
417 interstadial) (with hypothesized RSL at -50 m). F) Seawater flooding of the Lošinj marine lake at 10.5  
418 cal kyr B.P (with hypothesized RSL at -49 m). G) Holocene marine environment (modern sea level). The  
419 red circle marks the location of the Cres sill (-50 m). The white circle marks the location of Škarda-Ist  
420 sill (-70 m). Each environmental phase is marked with corresponding letter on the Middle Pleistocene-  
421 Holocene eustatic sea level curve (Waelbroeck et al., 2002; modified from Benjamin et al., 2017).

## 422 **5.2. Karst polje phase (>46.5 cal kyr B.P.)**

### 423 **5.2.1. Paleoenvironmental reconstruction based on seismic and core data**

424 An erosion event has been observed in the seismic data in the form of the strong reflector  
425 (UC1) between seismic units SU1 and SU2 (Fig. 2). In sediment core LK-12, this event could be detected  
426 as a very sharp contact between 2 different lithologies (units LU1 and LU2a) (Fig. 6).

### 427 **5.2.2. Paleoenvironmental reconstruction considering sea level fluctuations and sill depth**

428 Without a precise core chronology, it is difficult to estimate the existence and nature of this  
429 hiatus. It is possible that the UC1 is related to the MIS 4 lowstand. During this stage, the sea level was  
430 approximately 80-90 m lower than at present (Rohling et al., 2014), which could have caused the drop  
431 in the groundwater level and the development of a terrestrial environment in the investigated area  
432 (Lošinj karst polje) (Figs. 8B and 9B). Similar karst forms are present today along the eastern Adriatic  
433 coast (Ford and Williams, 2007; Bonacci, 2013; Kranjc, 2013).

## 434 **5.3. Lacustrine phase (46.5-44.7 cal kyr B.P.)**

### 435 **5.3.1. Paleoenvironmental reconstruction based on seismic and core data**

436 Both seismic (subunit SU2a) and LK-12 core data (unit LU2a) provided clear evidence of a  
437 distinctly different depositional environment at 46.5 cal kyr B.P., compared to the previously described  
438 marine succession (Fig. 6). Geometry of the bands of the reflectors of SU2a implies the deposition of  
439 layered sediments with different lithologic properties. The general increases in  $\text{CaCO}_3$  and Ca/Ti, with  
440 the dominant presence of calcite as the primary carbonate phase in lithological unit LU2a, is indicative  
441 of the development of the lacustrine environment (Lošinj paleolake). High carbonate content is  
442 common for deposition in karst lakes (Valero-Garcés et al., 2014; Hajek-Tadesse et al., 2018; Ilijanić et  
443 al., 2018). The cessation of marine conditions is also supported by a strong decrease in the Sr/Ca ratios  
444 (Fig. 6).

445 Smaller variations in certain geochemical proxies reveal the existence of somewhat different  
446 environmental conditions at the onset and end of the recorded lacustrine phase (Fig. 4). First, dark and  
447 laminated sediments were dominated by terrestrial organic matter. The significant increase in TOC  
448 content, with values >4%, results from the rise in productivity most likely due to the formation of an  
449 isolated and very shallow environment (shallow lake or marsh). An organic-rich sediment succession is  
450 characterized by the presence of Chara remains, implying deposition in a shallow freshwater  
451 environment. The upper part of unit LU2a, with dark and light laminations, is characterized by algal  
452 organic matter and the higher carbonate content (Fig. 4). This change within LU2a possibly reflects the  
453 deepening of the Lošinj paleolake and variations in the main organic matter source over time. Aeolian  
454 material could also contribute to the deposition in the Lošinj paleolake, as evidenced by the increase  
455 in grain size (Fig. 4). Strong winds in the region during MIS 3 were assumed in the research of aeolian  
456 and pedosedimentary successions conducted by Wacha et al. (2011a,b; 2017) and Mikulčić-Pavlaković  
457 et al. (2011) on the nearby Island of Susak. The presence of brackish-to-freshwater macrofossil  
458 assemblages throughout LU2a proves the development of a predominantly freshwater lacustrine body  
459 with limited marine influence. The recognized mollusk genera (*Bithynia tentaculata*) usually inhabit  
460 freshwater environments (Seddon, 2014), but they are tolerant to a wider salinity range (Carlsson,  
461 2006; Cadée, 2015). The presence of foraminifera specimens that are poorly preserved could be

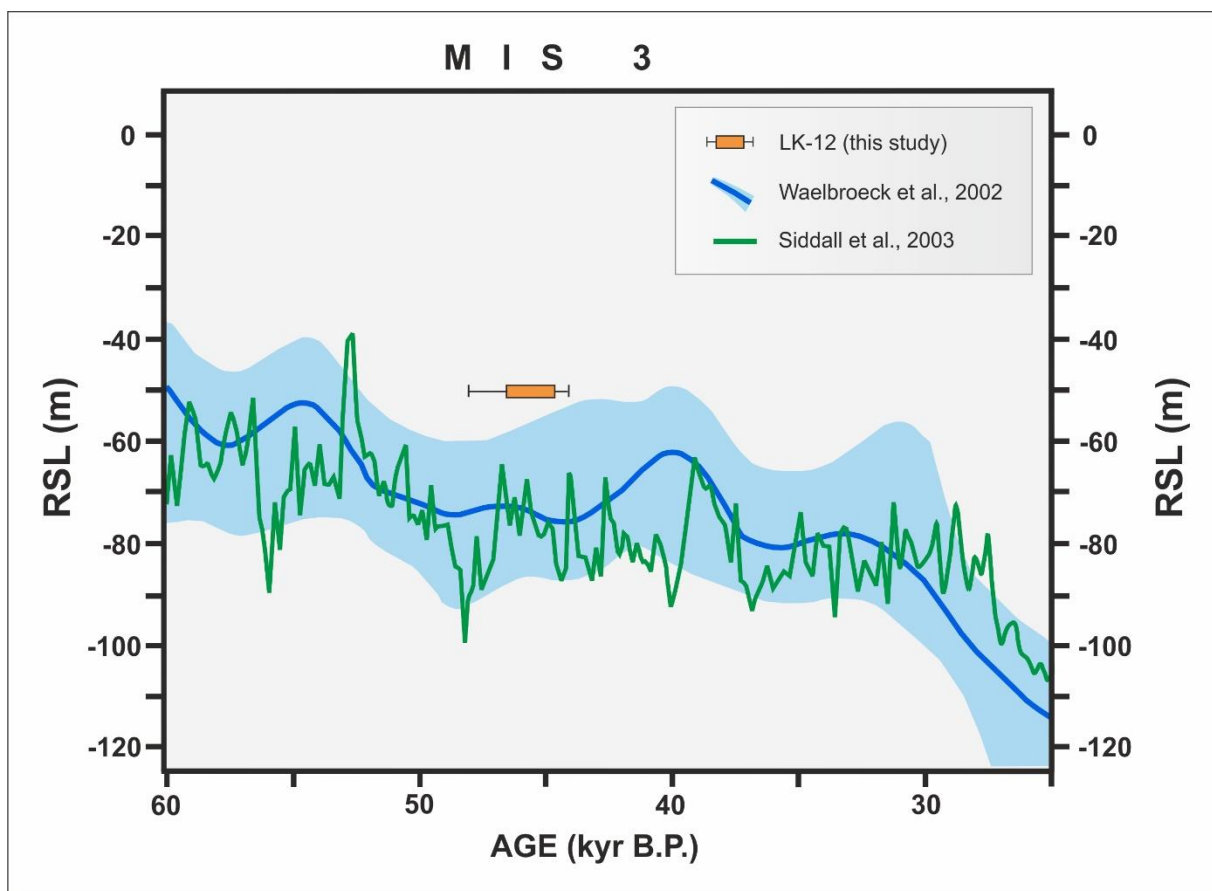
462 indicative of the establishment of unfavorable environmental conditions for their preservation, or they  
463 could be reworked.

### 464 **5.3.2. Paleoenvironmental reconstruction considering sea level fluctuations and sill depth**

465 A sea level rise after the MIS 4 lowstand probably led to a rise in the groundwater table in the  
466 investigated area and a karst lake was formed during MIS 3 (46.5 - 44.7 cal kyr B.P.) (Figs. 8C and 9C).  
467 The formation of the Lošinj paleolake was probably facilitated by favorable climatic conditions in the  
468 region. MIS 3 is characterized by significant variations in climate and sea level on centennial and  
469 millennial time scales (Siddall et al., 2008; Rasmussen et al., 2014; Badino et al., 2019). The presence  
470 of lacustrine sediments in the Lošinj basin suggests that the RSL between 46.5 - 44.7 cal kyr B.P. was  
471 below the Cres sill depth of -50 m (sea level limiting point; Fig. 10). Global sea level data placed MIS 3  
472 sea level at -60 to -90 m (Waelbroeck et al., 2002; Siddall et al., 2003; Siddall et al., 2008; Rohling et  
473 al., 2008) (Fig. 10). Previously conducted studies in the Kvarner area also implied that MIS 3 RSL was  
474 50-60 m lower than at present (Surić et al., 2014), which would have enabled marine flooding of the  
475 Kvarnerić Bay through Škarda-Ist sill. Therefore, it is likely that during this time interval Kvarnerić Bay  
476 was a marine environment. However, the Cres sill (-50 m) acted as a barrier, allowing the formation of  
477 an isolated Lošinj paleolake (Fig. 9C). Possible seawater seepage from the Kvarnerić Bay to the Lošinj  
478 paleolake, as evidenced by brackish fauna, occurred through karstified limestones in the southeastern  
479 part of the investigated area where the limestone barrier is narrow. A preserved 89-cm-thick lacustrine  
480 sequence proved dynamic environmental conditions in the study area during this stage. It is likely that  
481 the Lošinj paleolake existed for a longer time period, but deposits were eroded or possibly never  
482 deposited in the investigated part of the Lošinj basin due to the basin morphology (Fig. 2).

483 The existence of lacustrine deposits below postglacial marine deposits in karst depressions  
484 along the eastern Adriatic coast has only been hypothesized and partially proved (Juračić et al., 1999;  
485 Wunsam et al., 1999; Schmidt et al., 2001). This research provides clear evidence of the development  
486 of a restricted, lacustrine environment with possible marine influence during MIS 3 sea level lowstand

487 (Figs. 8C and 9C). A similar paleoenvironmental evolution has been investigated in the Black Sea and  
488 Marmara Sea (Çağatay et al., 2003; Bahr et al., 2005; Taviani et al., 2014; Filikci et al., 2017), where  
489 lacustrine deposits preceded the Holocene marine deposition due to the existence of a sill. The  
490 distinctiveness of the Lošinj paleolake is that it was formed during MIS 3 in a karstified environment.  
491 Furthermore, MIS 3 lacustrine or marine deposits have not been previously reported with certainty  
492 along the eastern Adriatic coast, although sedimentary records of this age have been studied along the  
493 western coast of the Adriatic Sea (Amorosi et al., 2004).



494

495 Fig. 10. MIS 3 sea level limiting point from the Lošinj Channel (LK-12) plotted against global eustatic  
496 sea level curve by Waelbroeck et al. (2002) (blue line) and sea level curve given by Siddall et al. (2003)  
497 (green line).



## 498 **5.4. Karst polje phase (?44.7-13.7 cal kyr B.P.)**

### 499 **5.4.1. Paleoenvironmental reconstruction based on seismic and core data**

500 Seismic data revealed the existence of several phases of erosion within SU2 and between SU2  
501 and SU3. These events were recognized as high amplitude unconformities (UC2, UC3 and UC4) that  
502 truncate underlying reflectors (Fig. 2). Evidence of these events can also be observed in core LK-12. An  
503 age-depth model provided an age of the top of lower laminated lacustrine lithological unit (LU2a) of  
504 44.7 cal kyr B.P., whereas the upper brown homogenous unit (LU3) was dated at 13.7 cal kyr B.P (Fig.  
505 3). This suggests the existence of a long erosional and/or depositional hiatus in LK-12 coring area.  
506 However, the basal part of sediment core LK-15 (lithological unit LU2b) corresponds to the seismic  
507 subunit SU2c, deposited after the development of UC3 and prior to the development of UC4 (Fig. 6  
508 and Table 2). The results revealed the deposition of predominantly chaotic silty sediments, with high  
509 carbonate content. It is possible that LU2b sediments are redeposited lacustrine sediments. The  
510 occurrence of larger gravel-sized carbonate clasts that were most likely eroded from the surrounding  
511 islands was observed. This part of the core is almost devoid of macropaleontological remains, except  
512 for a few heavily fragmented gastropod shells, indicating unfavorable conditions for their preservation  
513 and/or transport. Time constraints on the deposition of these sediments cannot be obtained, since  
514 reliable and datable material is not present.

### 515 **5.4.2. Paleoenvironmental reconstruction considering sea level fluctuations and sill depth**

516 We suggest that with the substantial decrease in sea level leading to the LGM (Fairbanks, 1989;  
517 Lambeck and Purcell, 2005; Lambeck et al., 2014), lacustrine deposition in the Lošinj basin ceased due  
518 to the drop in the groundwater table. Therefore, favorable conditions for the formation of a karst polje  
519 were established again (Figs. 8D and 9D). Periodical streams in a karst polje most likely partially eroded  
520 previously deposited MIS 3 lacustrine sediments. We assume that the clasts found in basal part of LK-  
521 15 core were deposited during the discharge periods. It is probable that phases of lacustrine and karst  
522 polje environments exchanged in the Lošinj basin during the Last Glacial cycle in relation to the

523 oscillations in the RSL and climate, whereas in the northern Adriatic Shelf a large alluvial plain has been  
524 developed (Fig. 1B) (e.g., Amorosi et al., 2003; Pellegrini et al., 2018).

## 525 **5.5. Marine lake phase (13.7-10.5 cal kyr B.P.)**

### 526 **5.5.1. Paleoenvironmental reconstruction based on seismic and core data**

527 Re-establishment of sediment accumulation in the area where sediment core LK-12 was  
528 collected commenced at 13.7 cal kyr B.P. (subunits LU3a and LU3b) (Fig. 6). Sediments from these  
529 lithological subunits can probably be attributed to the base of the semi-transparent seismic unit SU3,  
530 deposited after UC4 erosional event (Table 2). Acoustically semi-transparent seismic unit SU3 onlaps  
531 (marine onlap) onto the previously described units and acoustic basement (Fig. 2). Sediments  
532 attributed to LU3 are organic-rich (TOC >2%) and predominantly silty. A gradual increase in the Sr/Ca  
533 ratios implies a growing marine influence in the Lošinj basin (Fig. 6). Two distinct paleoenvironmental  
534 subphases were recognized in the period from 13.7 cal kyr B.P. to 10.5 cal kyr B.P., corresponding to  
535 the lithological subunits LU3a and LU3b in core LK-12 (Fig. 6).

536 High Ti/Ca ratios and MS, during the first subphase from 13.7-13.6 cal kyr B.P. (LU3a), indicate  
537 significant siliciclastic terrestrial input, most likely due to the proximity of the coast to the coring  
538 location. It is probable that erosion and redeposition of sediments were significant during this phase.  
539 This could also suggest enhanced precipitation in the investigated area. Increase in terrestrial input  
540 during Bølling-Allerød was also observed in other parts of the Adriatic Sea (Goudeau et al., 2014). The  
541 contribution of algal organic matter in subunit LU3a was less important compared to terrestrially  
542 derived organic matter, as evidenced by higher C/N ratios (Fig. 4). The results imply the development  
543 of a shallow water environment with increased productivity. It is probable that a marsh or a shallow  
544 lake was formed during this subphase. This interpretation was reinforced by mollusk assemblages that  
545 are typical for freshwater-to-brackish-water conditions (*Theodoxus* sp., *Bithynia tentaculata*). In the  
546 analyzed samples, shallow marine or brackish water foraminifera species *Aubignyna planidorso*,

547 *Elphidium translucens* and *Ammonia tepida* (Murray et al., 2000; Debenay and Guillou, 2002; Murray,  
548 2006) were present, indicating the marine influence.

549 At 13.6 cal kyr B.P. (subunit LU3b), a marked change in sedimentation occurred. Sediments in  
550 this subunit show increased CaCO<sub>3</sub> and TOC content, with poorly preserved laminations. The organic  
551 matter is predominantly of algal source (Meyers, 1994; Meyers, 2003; Lamb et al., 2006). Terrestrial  
552 input proxies (Ti/Ca, MS) account for a smaller contribution of the detrital sediment component. This  
553 might indicate a phase of arid conditions in the area at 13.6 cal kyr B.P. and prior to the onset of the  
554 Younger Dryas or shoreline migration and establishment of a deeper lacustrine environment. Rich  
555 molluscan fauna (*Theodoxus* sp., *Bithynia tentaculata*) support the existence of brackish water  
556 environmental conditions. Foraminifera specimens are well preserved and slightly more abundant  
557 compared to LU3a, implying a growing marine influence. The dominant species (*Ammonia tepida* and  
558 *Criboelphidium gunteri*) can dwell in brackish water environments (Debenay and Guillou, 2002;  
559 Boudreau et al., 2001), and their abundances in the analyzed samples are high.

#### 560 **5.5.2. Paleoenvironmental reconstruction considering sea level fluctuations and sill depth**

561 We propose that the formation of shallow and eventually deeper brackish water lacustrine  
562 environment (marine lake) in the Lošinj karst basin, occurred with the rapidly rising sea level during  
563 the Allerød interstadial, at 13.7 cal kyr B.P. The onset of the abrupt post-LGM sea level rise (Waelbroek  
564 et al., 2002; Lambeck et al., 2014) led to the rise in the groundwater table in the investigated area. The  
565 data obtained in this study suggest that RSL in the Lošinj Channel during the Allerød was <-50 m. It is  
566 considered that during the Allerød interstadial, the global sea level was approximately -75 to -60 m  
567 lower than at present (Waelbroeck et al., 2002; Lambeck et al., 2014). It is probable that during this  
568 time period Kvarnerić Bay was a marine environment (Fig. 9E). However, the Cres sill was again a  
569 barrier that isolated the Lošinj marine lake from the direct marine influence from the Kvarnerić Bay  
570 (Figs. 8E and 9E). The formation of marine lake was aided by strong diffusion of seawater through  
571 karstified Cres sill from the Kvarnerić Bay and high precipitation. Similar environments have been

572 recognized along the present-day eastern Adriatic coast (e.g., Mljet Lakes, Lake Mir, Zmajevsko oko)  
573 (Surić, 2002; Surić, 2005; Pikelj and Juračić, 2013).

574 Although the Allerød sediment sequence in the Lošinj basin is well preserved, Schmidt et al.  
575 (2000) have postulated that a gap in sedimentation occurred during the Allerød interstadial in the  
576 nearby Lake Vrana on the Island of Cres. In the same time frame, the paleoenvironmental evolution of  
577 the northern Adriatic shelf was significantly different, with alluvial channels and plains developed  
578 during the LGM exhibiting retrogradational patterns (e.g., Amorosi et al., 2003; Correggiari et al., 2005;  
579 Moscon et al., 2015; Benjamin et al., 2017).

## 580 **5.6. Marine phase (10.5 cal kyr B.P.-present)**

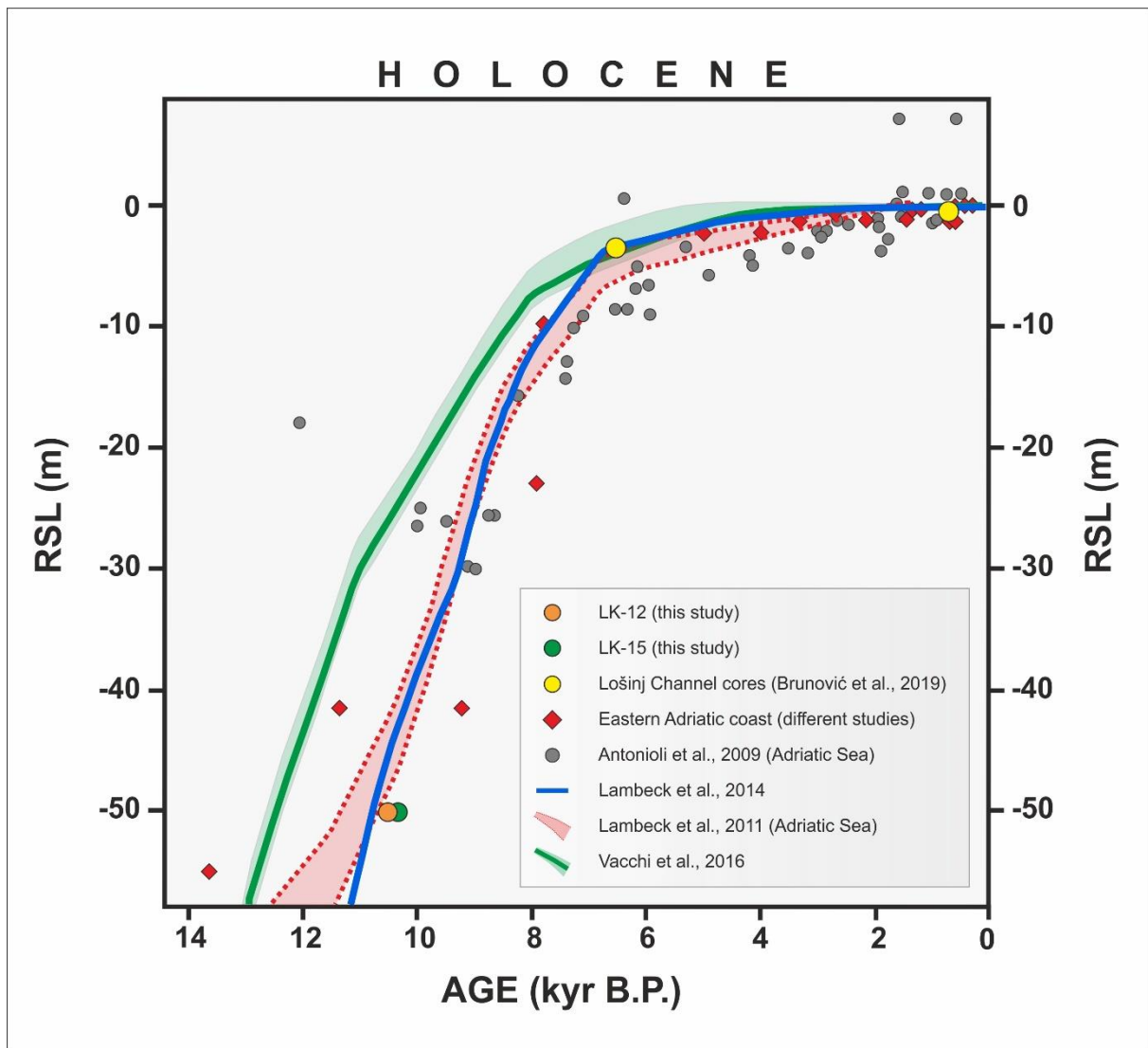
### 581 **5.6.1. Paleoenvironmental reconstruction based on seismic and core data**

582 An environmental phase during which the Lošinj marine lake was a restricted environment,  
583 without surface connection to the sea on the other side of the Cres sill, existed for approximately 3000  
584 years. At 10.5 cal kyr B.P., a noticeable shift can be observed in the multi-proxy data from sediment  
585 core LK-12 (unit LU4) (Fig. 6). In sediment core LK-15 this transition was dated at 10.3 cal kyr B.P.  
586 Seismic data (SU3) also indicated the deposition of sediments with different lithologic properties (Fig.  
587 2 and Table 2). The Sr/Ca ratio abruptly increased (Fig. 6), implying marine flooding of the Lošinj karst  
588 basin (Figs. 8F and 9F). The Holocene marine sedimentary succession is characterized by a coarser  
589 grain-size, low productivity, terrestrial organic matter input and a rise in terrigenous siliciclastic input  
590 (high MS, Ti/Ca) (Fig. 4). This rise is likely related to the onset of a pluvial period with intensified soil  
591 erosion from the catchment. The Holocene pluvial period has been previously described in the Adriatic  
592 Sea (Wunsam et al., 1999; Schmidt et al., 2000; Schmidt et al., 2001; Combourieu-Nebout et al., 2013).  
593 The topmost part of the core LK-12 (from 37 cm upcore) is characterized by decreases in MS and Ti/Ca  
594 ratios at 5.8 cal kyr B.P., which could mark the end of the humid climate conditions. This is in general  
595 accordance with the previously published data (Wunsam et al., 1999; Schmidt et al., 2001;  
596 Combourieu-Nebout et al., 2013). Paleontological analysis provided strong evidence of surface

597 connectivity with the Kvarnerić Bay (Fig. 6). Typical marine mollusks appear (*Mytilus* sp., *Cerastoderma*  
598 sp.), and foraminifera specimens become significantly more abundant and diversified compared to the  
599 previous phase. Assemblages are dominated by *Elphidium translucens*, *Epistominella exuiga*,  
600 *Asterigerinata adriatica* and *Textularia conica*. The recognized Holocene assemblage is similar to  
601 assemblages described in greater water depth and high productivity environments along the eastern  
602 Adriatic coast (Vidović, 2010).

### 603 **5.6.2. Paleoenvironmental reconstruction considering sea level fluctuations and sill depth**

604         Based on the two analyzed sediment cores, we have determined with confidence that sea level  
605 reached the Cres sill depth of -50 m during the Holocene, in the period between 10.5-10.3 cal kyr B.P.  
606 At that time RSL was high enough for marine sedimentation to occur and Cres sill no longer had a  
607 function of a barrier (Figs. 8F and 9F). Many papers assessed the Holocene RSL changes in the Adriatic  
608 (e.g., Lambeck et al., 2004, 2011; Antonioli et al., 2009; Faivre et al., 2011, 2013; Vacchi et al., 2016;  
609 Shaw et al., 2016, 2018). However, most of the observational data are of Late Holocene age and were  
610 collected along the western coast of the Adriatic Sea. In Fig. 11 we compared our RSL data with the  
611 already published observational RSL evidence from the region (Malez et al., 1979; Wunsam et al., 1999;  
612 Govorčin et al., 2001; Schmidt et al., 2001; Surić et al., 2004; Antonioli et al., 2009; Surić and Juračić,  
613 2010; Faivre et al., 2013; Brunović et al., 2019), predicted RSL obtained using the models published for  
614 the Adriatic Sea and Mediterranean (Lambeck et al., 2011, Vacchi et al., 2016), and eustatic sea level  
615 changes (Lambeck et al., 2014). We highlight the possibility that the Lošinj basin data suggest a tectonic  
616 subsidence of the area during the Holocene, considering that the observed data lie below the predicted  
617 and eustatic values. The Holocene subsidence trends along the eastern Adriatic coast have been  
618 previously reported by Antonioli et al. (2009), Faivre et al. (2011; 2019) and Shaw et al. (2018).  
619 However, we also do not dismiss the possibility that the Lošinj basin was flooded with seawater before  
620 10.5 cal kyr B.P when marine sedimentation started. Therefore, the obtained data are sea level limiting  
621 points.



622  
 623 Fig. 11. The Holocene RSL observations from this study (LK-12 and LK-15), Adriatic Sea (Antonioli et al.,  
 624 2009) and eastern Adriatic coast (Malez et al., 1979; Wunsam et al., 1999; Govorčin et al., 2001;  
 625 Schmidt et al., 2001; Surić et al., 2005; Surić and Juračić, 2010; Faivre et al., 2013) plotted against  
 626 eustatic sea level curve by Lambeck et al., 2014 (blue line), and regional RSL models by Lambeck et al.  
 627 (2011) (red line) and Vacchi et al. (2016) (green line). Previously published sea level data from the  
 628 Lošinj Channel are also plotted on the graph (Brunović et al., 2019).

## 629           **6. Conclusions**

630           This research provided an insight into the long-term Late Pleistocene and Holocene  
631 paleoenvironmental development of the Lošinj Channel. A crucial factor for preservation of the thick  
632 Quaternary sediment succession is the geomorphological setting of the eastern Adriatic coast. Silled  
633 karst basins, such as the Lošinj Channel, act as a trap for sediments and therefore contain long records  
634 of paleoenvironmental changes. These changes were driven by substantial sea level and climate  
635 variations that occurred during the Quaternary glacial-interglacial transitions.

636           Extracted sediment cores LK-12 and LK-15 and seismic reflection profile revealed a complex  
637 suite of very different depositional environments in the Lošinj karst basin. The combined use of  
638 geochemical, sedimentological, and paleontological proxies combined with radiocarbon dating are  
639 shown to be valuable indicators for the interpretation of past environments in these settings. Our  
640 results include a presumed MIS 5a marine sediment succession deposited when the RSL was higher  
641 than -50 m Cres sill depth. An important feature is the development of a brackish-to-freshwater Lošinj  
642 paleolake during MIS 3. This is significant since it suggests the presence of an isolated lacustrine karst  
643 basin along the eastern Adriatic coast. The sea level drop that followed was characterized by the  
644 formation of a karst polje, with the probable occurrence of periodic streams. The post-LGM period was  
645 marked by re-establishment of the deposition in a brackish water marine lake. The RSL reached a depth  
646 of -50 m at 10.5 cal kyr B.P., which led to a marine flooding of the Lošinj Channel. The obtained data  
647 are important for the reconstruction of RSL and climate variations along the eastern Adriatic coast.  
648 Furthermore, the investigated submerged karst basin enhances our understanding of  
649 paleoenvironmental development in karstified systems and implies the formation of brackish water  
650 conditions prior to the actual flooding of the basin due to the rising sea level.

651           Further importance of our study stems from the fact that only 15 cores included in the  
652 Mediterranean sediment core database published by Alberico et al. (2017) penetrated the Younger  
653 Dryas boundary. Therefore, the Lošinj Channel data are also significant on a wider regional scale.

654           Although this research provided many new observations, some questions still remain  
655           unanswered. The age of older marine succession and possible variations in the depth of the Cres sill in  
656           relation to the vertical tectonic movements and glacio-hydro-isostatic adjustment should be  
657           investigated in the future. We can also assume that there is a cyclicity in the development of  
658           depositional environments in the deep silled karst depressions, which even further stresses the  
659           importance of the eastern Adriatic coast for Quaternary research.

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