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

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Abstract

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

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

1. Introduction

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

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

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

The research conducted so far along the eastern coast of the Adriatic Sea has indicated different paleoenvironmental evolution of this area. The existence of submerged lacustrine environments (paleolakes) along the eastern coast of the Adriatic Sea was suggested by Juračić et al. (1999), who proposed the development of brackish or freshwater lacustrine environments during the glacial sea level lowstands. Schmidt et al. (2001) and Wunsam et al. (1999) described the Last Glacial and Holocene lacustrine deposits that preceded the onset of the marine deposition in the Valun Bay in the Kvarner region and Mljet Lakes in the southern Dalmatia. Recent studies based on marine sediment cores are mostly limited to the Holocene (Faivre et al., 2011; Marriner et al., 2014; Felja et al., 2015; Shaw et al., 2016; Brunović et al., 2019). Research that encompasses a long-term high-resolution Pleistocene sedimentary record is still missing. Data regarding RSL and climate variations in the eastern Adriatic during the Pleistocene have been mostly derived from analysis of submerged speleothems. Evidence of these changes is presented in the research published by Surić et al. (2005, 2009) and Surić and Juračić (2010).

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

2. Regional setting

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

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

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

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

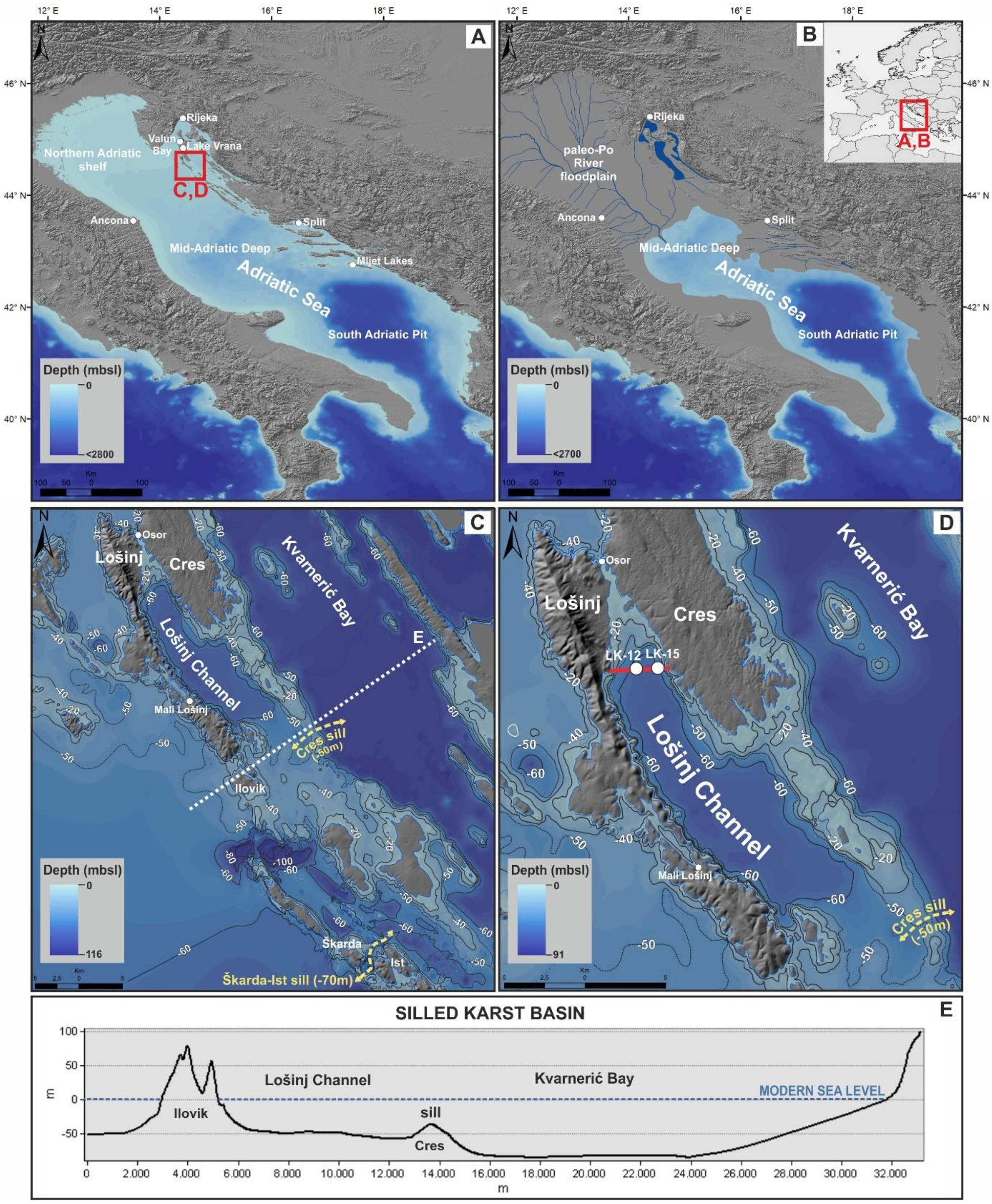

Fig. 1. Maps and cross-section of the investigated area. A) Map of the present-day Adriatic Sea. B) Schematic map of the Adriatic Sea during the LGM (western Adriatic coast is modified from Maselli et al., 2011 and Maselli and Trincardi, 2013; eastern Adriatic coast is reconstructed using bathymetry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

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

3. Materials and methods

3.1. High-resolution seismic survey

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

3.2. Sediment cores

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

3.3. Sediment core analysis

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

3.3.1. Magnetic susceptibility

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

3.3.2. Grain size

The grain size analyses were carried out on 148 samples using a Shimadzu SALD-2300 laser diffraction particle size analyzer. To analyze the grain size distribution of the siliciclastic component in the carbonate-rich environment, it was necessary to remove both organic material with hydrogen peroxide (H_2O_2) and carbonates with hydrochloric acid (HCl) (Murray, 2002). Furthermore, sodium hexametaphospate ($(NaPO_3)_6$) was added to the samples to prevent particle aggregation, whereas larger mollusk shells were removed manually from the sediment prior to the pretreatment. Using the GRADISTAT software package (Blott and Pye, 2001), main statistical parameters were determined following the Folk and Ward (1957) method.

3.3.3. Mineralogy

Bulk mineralogical analyses were performed on selected powder samples taken throughout the cores using an X'Pert Powder diffractometer (XRD) equipped with Ni-filter CuKα radiation, a vertical goniometer with a θ/θ geometry, and a PIXcel detector. The scan conditions were set to 45 kV and 40 mA, alongside ¼ divergence and antiscatter slits, and with a step size of 0.02° 2θ and a 4 s time per step within a range between 4° 2θ and 66° 2θ.

3.3.4. XRF core scanning

The downcore relative elemental composition of sediment cores in 1 cm resolution was analyzed at the Institute of Marine Science (CNR-ISMAR) in Bologna using an AVAATECH µXRF core scanner. Analysis of the elemental composition was performed using an X-ray source with the voltage set to 10 and 30 kV, which enabled measurements of major and minor elements. The acquired XRF scanning data are semi-quantitative and reported as elemental ratios (Croudace et al., 2006).

3.3.5. Total organic and inorganic carbon and total nitrogen

Total organic (TOC) and inorganic carbon (TIC) and nitrogen (TN) abundances in 157 samples were determined using a Thermo Fisher Scientific Flash 2000 NC Analyzer. This method allows direct measurements of the total carbon (TC) and TN. The addition of HCl removes the carbonate component and allows the determination of TOC (Tung and Tanner, 2003). The difference between TC and TOC was used for calculation of TIC, whereas the calcium carbonate ($CaCO_3$) content was calculated from the obtained TIC values. The C/N ratio was calculated by dividing the TOC and TN.

3.3.6. Paleontology

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

3.3.7. Core chronology

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

The radiocarbon data were further analyzed using Clam software package (Blaauw, 2010) to obtain reliable age-depth models for each core. The marine reservoir age correction of 456±46 ($\Delta R=100\pm20$ ^{14}C yr) was adopted (Faivre et al., 2015). The ages obtained from the specimens of the freshwater mollusk species *Bithynia tentaculata* were also corrected for marine reservoir effects due to their stable isotopes shell values ($\delta^{13}C$=-1.6-+2.8), which are typical for growth in the water with marine influence (Stuiver and Polach, 1977). The Marine13 calibration curve was used for calibration of the obtained data into calendar years (Reimer et al., 2013).

4. Results

4.1. High-resolution seismic data

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

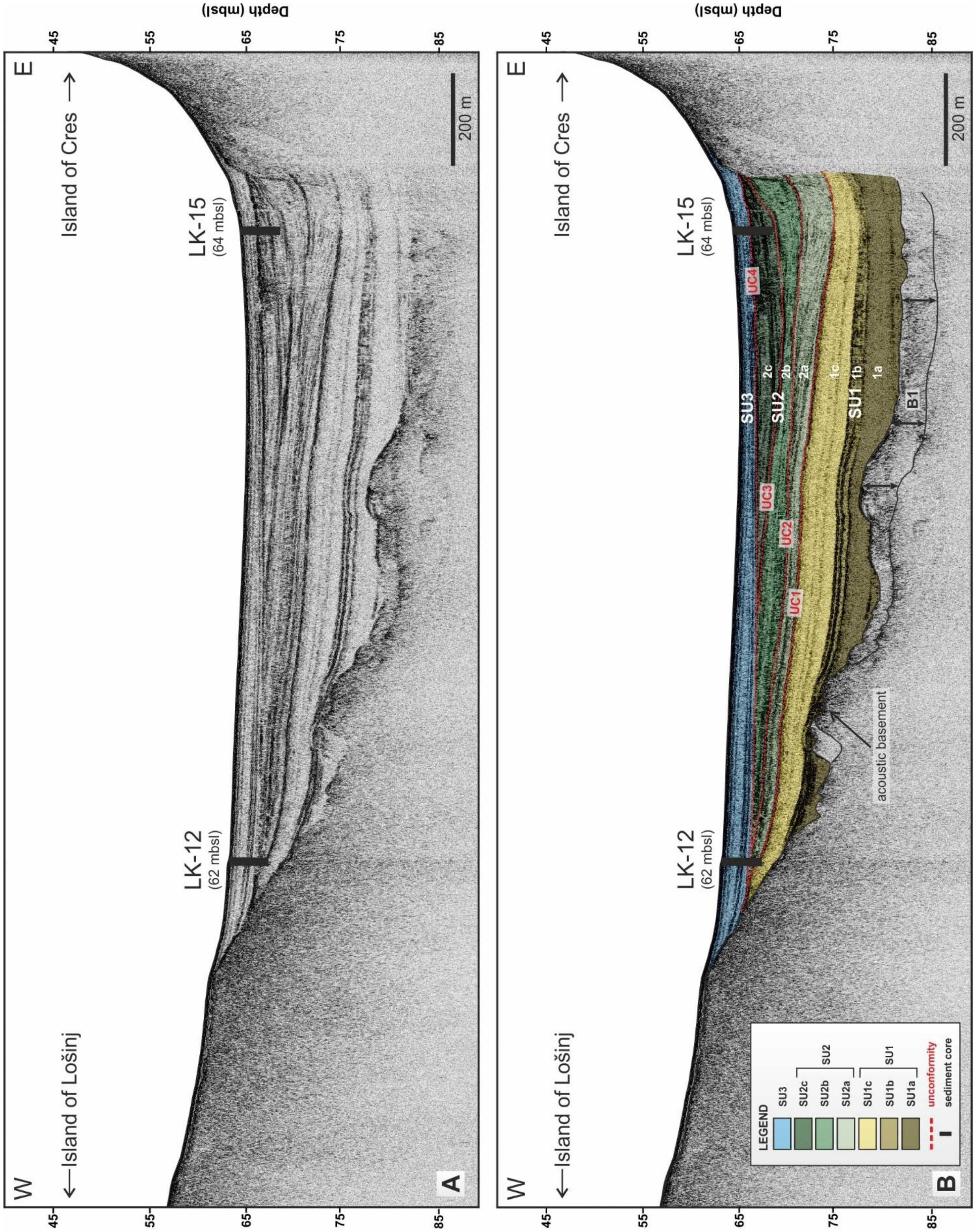

Fig. 2. (A) Seismic profile of Seismic line 1 and (B) its stratigraphic interpretation.

4.2. Sediment core data

4.2.1. Core chronology

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

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

Sediment core	Depth (cm)	Sample ID	Material	$\delta^{13}C$ (‰)	Conventional radiocarbon age (^{14}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

4.2.2. Core lithology and multi-proxy analysis

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

Sediment core LK-12 was subdivided into four lithological units (Fig. 3). Homogenous grey sediments of the lowermost lithological unit LU1 (>46.5 cal kyr B.P.), recognized in the interval from 422 to 329 cm, are predominantly constituted of high percentages of silt-sized particles (77-84%) (Fig. 4; Supplement 1). Magnetic susceptibility is low in this unit (2.9-13.7 × 10^{-5} SI), whereas the main mineralogical constituents of the bulk samples are quartz, dolomite, calcite and aragonite. The lowermost part of core LK-12 is characterized by high Sr/Ca and Ti/Ca ratios (Fig. 4). The TOC content (0.42-0.97%) and C/N ratios (7.95-13.57) are low. The $CaCO_3$ content vary between 41.61-56.43% (Fig. 4; Supplement 2). Benthic foraminiferal assemblages are dominated by species *Aubignyna planidorso*, *Elphidium translucens* and *Ammonia tepida*. The relative abundances of foraminifera specimens are provided in Supplement 3. Recognized mollusks include *Cerastoderma* sp., *Turritella* sp. and *Cerithium* sp. Significant number of fragmented shells was observed.

Sediments of the overlying unit LU2a in core LK-12 (329-240 cm; 46.5-44.7 cal kyr B.P) are distinguished by light and dark brown laminations (Fig. 3). This unit is characterized by a slightly coarser grain size and low MS (0.2-13.6 × 10^{-5} SI) (Fig. 4). Calcite predominantly builds sediments from LU2a, whereas quartz and dolomite are less abundant. The acquired XRF data exhibit an increase in Ca/Ti and a decrease in Sr/Ca ratios in LU2a. The Mn/Fe ratios abruptly increase in the interval from 277 to 240 cm. The Zr/Rb ratios reached maximum in the core interval from 286 to 254 cm (Fig. 4). The lower part of unit LU2a (329-281 cm) is composed of organic-rich sediments, with TOC content of up to 6.18% (Fig. 4). The upper part of this unit (281-240 cm) has a lighter color and is dominated by high $CaCO_3$ content (up to 77.7%). The C/N ratios vary between 11.36-22.19 (Fig. 4; Supplement 2). Foraminiferal analysis of 9 samples revealed poor preservation of foraminifera specimens and their low abundances. The exception is the sample from the core depth of 260-261 cm, in which a low number of well-preserved foraminifera specimens was observed. The mollusk fauna are dominated by *Bithynia tentaculata*. In the basal part of this unit, Chara oogonia are especially abundant.

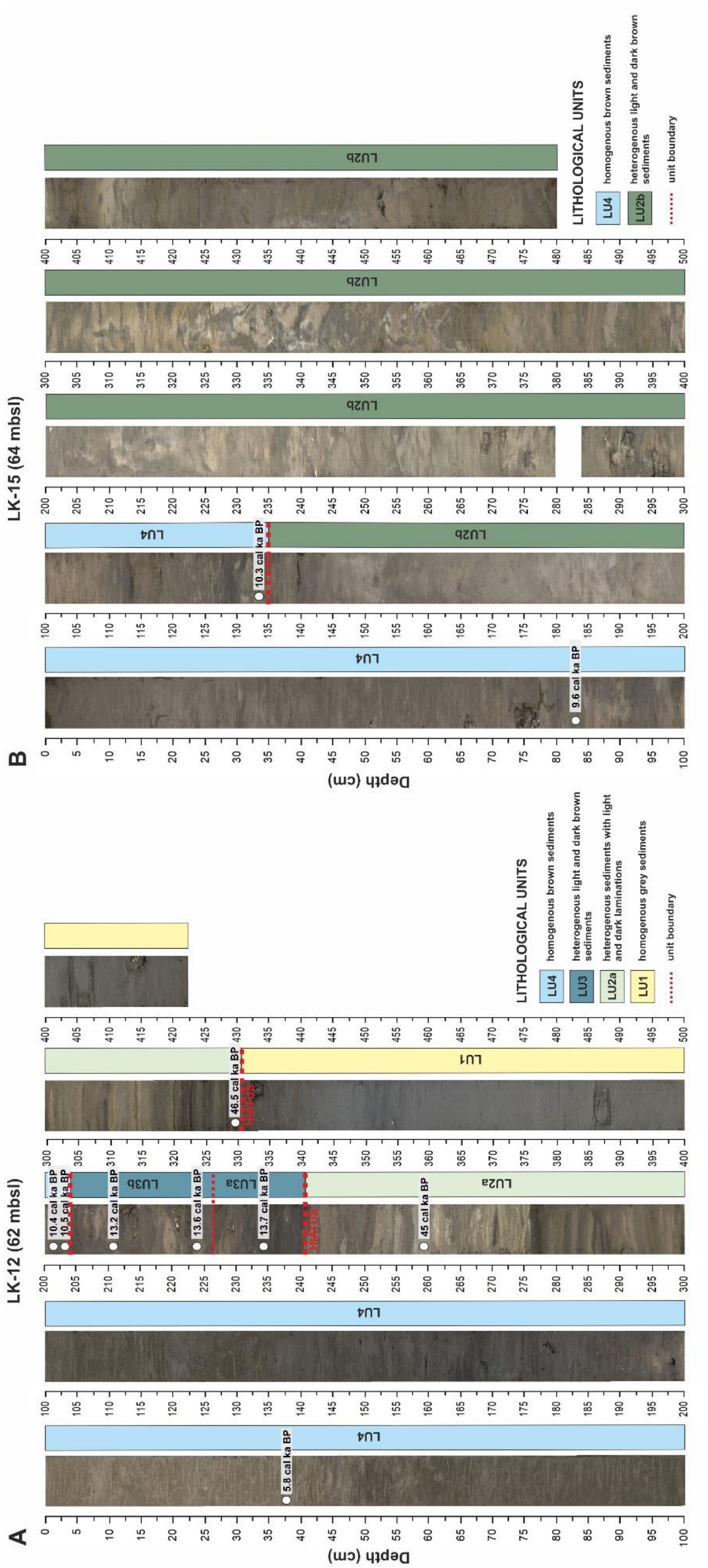

Fig. 3. Recognized lithological units in: A) sediment core LK-12, B) sediment core LK-15.

The third lithological unit LU3 is recognized in the core interval from 240-204 cm. Sediments from LU3 were deposited from 13.7 cal kyr B.P. to 10.5 cal kyr B.P. In the dark brown faintly-laminated sediments, silt-sized particles predominate (89-93%) (Fig. 4; Supplement 1). Quartz is the dominant mineral phase in all analyzed samples. Aragonite, calcite and dolomite were also determined. Significant variations in the obtained data enabled the differentiation of subunits LU3a and LU3b. High MS (up to 23.6 × 10^{-5} SI) was measured in the basal part of the unit (LU3a), whereas Ti/Ca ratios were also high. Fig. 4 demonstrates that after peaking in LU3a, C/N ratios decreased in LU3b (11.49-16.08). Towards the upper subunit, Ca/Ti, Sr/Ca and Mn/Fe ratios increased (Fig. 4). Subunit LU3b is characterized by $CaCO_3$ content of up to 60.9%, and higher TOC (2-4.2%) (Fig. 4; Supplement 2). A low number of foraminifera specimens -but in a good preservational state- were observed throughout unit LU3. Subunit LU3b is dominated by almost-monospecific foraminifera assemblages, composed of *Ammonia tepida* and *Cribroelphidium gunteri* (Supplement 3). Mollusks *Theodoxus* sp., *Bithynia tentaculata*, *Turritella* sp. were recognized.

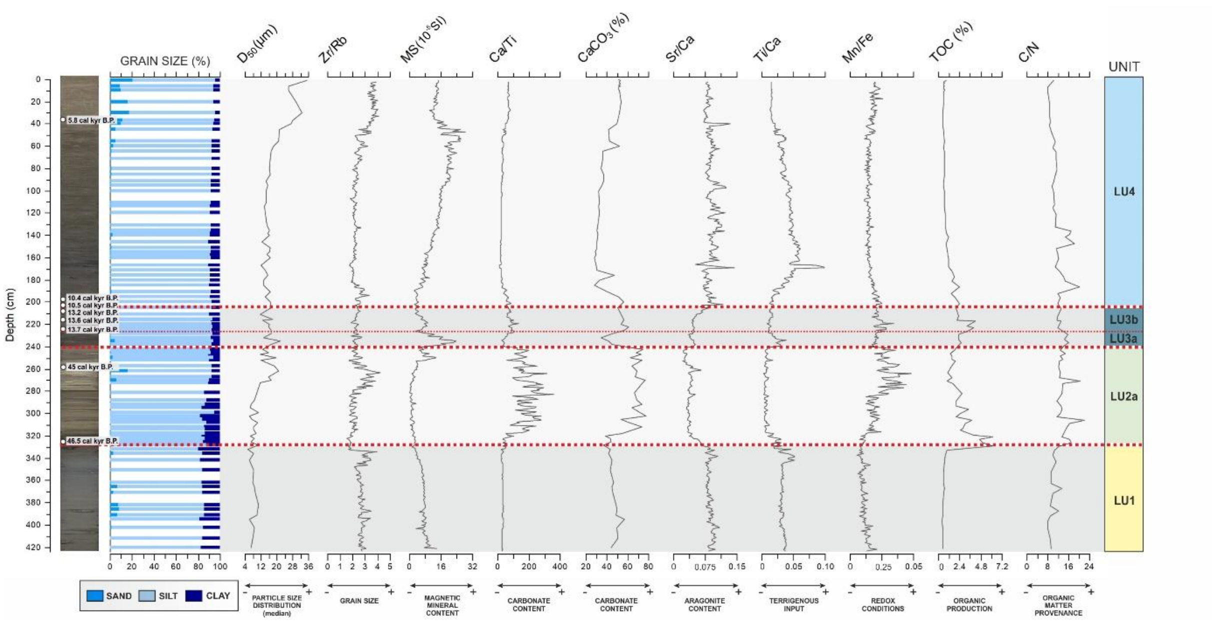

Fig. 4. Downcore variablility of grain size, MS, elemental ratios obtained using XRF core scanner, TOC and $CaCO_3$ content, and C/N ratios in sediment core LK-12.

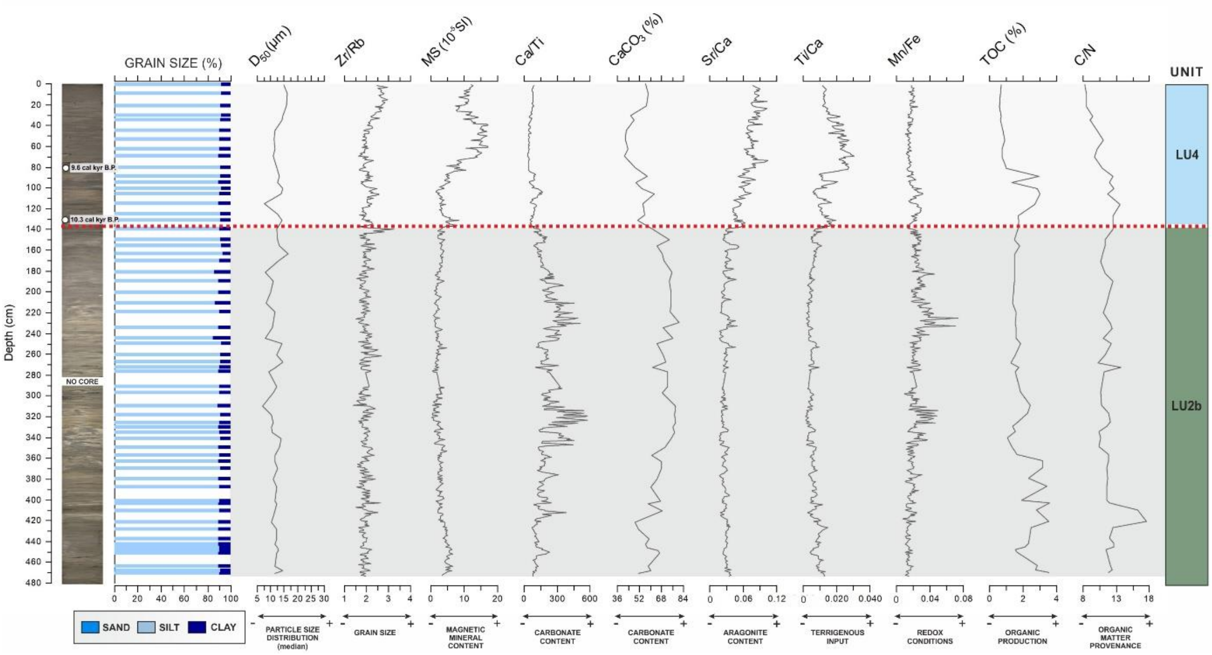

Fig. 5. Downcore variablility of grain size, MS, elemental ratios obtained using XRF core scanner, TOC and $CaCO_3$ content, and C/N ratios in sediment core LK-15.

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

Sediment core LK-15 was subdivided into two lithological units (Figs. 3 and 4). Differentiated units in sediment cores LK-12 and LK-15 are challenging to correlate, with the exception of the topmost unit, because they have been deposited in different settings as evidenced by seismic data (Fig. 2). The similarities in the sediment composition of the topmost unit LU4, in cores LK-12 and LK-15, can be observed in Figs. 4 and 5. However, LU4 is less thick in core LK-15 (135-0 cm), and encompasses a shorter time interval (10.3 cal kyr B.P.-present). Sediments of units LU1 and LU3, recognized in core LK-12, are missing in core LK-15. However, additional lithological unit (LU2b) was distinguished in core LK-15. There are certain similarities in the geochemical composition of this unit and lithological unit LU2a from sediment core LK-12.

Faint laminations and possible dewatering structures were recognized in sediments from the lowermost unit LU2b in core LK-15 (480-135 cm). Generally, silty sediments are characterized by high Ca/Ti ratios and $CaCO_3$ content (up to 80.52%). Occasionally, pebble-sized carbonate clasts were embedded in a matrix. The main mineralogical constituent of LU2b sediments is calcite. Both TOC content (1.06-3.6%) and C/N ratios (10.32-17.55) are relatively high (Fig. 5). This unit is devoid of macrofossils, apart from the poorly preserved gastropod shell at a core depth of 392 cm.

5. Discussion

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

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

5.1.1. Paleoenvironmental reconstruction based on seismic and core data

Sediments that were deposited at the bottom of the silled basin were not penetrated by sediment cores (Fig. 2). Therefore, in this paper, we will not discuss the paleoenvironmental history of the Lošinj Channel during the deposition of sediments from seismic subunits SU1a and SU1b. The overlying acoustically semi-transparent seismic subunit SU1c onlaps (marine onlap) onto the acoustic basement in the western part of the basin. Carbonate rocks that occur on the surrounding islands constitute the acoustic basement, whereas the upper part of the acoustic basement (B1) exhibits amorphous acoustic facies representing karstified carbonates (Fig. 2). As evidenced by the core-to-seismic correlation, subunit SU1c corresponds to the basal part of the sediment core LK-12 (LU1) (Fig. 6 and Table 2). Several analyzed parameters in lithological unit LU1 show distinctive patterns, based on which we were able to interpret the paleoenvironmental conditions in the Lošinj karst basin during the deposition of sediments from this unit. The carbonate content is moderate to high throughout the succession, emphasizing both marine and karst influence. However, the most important geochemical feature of LU1 is the high Sr/Ca ratio, which can be used as a proxy of shallow marine environmental conditions in the study area (Figs. 6 and 7A). The Sr-enriched seawater enables the precipitation of aragonite in marine environment, contributing to the high Sr/Ca ratios (Croudace et al., 2006; Goudeau et al., 2014; Filikci et al., 2017; Çağatay et al., 2019). The presence of aragonite in this interval is also supported by XRD. Indicators for terrestrially sourced lithogenic material (e.g., Ti/Ca) (Bahr et al., 2005; Blanchet et al., 2013; Croudace and Rothwell, 2015) show significant input of siliciclastics from soil erosion from the catchment into the Lošinj basin (Figs. 4 and 7B). This is also evidenced by relatively high MS (Fig. 4). The obtained data suggest that despite the prevalence of marine conditions, input of terrestrially sourced material, possibly as a result of humid climate conditions and/or proximity of the coring location to the coast, was important. The Mn/Fe ratio is frequently used as a proxy of redox conditions (Haenssler et al., 2014; Croudace and Rothwell, 2015). The low values of Mn/Fe in LU1 likely indicate that the Lošinj basin was not a fully oxygenated environment. We believe that in this unit, Mn/Fe could be used as a proxy of redox conditions due to the poor correlation of Mn and terrestrial elements (e.g., Ti) and Mn and trace metals (e.g., Zn) (Fig. 7C,D). Therefore, the existence of an enclosed marine environment with limited water circulation due to the presence of the submerged sill is postulated (Figs. 8A and 9A). Density stratification, and resulting anoxic conditions, in silled marine basins has been reported and described in environmental studies of the enclosed Black Sea (Major et al., 2002; Aksu et al., 2002). In the established marine environment in the Lošinj basin productivity was low (<TOC), whereas preserved organic matter was aquatically sourced (<C/N; Meyers, 1994; Meyers, 2003; Lamb et al., 2006). Diverse foraminiferal assemblages and rich marine molluskan fauna support the existence of marine environmental conditions (Fig. 6). The dominant foraminifera species *Aubignyna planidorso*, *Elphidium translucens* and *Ammonia tepida* usually inhabit shallow marine-to-brackish water environments (Murray et al., 2000; Debenay and Guillou, 2002; Murray, 2006).

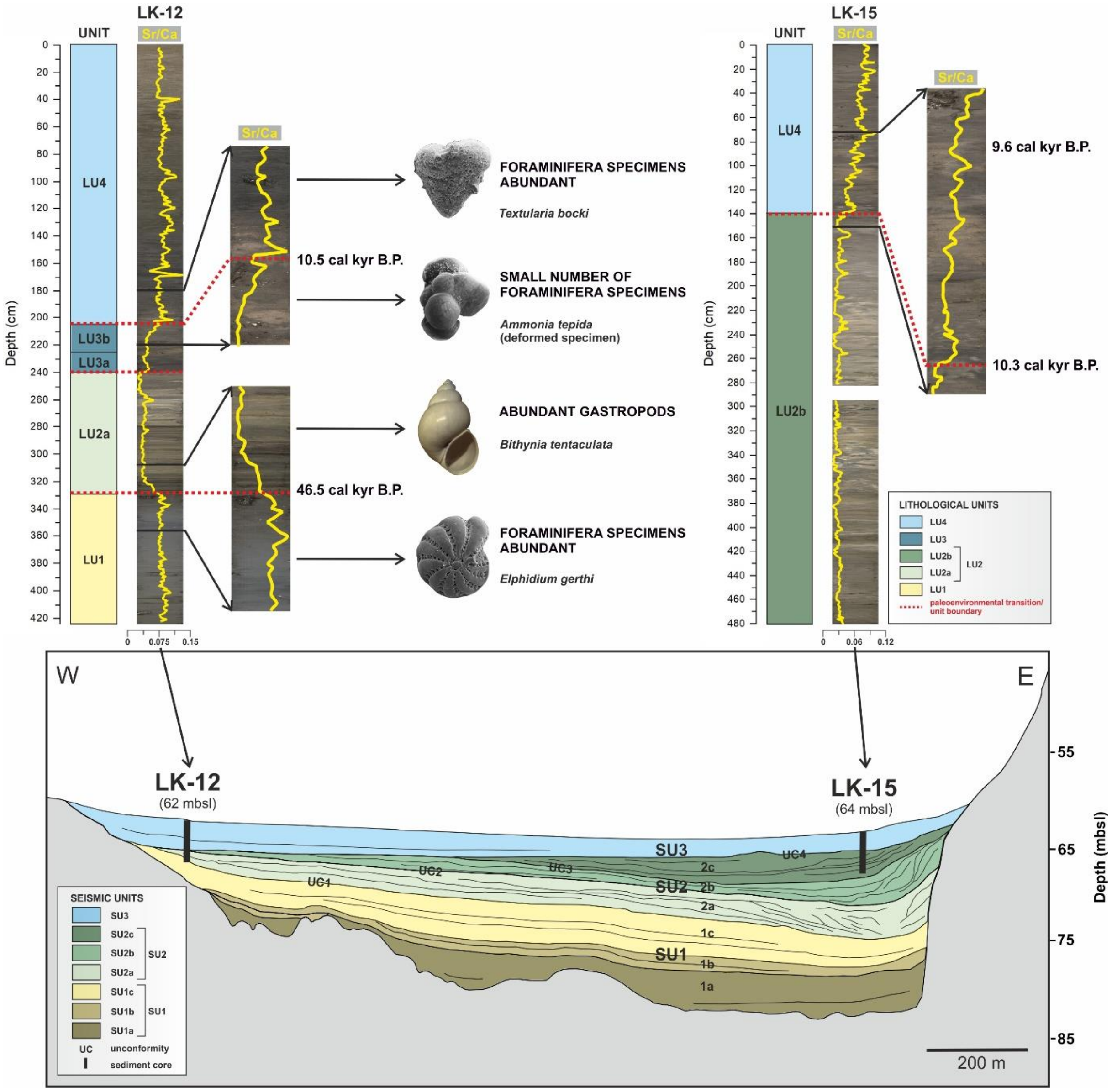

Fig. 6. Illustration of seismic and lithological units. Variations in Sr/Ca ratios in sediment cores LK-12 and LK-15 are plotted and main paleontological components of differentiated units are shown.

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) LK-15 (135-0 cm)	MIS 1	MARINE ENVIRONMENT	F, G

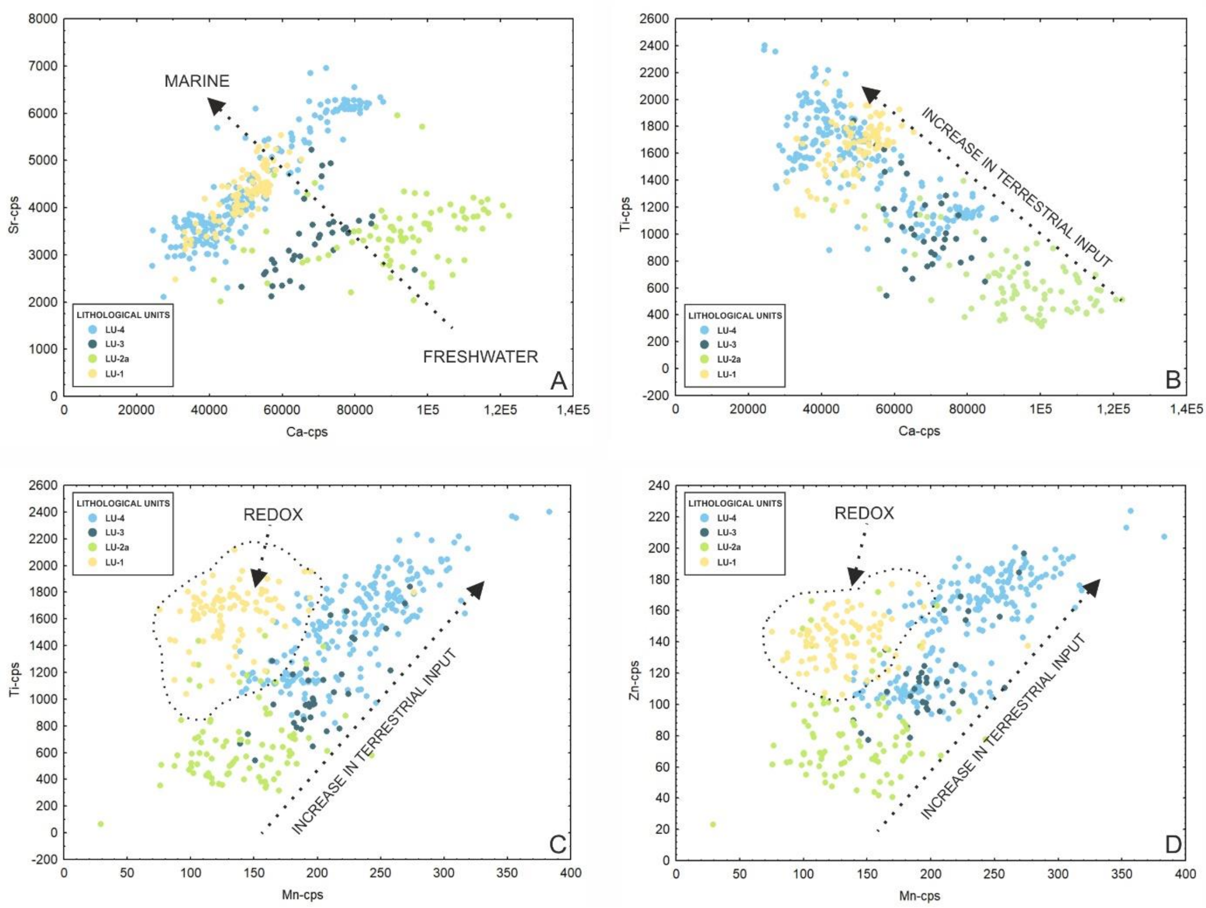

Fig. 7. Scatterplots of A) Ca (cps) against Sr (cps), B) Ca (cps) against Ti (cps), C) Mn (cps) against Ti (cps), D) Mn (cps) against Zn (cps). Sediment core LK-12 was subdivided into units representing different depositional environments: LU1- marine; LU2a- lacustrine; LU3- marine lake; LU4-marine.

5.1.2 Paleoenvironmental reconstruction considering sea level fluctuations and sill depth

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

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

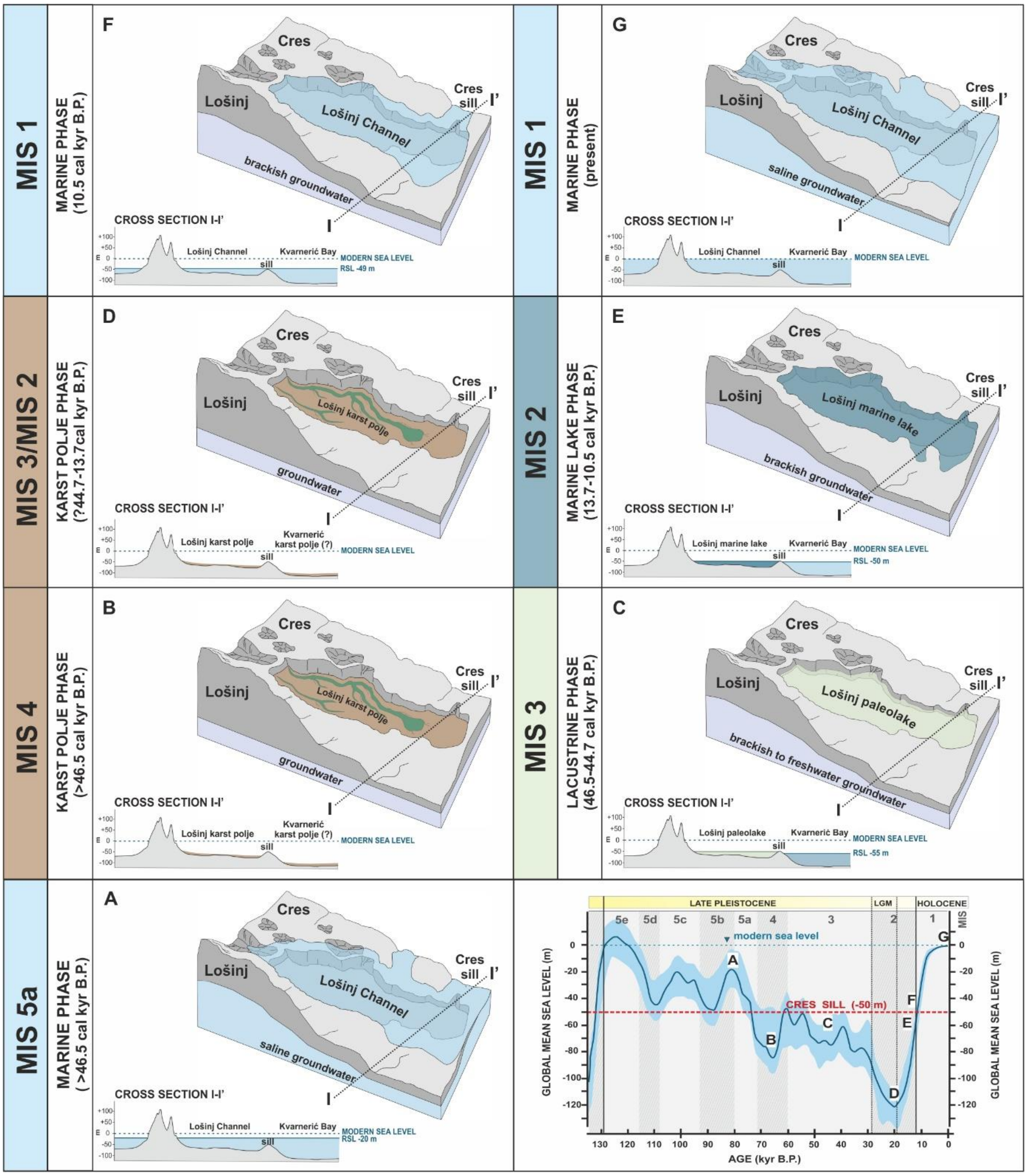

Fig. 8. Schematic paleoenvironmental reconstructions of the Lošinj Channel karst basin during the Late Pleistocene and Holocene and schematic cross-sections of the Lošinj basin with a marked connection to the Kvarnerić Bay RSL. A) MIS 5a marine environment. B) MIS 4 karst polje. C) MIS 3 Lošinj paleolake. 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

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

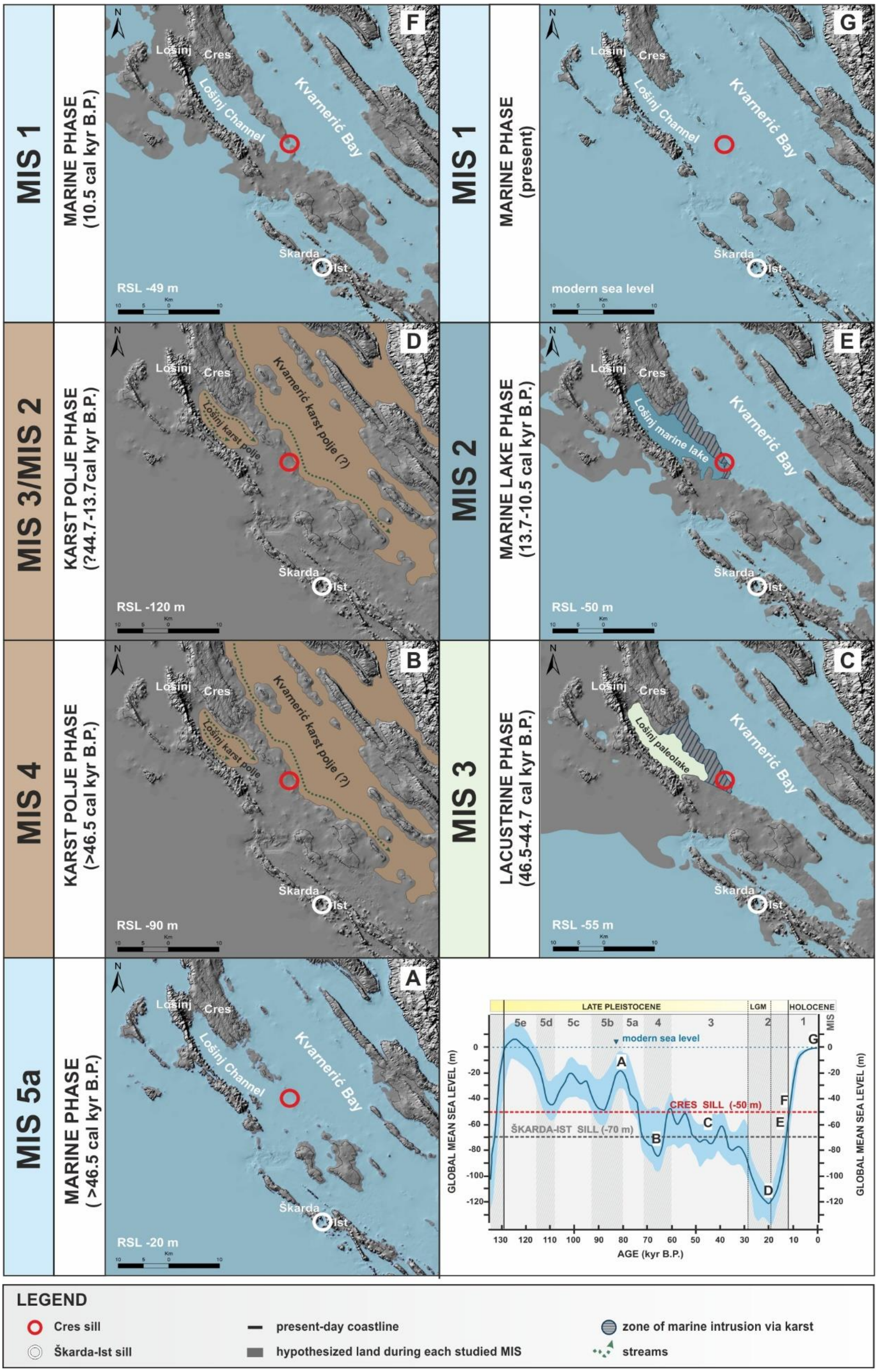

Fig 9. Schematic Late Pleistocene and Holocene palaeogeographic maps of the Lošinj Channel karst basin, based on bathymetric data (Tk25 topographic map to the scale 1:25 000, State Geodetic

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

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

5.2.1. Paleoenvironmental reconstruction based on seismic and core data

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

5.2.2. Paleoenvironmental reconstruction considering sea level fluctuations and sill depth

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

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

5.3.1. Paleoenvironmental reconstruction based on seismic and core data

Both seismic (subunit SU2a) and LK-12 core data (unit LU2a) provided clear evidence of a distinctly different depositional environment at 46.5 cal kyr B.P., compared to the previously described marine succession (Fig. 6). Geometry of the bands of the reflectors of SU2a implies the deposition of layered sediments with different lithologic properties. The general increases in $CaCO_3$ and Ca/Ti, with the dominant presence of calcite as the primary carbonate phase in lithological unit LU2a, is indicative of the development of the lacustrine environment (Lošinj paleolake). High carbonate content is common for deposition in karst lakes (Valero-Garcés et al., 2014; Hajek-Tadesse et al., 2018; Ilijanić et al., 2018). The cessation of marine conditions is also supported by a strong decrease in the Sr/Ca ratios (Fig. 6).

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

5.3.2. Paleoenvironmental reconstruction considering sea level fluctuations and sill depth

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

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

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

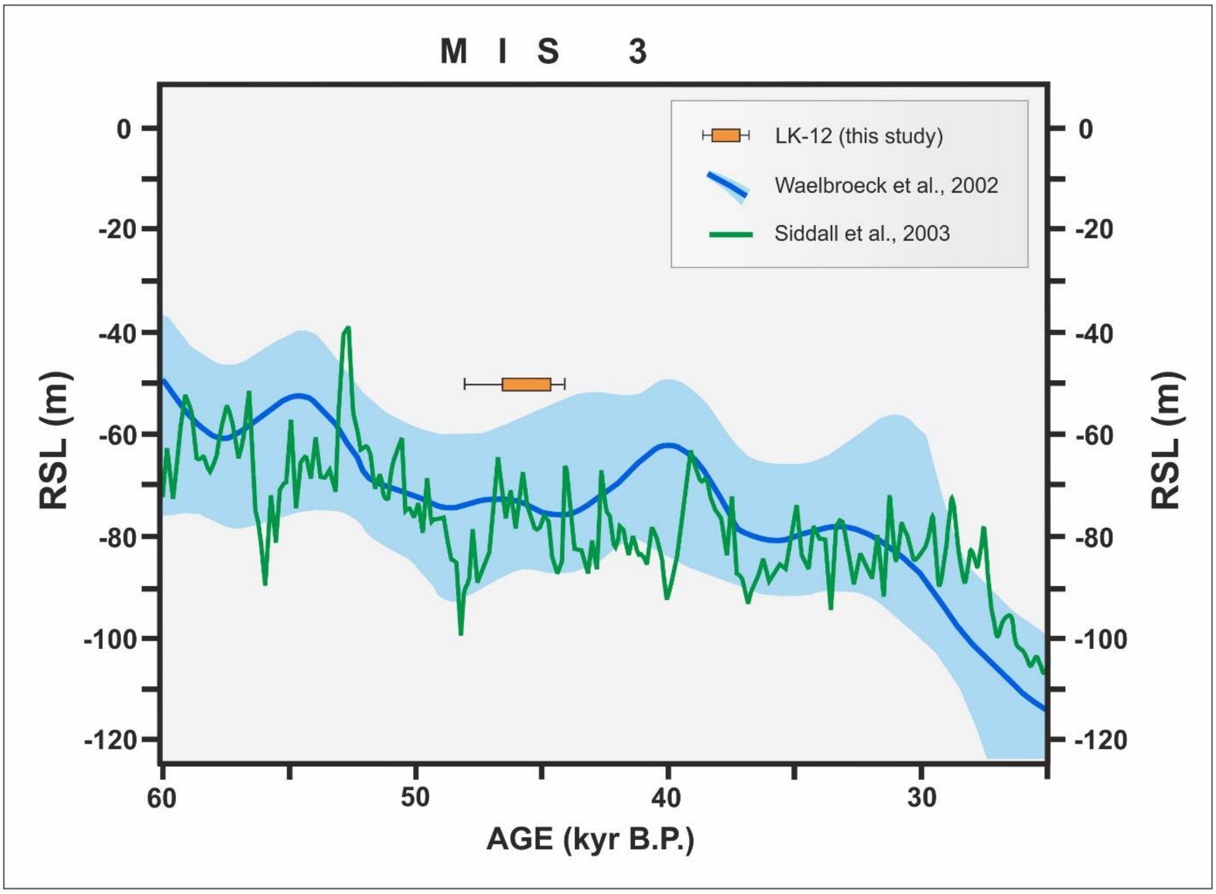

Fig. 10. MIS 3 sea level limiting point from the Lošinj Channel (LK-12) plotted against global eustatic sea level curve by Waelbroeck et al. (2002) (blue line) and sea level curve given by Siddall et al. (2003) (green line).

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

5.4.1. Paleoenvironmental reconstruction based on seismic and core data

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

5.4.2. Paleoenvironmental reconstruction considering sea level fluctuations and sill depth

We suggest that with the substantial decrease in sea level leading to the LGM (Fairbanks, 1989; Lambeck and Purcell, 2005; Lambeck et al., 2014), lacustrine deposition in the Lošinj basin ceased due to the drop in the groundwater table. Therefore, favorable conditions for the formation of a karst polje were established again (Figs. 8D and 9D). Periodical streams in a karst polje most likely partially eroded previously deposited MIS 3 lacustrine sediments. We assume that the clasts found in basal part of LK-15 core were deposited during the discharge periods. It is probable that phases of lacustrine and karst polje environments exchanged in the Lošinj basin during the Last Glacial cycle in relation to the oscillations in the RSL and climate, whereas in the northern Adriatic Shelf a large alluvial plain has been developed (Fig. 1B) (e.g., Amorosi et al., 2003; Pellegrini et al., 2018).

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

5.5.1. Paleoenvironmental reconstruction based on seismic and core data

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

High Ti/Ca ratios and MS, during the first subphase from 13.7-13.6 cal kyr B.P. (LU3a), indicate significant siliciclastic terrestrial input, most likely due to the proximity of the coast to the coring location. It is probable that erosion and redeposition of sediments were significant during this phase. This could also suggest enhanced precipitation in the investigated area. Increase in terrestrial input during Bølling-Allerød was also observed in other parts of the Adriatic Sea (Goudeau et al., 2014). The contribution of algal organic matter in subunit LU3a was less important compared to terrestrially derived organic matter, as evidenced by higher C/N ratios (Fig. 4). The results imply the development of a shallow water environment with increased productivity. It is probable that a marsh or a shallow lake was formed during this subphase. This interpretation was reinforced by mollusk assemblages that are typical for freshwater-to-brackish-water conditions (*Theodoxus* sp., *Bithynia tentaculata*). In the analyzed samples, shallow marine or brackish water foraminifera species *Aubignyna planidorso*, *Elphidium translucens* and *Ammonia tepida* (Murray et al., 2000; Debenay and Guillou, 2002; Murray, 2006) were present, indicating the marine influence.

At 13.6 cal kyr B.P. (subunit LU3b), a marked change in sedimentation occurred. Sediments in this subunit show increased $CaCO_3$ and TOC content, with poorly preserved laminations. The organic matter is predominantly of algal source (Meyers, 1994; Meyers, 2003; Lamb et al., 2006). Terrestrial input proxies (Ti/Ca, MS) account for a smaller contribution of the detrital sediment component. This might indicate a phase of arid conditions in the area at 13.6 cal kyr B.P. and prior to the onset of the Younger Dryas or shoreline migration and establishment of a deeper lacustrine environment. Rich molluskan fauna (*Theodoxus* sp., *Bithynia tentaculata*) support the existence of brackish water environmental conditions. Foraminifera specimens are well preserved and slightly more abundant compared to LU3a, implying a growing marine influence. The dominant species (*Ammonia tepida* and *Cribroelphidium gunteri*) can dwell in brackish water environments (Debenay and Guillou, 2002; Boudreau et al., 2001), and their abundances in the analyzed samples are high.

5.5.2. Paleoenvironmental reconstruction considering sea level fluctuations and sill depth

We propose that the formation of shallow and eventually deeper brackish water lacustrine environment (marine lake) in the Lošinj karst basin, occurred with the rapidly rising sea level during the Allerød interstadial, at 13.7 cal kyr B.P. The onset of the abrupt post-LGM sea level rise (Waelbroek et al., 2002; Lambeck et al., 2014) led to the rise in the groundwater table in the investigated area. The data obtained in this study suggest that RSL in the Lošinj Channel during the Allerød was <-50 m. It is considered that during the Allerød interstadial, the global sea level was approximately -75 to -60 m lower than at present (Waelbroeck et al., 2002; Lambeck et al., 2014). It is probable that during this time period Kvarnerić Bay was a marine environment (Fig. 9E). However, the Cres sill was again a barrier that isolated the Lošinj marine lake from the direct marine influence from the Kvarnerić Bay (Figs. 8E and 9E). The formation of marine lake was aided by strong diffusion of seawater through karstified Cres sill from the Kvarnerić Bay and high precipitation. Similar environments have been recognized along the present-day eastern Adriatic coast (e.g., Mljet Lakes, Lake Mir, Zmajevo oko) (Surić, 2002; Surić, 2005; Pikelj and Juračić, 2013).

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

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

5.6.1. Paleoenvironmental reconstruction based on seismic and core data

An environmental phase during which the Lošinj marine lake was a restricted environment, without surface connection to the sea on the other side of the Cres sill, existed for approximately 3000 years. At 10.5 cal kyr B.P., a noticeable shift can be observed in the multi-proxy data from sediment core LK-12 (unit LU4) (Fig. 6). In sediment core LK-15 this transition was dated at 10.3 cal kyr B.P. Seismic data (SU3) also indicated the deposition of sediments with different lithologic properties (Fig. 2 and Table 2). The Sr/Ca ratio abruptly increased (Fig. 6), implying marine flooding of the Lošinj karst basin (Figs. 8F and 9F). The Holocene marine sedimentary succession is characterized by a coarser grain-size, low productivity, terrestrial organic matter input and a rise in terrigenous siliciclastic input (high MS, Ti/Ca) (Fig. 4). This rise is likely related to the onset of a pluvial period with intensified soil erosion from the catchment. The Holocene pluvial period has been previously described in the Adriatic Sea (Wunsam et al., 1999; Schmidt et al., 2000; Schmidt et al., 2001; Combourieu-Nebout et al., 2013). The topmost part of the core LK-12 (from 37 cm upcore) is characterized by decreases in MS and Ti/Ca ratios at 5.8 cal kyr B.P., which could mark the end of the humid climate conditions. This is in general accordance with the previously published data (Wunsam et al., 1999; Schmidt et al., 2001; Combourieu-Nebout et al., 2013). Paleontological analysis provided strong evidence of surface connectivity with the Kvarnerić Bay (Fig. 6). Typical marine mollusks appear (*Mytilus* sp., *Cerastoderma* sp.), and foraminifera specimens become significantly more abundant and diversified compared to the previous phase. Assemblages are dominated by *Elphidium translucens*, *Epistominella exuiga*, *Asterigerinata adriatica* and *Textularia conica*. The recognized Holocene assemblage is similar to assemblages described in greater water depth and high productivity environments along the eastern Adriatic coast (Vidović, 2010).

5.6.2. Paleoenvironmental reconstruction considering sea level fluctuations and sill depth

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

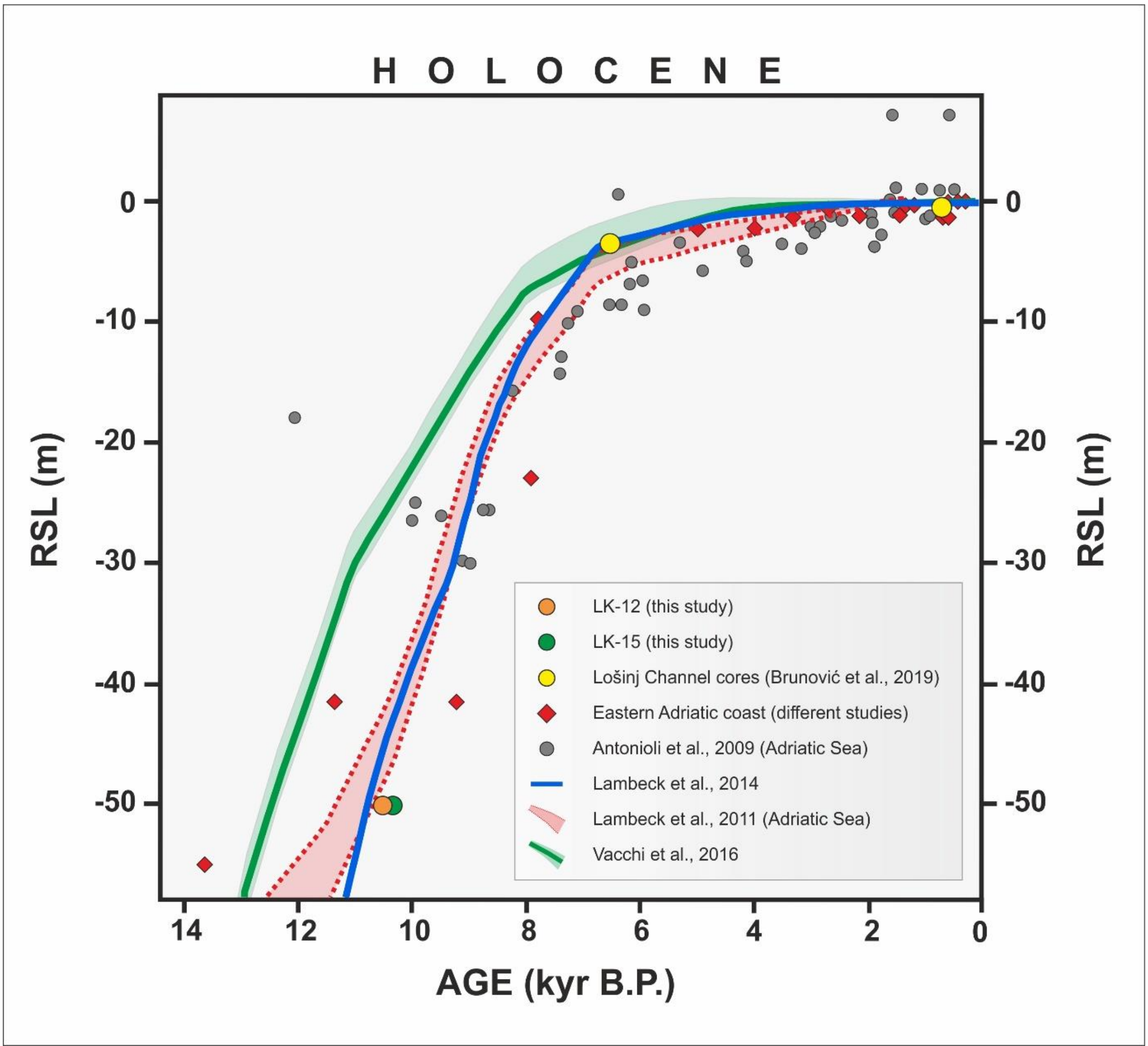

Fig. 11. The Holocene RSL observations from this study (LK-12 and LK-15), Adriatic Sea (Antonioli et al., 2009) and eastern Adriatic coast (Malez et al., 1979; Wunsam et al., 1999; Govorčin et al., 2001; Schmidt et al., 2001; Surić et al., 2005; Surić and Juračić, 2010; Faivre et al., 2013) plotted against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

6. Conclusions

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

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

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

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

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