Dip Your Finger in the Sea… Geoarchaeological View on Coastal Setting and Maritime Accessibility of the Coastal Town of Osor, Northern Adriatic[1, 2]

Potopi prst v morje… Geoarheološki pogled na obalno okolje in pomorsko dostopnost obalnega mesta Osor v severnem Jadranu

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Abstract

Erosion, sedimentation and rising sea levels can have a significant impact on archaeological research. They have altered the coastline and small-scale topography, both above and below the water's surface. Consequently, the spatial context of historical coastal cities and settlements is lost forever. Osor, an Iron Age and Roman town situated on the island of Cres in the northern Adriatic, exemplifies the methodological challenges posed by coastal archaeological sites.

In such cases, geoarchaeological studies can provide insights into the course of these changes, thus contributing to a better understanding of the past. In the case of Osor, the focus was on how its coastal location and maritime accessibility have changed since prehistoric times. In this context, the presumed locations of the city's ports and the formation of the Osor Channel were investigated. The study reports the results of these investigations and provides evidence that the Osor Channel evolved naturally prior to the Bronze Age, rather than being created by means of human intervention during the Iron Age or Roman period. Using the OSL-PD method, Jaz Bay is ruled out as a Roman port, and the possible urban harbour in Bijar Bay is briefly examined.

Keywords: Osor, geoarchaeology, Osor Channel, ALS/ALB, OSL profiling and dating

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[1] Reseach data (appendix) will be published in the the repository of University of Primorska.

[2] The editorial team used the AI tools DeepL, Grammarly, and Instatext to proofread the English text.

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Izvleček
Erozija, sedimentacija in dvig morske gladine lahko pomembno vplivajo na arheološke raziskave. Ti procesi so preoblikovali obalno linijo in drobno topografijo, tako nad kot pod morsko gladino. Posledično je prostorski kontekst zgodovinskih obalnih mest in naselbin za vedno izgubljen. Osor, železnodobno in rimsko mesto na otoku Cresu v severnem Jadranu, ponazarja metodološke izzive, s katerimi se sooča obalna arheologija.
V takšnih primerih geoarheološke raziskave omogočajo vpogled v potek teh sprememb in prispevajo k boljšemu razumevanju preteklosti. V primeru Osorja je bila pozornost usmerjena v spremembe njegove obalne lege in pomorske dostopnosti od prazgodovine dalje. V tem kontekstu so bile raziskane domnevne lokacije mestnih pristanišč ter nastanek Osorskega kanala. Prispevek predstavlja rezultate teh raziskav in dokazuje, da se je Osorski kanal nastal naravno že pred bronasto dobo, ne pa kot posledica človeškega posega v železni dobi ali rimskem obdobju. Z uporabo metode OSL-PD je zaliv Jaz izključen kot rimsko pristanišče, na kratko pa je obravnavano tudi morebitno urbano pristanišče v zalivu Bijar.

Ključne besede: Osor, geoarheologija, Osorski kanal, ALS/ALB, OSL-profiliranje in datiranje

Introduction

During the post-Last Glacial Maximum (LGM) period, the melting of ice sheets caused coastal areas around the world to be inundated, resulting in the formation of the present-day embayments, channels and indentations (Pikelj and Juračić 2013). These changes also shaped the eastern Adriatic, resulting in the formation of the Dalmatian coastline. Marine waters flooded many coastal basins (paleolakes) and paleo-river valleys (Sikora et al. 2014, Brunović et al. 2020; 2024; Hasan et al. 2020; Smrkulj et al. 2024). As the sea level stabilised during the Middle and Late Holocene, deltas or estuaries formed in river mouth regions (Sikora et al. 2014; Felja et al. 2015; Hasan et al. 2020; Smrkulj et al. 2024). These coastal landforms are largely influenced by the region's relative sea-level history, the amount of sediment supplied by their rivers and other coastal processes, such as tides and waves. Human activity in the Late Holocene also had a considerable role in shaping of the coastal environments (Benjamin et al. 2017).

The global rise in sea levels over the last millennium was a relatively slow process (Lambeck et al. 2014). However, rapid, episodic sea-level changes can result from vertical tectonic movements (e.g. Marriner et al. 2017; Benjamin et al. 2017). Measurements of present-day tectonic activity using continuous GPS networks indicate crustal lowering in the Kvarner Gulf area, consistent with tectonic subsidence of 0.63–0.89 mm/year as inferred from Roman fish tanks (Florido et al. 2011). Faivre et al. (2010) concluded that the sea level in the Istrian and Kvarner region was approximately 1.0–1.5 metres lower than it is today during the first and second centuries AD. Vacchi et al. (2016) reviewed the local sea-level rise in the western Mediterranean over the last 10,000 years.

The Croatian proverb 'Dip your finger in the sea and you are connected to the whole world' applies to all coastal and island settlements and to all historical periods. The gradual rise in sea levels therefore has a number of effects on archaeological research (e.g. Benjamin et al. 2017). Erosion, sedimentation and rising sea levels have changed the coastline and the small-scale topography above and below the water. Consequently, the spatial context of historical coastal cities and settlements is lost forever, which makes interpreting the remains of buildings or marine infrastructure challenging. Osor, an Iron Age and Roman town situated on the island of Cres in the northern Adriatic, is an example that illustrates the methodological challenges posed by coastal archaeological sites (fig. 1).

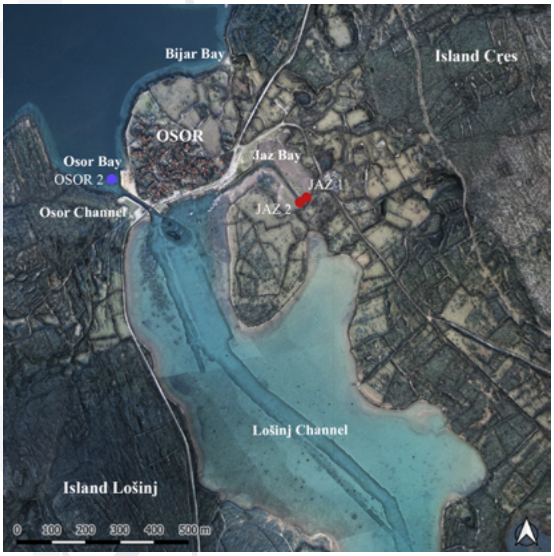

Figure 1: The Wider Location of the Studied Area Surrounding Osor, and the Position of the Marine Core OSOR 2 and the Terrestrial Cores JAZ 1 and 2 (project-owned data, orthophoto and ALS/ALB visualisation, elaborated by Martin Fera, 2025)

Osor is located on a circular land bridge between the islands of Cres and Lošinj, which are separated by the 10-metre-wide Osor Channel (fig. 2). The city wall from the Iron Age and Roman times originally enclosed an area with a diameter of around 300 metres (Doneus et al. 2017). The city is further bounded by the sea to the south, west and north, while a waterlogged karst depression limits the settlement area to the north-east and east. It is widely believed that the Osor Channel is man-made. The possibility that it originated in the Iron Age has frequently been mentioned (e.g. Stražičić 1980, 214). Based on excavation results, Faber (1982, 62) argued that the channel was in use already in Roman times as the city's sewage system was centred on the Osor Channel. Recent rescue excavations in Osor (2022–2025) uncovered further evidence of a Roman sewer system which presumably led to the Osor Channel (Baričević 2023). However, no physical connection could be established between the sewer and the channel of Roman Osor.

Figure 2: Osor Channel Between the Islands of Cres (on the right) and Lošinj (on the left) (elaborated by Martin Fera, 2023)

Already Benndorf (1880) was of the opinion that the location of Osor was chosen for strategic reasons, namely, to control the narrow passage between Cres and Lošinj. This passage comprises the approximately 80-metre-long Osor Channel and the 13-kilometre-long Lošinj Channel to the south. Together, they provide an alternative sailing route between Cres and Lošinj, avoiding the more exposed western shores of both islands. Moreover, in a wider context, Osor can offer the first safe harbour on the route from Istria to Dalmatia after leaving the Istrian Peninsula. Controlling this passage would also allow some degree of control to the communications network from Central Europe to the Eastern Mediterranean. This would enable the inclusion of the city harbour into long-distance maritime routes. Its role as a maritime node since the Iron Age is evident from spectacular finds, including a wide variety of goods from the Pannonian Plain, the Italian peninsula, Macedonia and Greece (e.g. Blečić Kavur 2015; 2021).

Given Osor's strategic importance, it is surprising that hardly any details are known about its coastal setting in ancient times, especially considering Osor's potential as a maritime trading centre. These and a number of other research questions are therefore being addressed as part of the 'Osor beyond the myth' project. Palaeogeographic and paleoenvironmental reconstructions of the submerged coastal areas are particularly important for understanding the archaeological record of Osor's coastal setting. In the context of ongoing investigations, geoarchaeological studies include coring, marine surveys, stratigraphy, reconstruction of the depositional environment, radiocarbon dating, and evaluation of relative changes in sea level.

The Osor project builds on existing results through a series of new geological and archaeological investigations. The landscape-based approach introduced in 2012, which combined airborne laser scanning (ALS) and airborne laser bathymetry (ALB) surveys (Doneus et al. 2015), was crucial in this respect. Consequently, ALS data has provided a significant amount of information on human occupation in the densely overgrown areas of today. Furthermore, ALB has proven to be a valuable tool for rapidly scanning the topography of shallow underwater areas (Doneus et al. 2013).

The results of the geological 'LoLADRIA' project provided another important data set. The southeastern parts of the Lošinj Channel have been investigated at relatively low resolution within the frame of the LoLADRIA project with a focus on the evolution of submerged karst dolines (Brunović et al. 2019). These data provided a starting point for a new study focusing on the geomorphological changes of the coastal area in the shallow, NW part of the Lošinj Channel. The objective of this study was to reconstruct the timeline of Osor and its surrounding areas by combining archaeological findings with geochemical and geophysical data from the sedimentary records of Osor Bay. This multidisciplinary approach enabled the creation of a robust chronology spanning the past 5,000 years, highlighting the significance and temporal changes of various human activities during Osor's existence as a settlement, as well as the impact of rising sea levels.

Case Study Area

Cres belongs, together with the islands of Lošinj, Krk and Rab, to the most northern group of Croatian islands. They are situated in the Kvarner Bay, which is a semi-enclosed basin located between the Istria peninsula and the Vinodol-Velebit coast and encompasses numerous islands oriented parallel to the coastline (Dalmatian type coast) (e.g. Benac et al. 2008a). The Kvarner Bay is part of the northern Adriatic shelf, which is mostly shallow (up to 120 m) and low gradient (0.02°) continental shelf. Lithologically, the main units are Cretaceous carbonates deposited on the Adriatic/Dinaridic carbonate platform (Pamić et al. 1998; Vlahović et al. 2005), overlain by Paleogene carbonates and siliciclastic sediments. Accordingly, ~90% of the eastern Adriatic coast is formed by carbonates, whilst ~6% is formed in Eocene flysch (Pikelj and Juračić 2013). All units were strongly deformed during the Eocene Dinarid (Alpine) orogenesis and eventually uplifted during the latest mountain-building processes (Korbar 2009). Consequently, late orogenic exhumation and Quater-

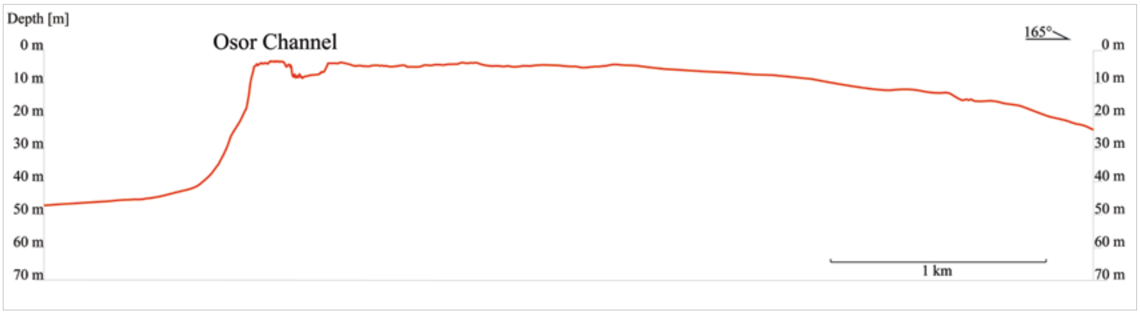

Figure 3: A Generalised Bathymetric Profile of the Osor Channel and the Surrounding Seas Shows the Distinct Sedimentary Environments of the Deep Osor Bay and the Shallow Lošinj Channel (elaborated by HGI, 2025)

nary climate led to the formation of a classical karst region – the Dinaric karst.

Osor lies at the northern most part of a karstified and tectonic depression (Lošinj Channel), with a sediment infill >200 m above a Cretaceous basement (Brunović et al. 2024) (fig. 3). The modern-day bathymetry of the Lošinj Channel indicated the existence of several distinct areas within the basin. The shallow northernmost part of the channel extends from the shoreline to a depth of ~40 m with a slope of <11° that separates this area from the central part of the Lošinj Channel with a maximum water depth of 74 m. The lateral decrease in depth along the basin margins occurs relatively abruptly (Brunović et al. 2024). Marine flooding of the Lošinj Channel occurred during the Holocene, with data from the channel indicating relative tectonic stability or weak subsidence during this period (Brunović et al. 2020; 2024).

Prevalent strata on the islands Lošinj and Cres are carbonate deposits of Cretaceous age (Korbar et al. 2001; Korbar and Husinec 2003, Fuček et al. 2014). The wider area is characterised by 18 lithostratigraphical units of various geological age (Cretaceous, Palaeogene, Quaternary). Several reverse faults were recognized on geological maps of islands Lošinj and Cres (Mamužić 1968; Magaš 1968, Fuček et al. 2014). Osor and its wider surroundings are located within two lithostratigraphic units, which are composed of alternations of dolomites and shallow marine limestones assigned to the Upper Albian-Lower Cenomanian boundary (Sis unit) and Cenomanian pelagic limestones (Belej unit) (Fuček et al. 2014). Town of Osor was built on the karstified limestones of the Belej lithostraigraphic unit (Fuček et al. 2014).

Methodology

Surveys

Airborne Laser Survey (ALS/ALB)

Airborne laser scanning (ALS, based on LiDAR technology) is an active remote sensing method in which the Earth's surface is measured directly from the air using infrared or green laser pulses. It allows large areas to be mapped relatively quickly using a dense point cloud. After the points are classified, products, primarily digital terrain models, can be derived. These show the terrain, and all traces of human activity preserved in relief. In the last decade, ALS has greatly improved large-scale archaeological research in the Mediterranean (e.g. Vinci et al. 2024). Of special interest is also the use of green laser scanners with small footprints for airborne laser bathymetry (ALB). They have the capability to penetrate clear water and consequently measure the underwater topography in high detail resulting in DSMs/DTMs with 0.5 m raster width combining the topography of underwater, terrestrial surfaces as well as the intertidal zone (Doneus et al. 2015; Doneus et al. 2013).

ALB data acquisition was conducted on 29th of March 2012 between 10:54 and 11:33 local time at low tide and at calm wind and water conditions. A RIEGL VQ-820-G was operated at an effective measurement rate of 200 kHz and a 60° scan angle. The flying height of 450 m resulted in footprints of 0.45 m diameter on the water surface. The flying strips had an overlap of 70%. Processing was done using the software RiPROCESS, OPALS (Mandlburger et al. 2009), and SCOP++ (Pfeifer et al. 2001) including strip adjustment to remove systematic errors between overlapping strips and robust interpolation with an eccentric and asymmetrical weight function to identify off-surface points (for a detailed description of the process, see Doneus et al. 2020). The average final ground point density is not uniform because it varies depending on the number of overlapping strips in an area, the density of vegetation, steepness of terrain or the presence of deeper water, which does not return echoes. Typical value is between 3 (dense maquis vegetation) and 20 points per square meter. The remaining point cloud was interpolated to a digital feature model (DFM – Pingel et al. 2015) with a raster width of 0.5 m using linear prediction (equivalent to ordinary Kriging, see Doneus et al. 2020) and imported into a GIS environ-

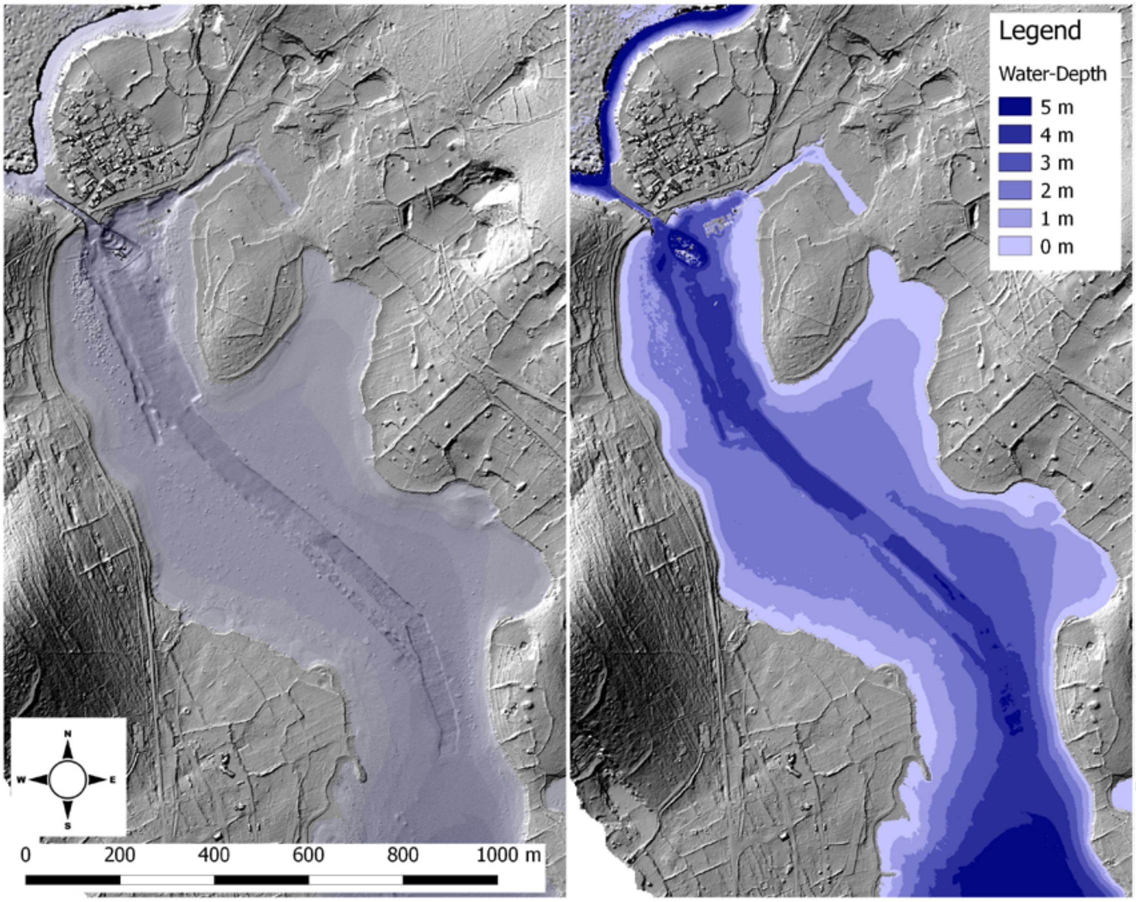

Figure 4: Digital Terrain Model (Combination of Slope and Hillshade) Derived From ALS/ALB Data. Left: Underwater Areas Depicted in Transparent Blue Colour. Right: Map of Water Depth in the Osor and Lošinj Channel (elaborated by Doneus et al. 2017)

ment for further visualisation. The penetration depth, which depends on the type of laser scanner and especially on water clarity was up to 10 meters below the water surface. This is sufficient for interpreting coastal settlements and identifying potential submerged archaeological structures (fig. 4).

Knowledge about the detailed underwater relief is of crucial importance for research into Osor, as it provides the maritime context necessary for assessing its coastal setting. Although the ALB-derived digital model only shows the current underwater relief, it clearly illustrates the challenges posed by maritime traffic due to the extremely shallow water depths. Today, small boats can navigate the Lošinj Channel due to dredging, which was probably carried out by the Italian government in the 1920s or 1930s and is still visible in the ALB data (fig. 4).

Multibeam and Sub-Bottom Sonar Survey

Multibeam (MBES) bathymetry data were obtained during the survey of Osor Bay and Lošinj Channel using a WASSP S3 MBES (Furuno ENL, Auckland, New Zealand), which was side-mounted on the MB Dide Rak. The vessel was moving at a speed of approximately 3.5 knots. The MBES operational frequency was 160 kHz, producing 224 beams in a 120-degree angle swath. The vessel positional data were provided

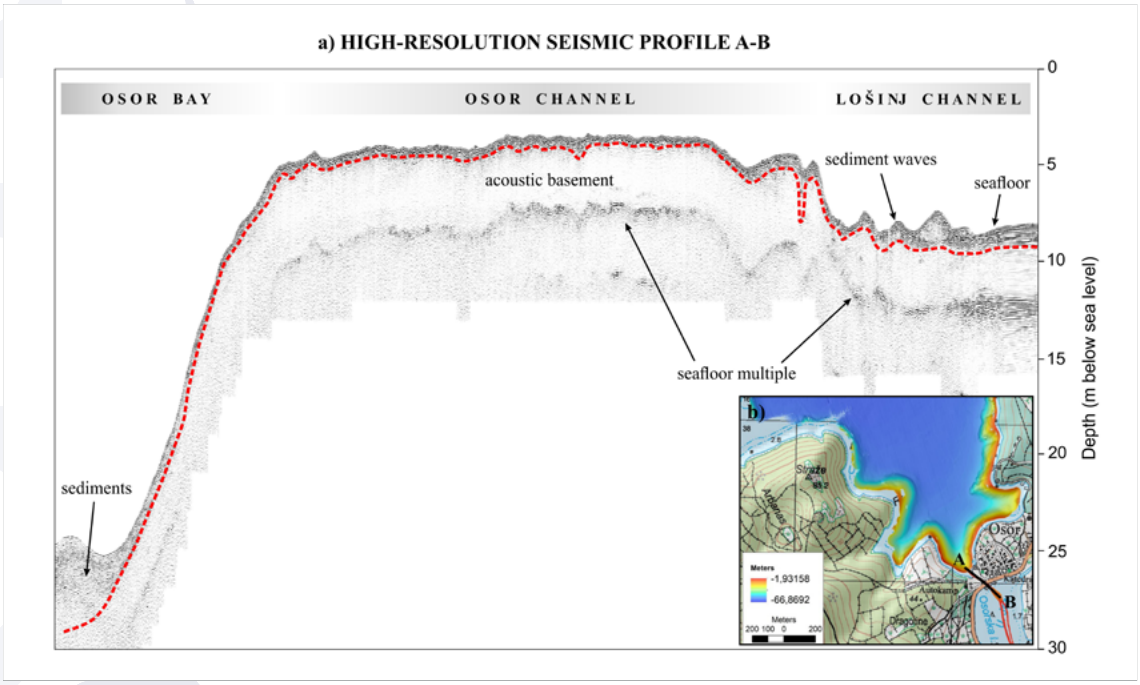

Figure 5: a) High-Resolution Seismic Profile Acquired in the Osor Channel Connecting Osor Bay and Lošinj Channel Using Sub-Bottom Profiler (SBP) (Red Line Marks the Transition to Acoustic Basement Through Which Penetration of the Acoustic Signal is Limited); b) Location of the Recorded Profile (elaborated by HGI, 2025)

using a Hemisphere V103 GPS GNSS antenna with SBAS motion corrections. The pitch, roll and heave motions were corrected with a WASSP Sensorbox (Furuno ENL, Auckland, New Zealand) inertial measuring unit (IMU). WASSP CDX software (version 3.9, Furuno ENL, Auckland, New Zealand) was used for the device control as well as for recording the MBES data, whereas the postprocessing of the data was performed with BeamworX Autoclean v2020.2 software. The MBES bathymetry and data were processed in BeamworX as a 0.5 m pixel ASCII grid for further analysis in ArcGIS with a Spatial Analyst extension (version 10.2.1, ESRI Inc., Redlands, CA, USA). First, we created a 0.5 m-cell-size digital terrain model (DTM) using an MBES bathymetry grid.

High-resolution seismic data were acquired with a parametric sub-bottom profiler Innomar SES-2000 light. The sub-bottom profiler operates at two low frequencies (6 and 10 kHz) to obtain the high frequency. The device was mounted on a small vessel moving at a speed of 3.5 knots. Seismic profiles were transformed from Innomar native format into SEGY format via SESConvert and integrated into GeoSuite Allworks software (v2021 R2) for processing and interpretation.

Surveys of the Osor Channel

To this end, a number of surveys have been carried out to determine the channel's location and depth in past times. Unfortunately, all efforts to make new observations, particularly with regard to the Osor Channel in Roman times, were unsuccessful.

Large-scale geophysical surveys were conducted in Osor in both 2023 and 2024, and the results are currently being prepared for publication. The two sides of the channel were surveyed in order to identify any old channel banks (fig. 6a). However, this was unsuccessful as the chan-

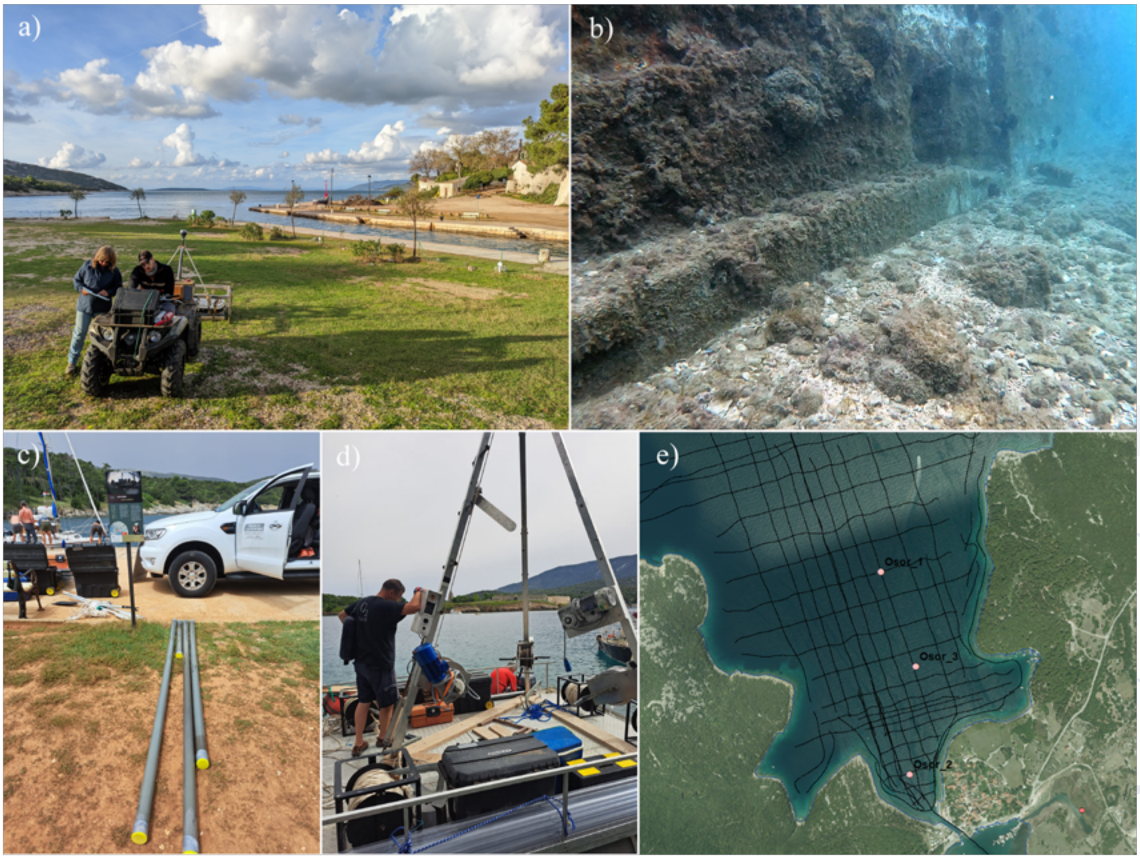

Figure 6: Surveys of the Osor Channel: a) Geophysical Survey of Both Sides of the Channel: b) Underwater Survey; c) - d) Cores Were Retrieved Using a Niederreiter Piston Corer (UWITEC, Austria) and Platform in Osor Bay; e) Coring Locations for the Three Cores (a) elaborated by Martin Fera, 2025; b) elaborated by Croatian Conservation Institute, 2023; c-e) elaborated by HGI, 2024)

nel had been rebuilt many times over the centuries, and the area between the city wall and the channel had been completely filled in during the last 100 years.

At the same time, Osor has been at the centre of infrastructural modernisation since the summer of 2022. Construction work was accompanied by large-scale rescue excavations, including underwater excavations at the south end of the Osor Channel. This opportunity was used to conduct a video documentation of the channel ground (fig. 6b), which clearly shows the modern mortared sides of the channel.

The high-resolution seismic profile acquired in the Osor Channel using a sub-bottom profiler (SBP) shows several metres of sediment on either side of the channel (see fig. 3, 5 and 6c–e). However, the seismic profile through the Osor Channel shows no penetration into the subsurface due to the tightly packed layer of sediment and stones of different sizes at the bottom of the channel. This was also confirmed during the underwater excavation (fig. 6b).

Geoarchaeological Research

Coring and Lithological Description

Three sediment cores (OSOR 1–3) were recovered from Osor Bay (fig. 1) at depths between 30 and 40 m below the present sea level. The cores were retrieved using a Niederreiter piston corer

Figure 7: Coring in Jaz Bay With an Eijkelkamp Percussion Drilling Set – Hammer Cobra TT, Cores JAZ 1 and 2 (elaborated by Nives Doneus, 2024)

(UWITEC, Austria) placed on the coring platform with a tripod. Cores were cut in the laboratory of the Croatian Geological Survey into 1.4 m-long segments and split longitudinally. One half of each core was archived, while the other half's surface was smoothed and photographed.

Two cores were also taken from the Jaz Bay tidal inlet, (JAZ 1 and 2, fig. 1 and 7) with an Eijkelkamp percussion drilling set – hammer Cobra TT. The water depth during coring varied from 0 to 20 cm depending on the tidal oscillations. The core JAZ 2 was dated using the OSL-PD method.

The cores were subsampled for particle size analysis (PSA); total carbon (TC), total organic carbon (TOC), total inorganic carbon (TIC) and total nitrogen (TN) concentration measurements. The results for cores OSOR 2 and JAZ 2 are discussed in this paper.

Grain-size Distribution

A Shimadzu (Kyoto, Japan) SALD-2300 laser diffraction particle size analyser was used to analyse the particle size distribution in sediment core samples. The instrument measures particle diameters between 0.017 and 2500 µm. First, the organic matter was removed from 0.1–0.2 g of the sample with hydrogen peroxide (H_2O_2) (Allen and Thornley 2004). Since most of the samples in this karst environment are predominantly composed of carbonate material, they were not pretreated with hydrochloric acid (HCl). Fossil shells were manually removed from the samples. Sodium hexametaphosphate ($(NaPO_3)_6$) was added to allow dispersion and prevent particle aggregation. We used the GRADISTAT 8 software (Blott and Pye 2001) for statistical data processing. For the sediment classification, the Folk and Ward (1957) method was applied.

Organic Carbon and Nitrogen

To measure organic carbon (TOC), total nitrogen (TN), total inorganic/carbonate carbon (TIC), and insoluble residuum (IR), a Thermo Fisher Scientific (Waltham, MA, USA) Flash 2000 NC Analyzer was used. Two grams of bulk sediment were freeze-dried and ground. The samples were packed into tin capsules for the analysis of total carbon (TC) and TN. To measure TOC, the carbonate component was removed by HCl. The TIC was calculated as the difference between TC and TOC. The C/N ratio was calculated by dividing the TOC and TN. Insoluble residuum was calculated as the mass difference between the sample treated with HCl and the untreated mass of sediment. The amount of insoluble matter in the sediment was used as a robust measure of the noncarbonate mineral matter in the sediment samples. The analytical precision of this method was controlled by repeated measurements of the individual samples and the standard reference material, Soil NC Reference Material (%N = 0.21 and %C = 2.29).

Chronology 14C AMS (Osor Bay)

The chronology of the core OSOR 2 drilled in vicinity of the town of Osor at a depth of 30 m was investigated through the AMS radiocarbon dating method (14C). Dating was performed on three well-preserved mollusc shells. AMS radiocarbon dating (14C) was performed at Beta Analytics Laboratory (Miami). Due to the small number of dates, an age–depth model was not reconstructed. Ages are reported as calibrated calendar years before the present (cal yr BP; present =1950 CE).

Optically Stimulated Luminescence Profiling and Dating (OSL-PD)

The OSL-PD method here, employs a two-stage approach to the luminescence investigation (Kinnaird et al. 2025; Srivastava et al. 2023): in the first stage, the luminescence properties of the bulk sediment in the core was evaluated using portable OSL equipment (Munyikwa et al. 2020). A relative luminescence stratigraphy was constructed and used to identify positions down-core for dating purposes. This was used to identify the most promising positions in the core for dating purposes, deemed to be either side of the terrestrial–marine boundary.

Its adaptability makes the OSL-PD method a highly valuable tool for dating discrete landscape features and terrestrial and marine sediments recovered in cores. It provides sediment chronologies that can be used to interpret the environmental archives contained in soils. The method was recently successfully tested in the karst landscape surrounding Osor, yielding a date range of 200 ± 100 AD for the municipal land survey of the Roman town (Doneus et al. 2024).

Two cores were taken in March 2024 from the Jaz Bay (fig. 1). While the HGI core (JAZ 2) is still undergoing sediment analysis, the second core (JAZ 1) has been used for OSL-PD dating, focusing on coastal changes outside Osor.

Results

Osor Bay

The Morphology of Osor Bay and the Lošinj Channel

For the needs of the current project, the ALB was fused with the multibeam sonar (MBES) data. Analysis of the ALB- and multibeam-based DTMs revealed a mean height difference of 5 cm in the small overlapping areas. Nevertheless, this was sufficient to integrate the point clouds using the previously mentioned OPALS software, creating a continuous relief extending from the shoreline to a depth of around 50 m below the sea level.

The bathymetric data of Osor Bay shows steep slopes down to 40 m, followed by a relatively flat seafloor that gradually deepens to 50 m below sea level (fig. 8, profile C-D). This flat morphology extends to the Istrian peninsula with very small variation between 49 and 52 m depth. The morphology to the south of Osor, which marks the northernmost part of Lošinj Channel, is a karstified extension of Cres and Lošinj islands with submerged dolines filled with up to 10 m of marine and terrestrial sediments (Brunović et al. 2019; 2020; 2024). The sea floor is a gently inclined shallow shelf disturbed by dredging to allow boat transport. Osor Bay and Lošinj Channel are connected with a 2.6 m deep modern channel.

Lithology and Sediment Texture

The sediment succession of OSOR 2 core exhibits coarsening-upwards trend, with a transition from coarse silt to sand at a depth of 185 cm, with a slight fining upwards trend at depths between 10 and 30 cm. Additionally, the colour

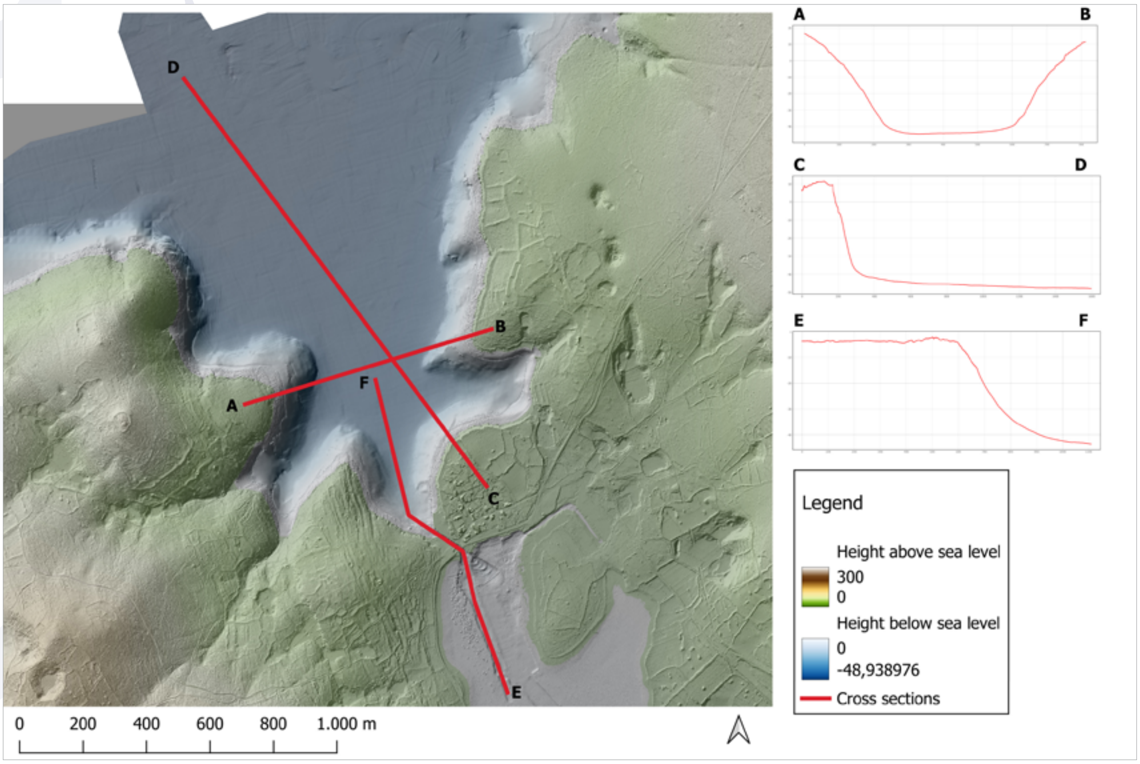

Figure 8: Combination of Terrain Models From Bathymetric LiDAR and Multibeam Sonar Data Delivered a Seamless Terrain Model of the Topography Onshore and Offshore, Allowing the Construction of Bathymetric Profiles, Which Clearly Show the Underwater Topography and the Steep Drop From Osor Towards Istria (elaborated by Michael Doneus, 2024)

of the sediments changes abruptly from grey to dark brown (185 cm) and to a brownish grey at a depth of 70 cm. The sedimentary succession of OSOR 2 is composed of three sections based on colour variability (from the base of the core to 185 cm, the dark brown section from 185 cm to 70 cm and a grey-light brown section from 70 to the core top). On a macroscopic scale, it is not possible to recognize a distinct layering, the core is homogenous in its structure.

The sediments can be predominantly classified as silty sand and sandy silt (Folk and Ward 1957) (tab. 1). The mean particle sizes range from fine silt to coarse sand (4.5–575.6 mm). The distribution of the particle size in the core sediments is shown in tab. 1. and fig. 8.

Table 1: Basic Statistical Parameters for Grain Size Distribution in the Sedimentary Succession of Core OSOR 2 (elaborated by HGI, 2025)

	Number of samples	Mean	Minimum	Maximum	Std.Dev.
% CLAY	36	2.18	0.09	10.63	2.30
% SILT	36	47.08	14.04	89.35	15.56
% SAND	36	50.74	0.02	85.62	17.71

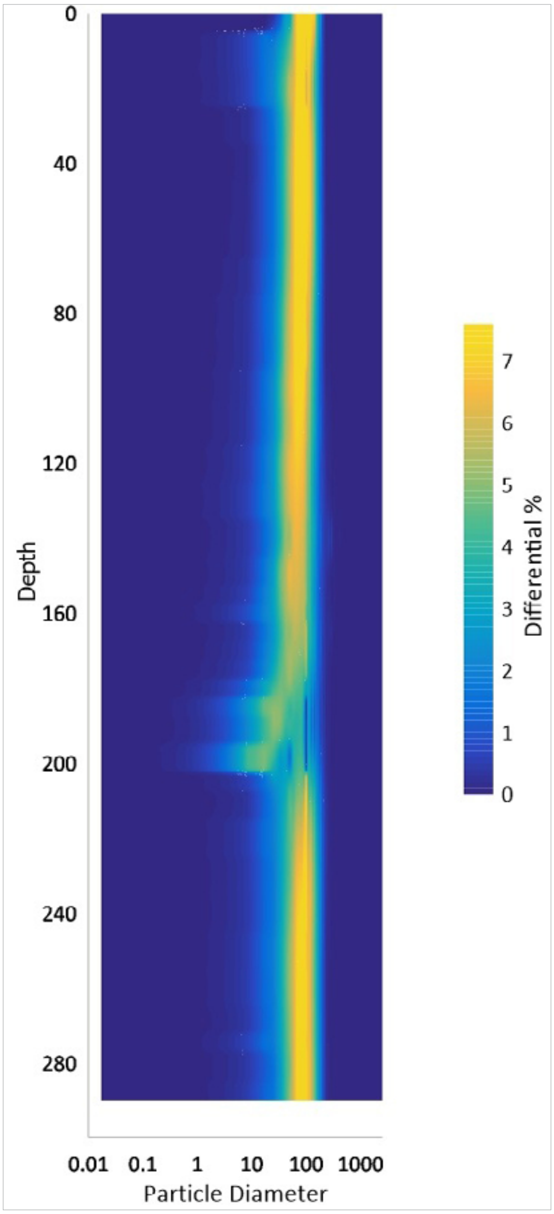

Figure 9: Particle Size Distribution (Particle Diameter in mm) in Core OSOR 2 (elaborated by HGI, 2025)

The sand content varies from 0.03 to 85.62% (average 50.74%) and the silt from 14.4 to 89.35% (average 47.08%), while the clay content ranges from 0.09 to 10.63% (average 2.18%) (tab. 1). In the silt fraction, coarse silts prevail. The gravel fraction is comprised of marine molluscs and lithogenic limestone grains, which were removed before the PSA by laser diffraction. The most abrupt change in the grain-size distribution is noted in the sediments at depths of 185 and 200 cm (fig. 9). This sedimentary succession is characterized by silt and clay fractions and the absence of sand. The oldest sediments below this abrupt change show a uniform grain size distribution with approx. 60% of sand and 40% silt. These silty sands indicate high hydrodynamics as the core is located close to shore (shoreface) while the finer fractions were transported to the more proximal environments (to be proved in cores OSOR 1 and OSOR 3).

Organic Carbon and Nitrogen

Organic carbon content (TOC) is generally below 1.0% and TN below 0.1% in the basal section of the sedimentary succession up to the depth of 190 cm. This section is characterised by the uniform low content of TOC and TN and was delineated as geochemical Zone 1 (tab. 2, fig. 10). Zone two shows a gradual increase in (TOC) peaking at the 70 cm to 6.7% (Zone 3) and then abruptly dropping below 3% (zone 3) to the top of the core. Nitrogen concentrations peaked in the interval between 155 and 100 cm, and do not follow the distribution of TOC, although the general distribution shows the highest TN in Zone 2 and a small increase in concentrations in the topmost samples of zone 3. The difference in the distribution of N in Zone 2 enabled us to divide Zone 2 into Subzone 21 (from 190 to 120 cm) and Subzone 22 (from 120 to 190 cm).

Table 2: Mean Values of TOC and TN Concentrations, Inorganic Carbon (TIC) and Insoluble Residuum (%) and Subdivision of Core OSOR 2 into Geochemical Zones (elaborated by HGI, 2025)

	Mean			
Zone	N%	insoluble res.%	TOC%	INC%
1	0.06	32.73	0.28	8.39
2	0.20	32.80	2.87	8.11
3	0.14	30.13	3.04	8.22
Average	0.14	32.17	2.02	8.23

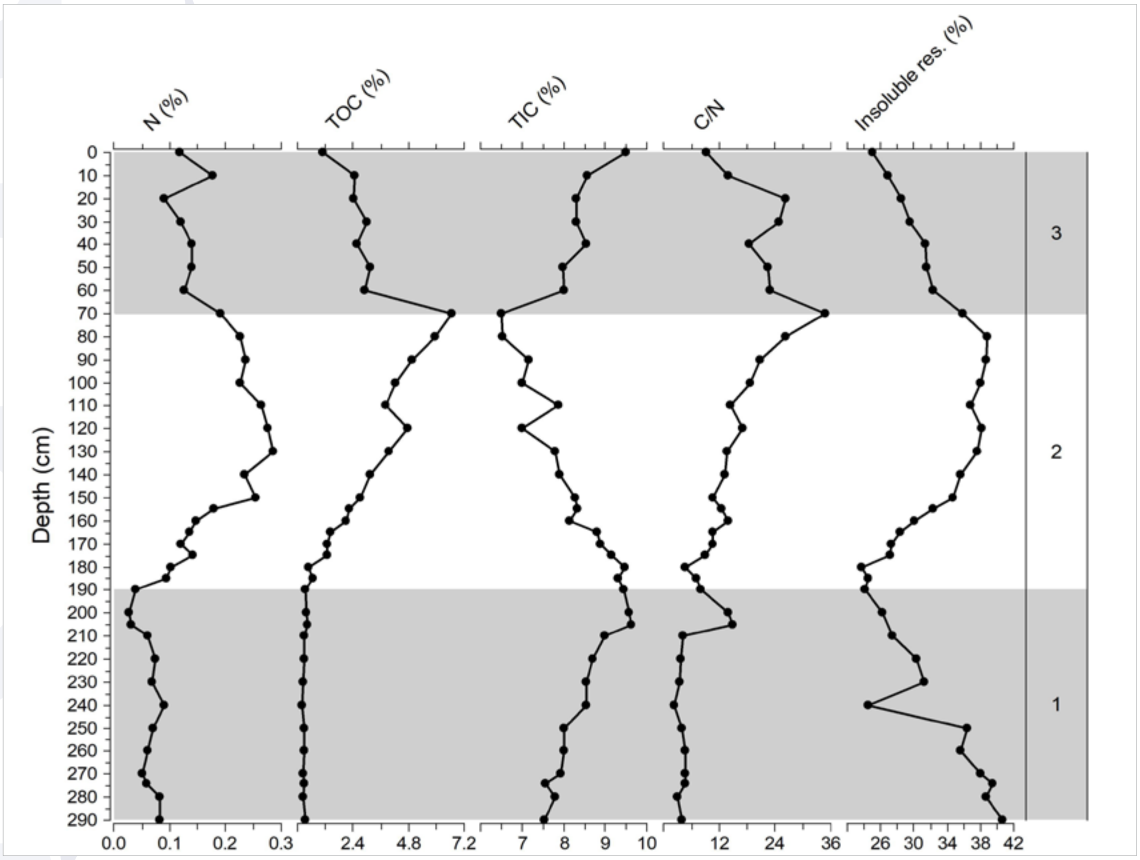

Figure 10: Geochemical Zones (1–3) and Subzones (21 and 22) of Core OSOR 2 and Depth Profiles of TOC and TN Concentrations, Inorganic Carbon (TIC) and C/N Weight Ratios and Insoluble Residuum (%) (elaborated by HGI, 2025)

Insoluble residuum follows the distribution of TIC (carbonate) with an upward decline in concentrations from the base of Zone 3 to the boundary of Zone 2. In Zone 2 the carbonate (TIC) content continues to decrease with the increase of organic carbon accumulation. The amount of TIC rises abruptly in Zone 3 and continues to rise to the top of the core, while the insoluble residuum follows an opposite trend in this zone (fig. 9). Smear slide inspection of the sediments showed that the organic carbon concentrations are related to the contents of silt-sized charcoal in the sediment. These higher TOC values are associated with increased charcoal deposition possibly sourced from human activities in Osor. The molar ratio C/N < 10 suggests that organic carbon (TOC) in Zone 1 is marine organic matter, while sediments in Zones 2 and 3 contain a mixed source of both marine and terrestrial organic carbon. The sedimentary succession at a depth of 70 cm shows a ratio of 24, which indicates that most of the organic carbon is of terrestrial origin. Zone 3 shows a gradual shift upwards towards the marine organic matter source C/N < 10 (fig. 10)

Core Chronology

Radiocarbon measurements on three mollusc shells revealed that sediment core OSOR 2 spans at least 5.5 calibrated ka BP (tab. 1). 14C analysis of the mollusc shells from the part of the core where a distinct change in colour (from grey

Table 3: Radiocarbon Ages for the Osor Bay (core OSOR 2) Sedimentary Succession (elaborated by HGI, 2025)

Depth (cm)	Lab.code	Material	Conventional age (BP)	$d^{13}C$	Calibrated Age (BP)	Calibrated Age (BC)	Prob. (%)
70–71	Beta - 703103	Marine Shell	2210 +/- 30 BP	+1.1 o/oo	1680–1366 cal BP	270–584 cal AD	95.4
122–124	Beta - 703104	Marine Shell	2740 +/- 30 BP	+1.6 o/oo	2318–1996 cal BP	369–47 cal BC	95.4
195–197	Beta - 703105	Marine Shell	5410 +/- 30 BP	+2.5 o/oo	5621–5313 cal BP	3672–3364 cal BC	95.4

to brown) and grain size occurred (195–197 cm) yielded ages of approximately between 5621–5313 cal BP (3672–3364 cal BC). The brown sedimentary succession gradually transitions to grey at the depth of 70 cm which was dated at 1680–366 cal BP (270–584 cal AD). Based on the chronology, the sedimentation rate is estimated to be 0.3 mm/year.

Jaz Bay

Lithology and Sediment Texture

The description of the core, taken for OSL-PD, includes the following units: unit 1, between 3.5–8 cm depth in core, a greyish brown silt with some clay and sand; unit 2, 8–21 cm depth, a light brownish grey coarse sand with some silt and clay; unit 3, 21–37 cm depth, a light grey very coarse sand, almost entirely shell and shell fragments; unit 4, 37–75 cm depth, dark grey clayey silt; unit 5, 78.5–82.5 cm depth, dark grey clayely silt, with shell fragments; unit 6, 82.5–102 cm depth, light yellowish brown middle- to coarse-grained sand, almost entirely shells and shell fragments; unit 7, 102–151 cm depth, dark grey clayey silt, some iron straining, shells and shell fragments; unit 8, 151–164 cm depth, light olive brown clayey silt; unit 9, 164–251 cm depth light olive brown clayey silt, iron oxide particles and nodules, possible greying, very few shells; unit 10, 235.5–284 cm depth, yellowish bown clayey silt, lots of iron oxide and manganese particles and nodules, some calcium carbonate nodules, very few shell fragments; and unit 11, 284–304 cm depth, light yellowish brown clayey silt, lots of iron oxide and manganese particles and nodules, some calcium carbonate nodules, very few shell fragments. Units 1 to 7 are marine; units 8 to 11, terrestrial.

Table 4: Effective Environmental Dose Rates Following Water Correction. aEffective Beta Dose Rate Combining Water Content Corrections With Inverse Grain Size Attenuation Factors Obtained Mejdahl (1979) for K, U, and Th; bweighted combination of estimates from ICP-MS, ICP-OES and uDOSE (elaborated by Tim Kinnaird, 2025)

Lab code	Position	Water content / %	Cosmic dose / mGy a-1	Effective dose rates, wet / mGy a-1		
				Betaa,b	Gammab	Totalb
1529_5	Core 2/5 OSL1	24 ± 7	0.15 ± 0.02	0.89 ± 0.07	0.76 ± 0.05	1.80 ± 0.09
1530_4	Core 3/4 OSL2	24 ± 7	0.15 ± 0.01	1.71 ± 0.13	1.49 ± 0.11	3.36 ± 0.17

Table 5: Burial Doses, Total Effective Environmental Dose Rates and Corresponding Depositional Ages for CERSA1529 and 1530 (elaborated by Tim Kinnaird, 2025)

Lab code	Paleodose / Gy	Aliquots / n	Dose rate / mGy a-1	Age /ka	Calender years
1529_5	3.35 ± 0.04	24 (24)	1.80 ± 0.09	1.86 ± 0.10	AD 170 ± 100
1530_4	23.08 ± 0.17	20 (20)	3.35 ± 0.17	6.89 ± 0.44	-

Core JAZ 2 Chronology

Through units 1 to 7, 23 to 140 cm depth in core, signal intensities progess with depth from 8.73 x103 to 1.53 x104 counts, spiking to 4.88 x104 counts at the base of unit 7, at 142 cm depth in core (tab. 4). OSL intensities are more heterogenous through unit 8, fluctuating around 7.90–7.41 x104 counts. Across the unit 8–9 boundary, there is a step-change in intensities from <7.4 x104 to > 1.5 x105 counts, cocinciding with the transition from marine to terrestrial sediments. The aim was to date marine transgression, so samples were taken either side of this bounday at 142 cm depth in core (base of marine sequence) and 171 cm depth (top of terrestrial sequence). Table 4 and table 5 list the palaeodoses and environmental dose rates for these samples, together with the corresponding depositional ages. Further details are provided in Appendix.

Discussion

Geological Perspective on Osor Bay and Lošinj Channel

The analysis of coastal marine sedimentary records can be used to assess the impact of human intervention over time on the surrounding environments. High-resolution land and bathymetric maps were produced by merging airborne laser scanning (ALS) and high-resolution multibeam sonar data, providing a holistic interpretation of the geomorphology of the town of Osor and its surroundings.

The core OSOR 2 was cored at a depth of 30 m on a gentle shoreface slope close to town of Osor but also close to the artificial channel, that connects Osor Bay with Lošinj Channel. The total sediment succession at the coring location is approximately 3.5 m thick, and the core penetrated 2.9 m of the sediment succession. The location of the core was chosen to allow access to an undisturbed sedimentary succession, which could record events related to the Osor site, but also to detect possible changes in the sediment records related to the construction of the channel and the influx and transport of sediments from Lošinj Channel. The opening of the channel should have had an influence on the sedimentary record in Osor Bay. The shallow south side of the channel, where the modern harbour is located, is unsuitable for the detection of environmental and human-induced changes because of dredging activities over time and the lack of stratification of cultural layers.

Osor Bay Prior to 5.5 cal ky BP (3500 cal BC)

In marine environments, organic carbon (TOC) and C/N are generally considered proxies for the relative contribution of terrestrial vs. marine organic matter and shifts in primary productivity. Ratio of total organic carbon and total nitrogen (C/N) has been largely used discriminate different origins related with sediment organic matter. Generally, the value of C/N ratio for organic matter of marine derived organic matter is less than 7, organic matter of soil has a ratio 8–20, and the ratio that exceeds 20 is characteristic for organic matter of terrigenous origin (Meyers, 1994). A low C/N ratio (<8) is found in the marine sediments in the core OSOR 2 in the sediment succession from the base of the core to a depth of 200 cm, three centimetres below the dated interval at 195–197 cm (5.6–5.3 ky cal BP / 3672–3364 cal BC). The sediment geochemistry and lithology (changes in grain size) indicate stable consistent hydrodynamics and the increase of carbonate content and decrease of insoluble residuum suggesting a low contribution of terrigenous soil input/washout from the land surface. The concentration of organic carbon and the C/N ratio correspond to those in the Holocene marine sediments of Lošinj Channel (TOC < 1.5% and C/N < 10) (Brunović et al. 2020).

The base of the core did not reach the carbonate bedrock and according to the relative sea level data from Brunović et al. (2020) for Lošinj Channel the shoreline, 30 m below the present sea level was attained at approx. 9.0 cal ky BP. This would indicate that the sediments at the base of the core were deposited in relatively shallow water in proximity to the coast. Although human occupation on island of Cres is continuous since the Mesolithic (Forenbaher and Miracle 2005), the geochemical and sedimentary record of core OSOR 2 does not imply any detectable environmental change that could be linked with human activities.

Insoluble residuum follows the distribution of TIC (carbonate) with an upward decline in concentrations from the base of Zone 3 to the boundary of Zone 2, this could be due to sea-level rise and deepening of the bay and reduced availability of soil mineral matter from the shores (the shore becomes more distal from the marine accumulation site).

Environmental Change in the Osor Bay Marine Sediments from Aprox. 5.5 cal ka BP (3500 BC) to 1.5 cal BP (270–584 AD)

The sediment core record in the interval between 200–185 cm shows an abrupt change in sediment texture with a significant decrease in grain size to dominantly silt and a shift from primary marine production of organic matter (C/N <10) to an erosion/terrestrial input (C/N >12) (figs. 10 and 11). The sudden influx of terrestrial organic matter input and change of sediment texture could be an indication of land clearance at a magnitude that it has been recorded in the sediment succession. The overall increasing and changing shifts of TOC concentrations and C/N ratios towards the top of core OSOR 2 are best visualised on the diagram in fig. 9. The distribution is complex and differs within Zone 2. Subzone 21 exhibits a trend of gradual increase of terrestrial organic carbon into the bay from 5.5 cal ka BP to 2.2 cal ka BP (3500–200 cal BC). The positive correlation between TOC and N is typical of natural environments and terrestrial plants. In Zone 22 (from 2.2 cal ka BP to 1.5 cal ka BP) this correlation does not exist: organic carbon is increasing, and nitrogen is decreasing. This is probably a consequence of the large input of charcoal from human activities in Osor. Carbon and nitrogen associations suggest that anthropogenic activity in the Osor area was gradually intensifying through Subzone 21 and then intensified in amount and peaked after 2.2 cal ka BP. During this period (Subzone 22), the altered C/N signature is possibly a consequence of more advanced technologies of firing used compared to the period of Subzone 21 or a change in source of organic matter.

Environmental Changes in Osor Bay Marine Sediments After 270–584 cal AD

The geochemical record of Osor Bay marine sediments dramatically and abruptly changes after 70 cm (1.7–1.4 cal ky BP/270–584 cal AD), the source of organic carbon is different than in Subzone 22, with a trend indicating a gradual demise of dominantly terrestrial derived organic carbon towards primary marine production of organic matter (fig. 11). The change in CN ratio indicates a progressive change in sources of organic matter and increased deposition of inorganic carbon (carbonates; fig. 10). The lower C/N ratio is most probably a consequence of several factors including decreased vegetation cover and loss of woodland surrounding Osor. The depositional environment through this period was less influenced by anthropogenic activities although higher nutrient loading can be detected in the youngest sediments indicated by an increase in nitrogen content (figs. 10 and 11). Resolving the complex system of anthropogenic influence of Osor in the future would be through an evaluation of the contribution from each source and to pinpoint human signatures on nutrient inputs to the coastal area. However, although multiple organic matter sources have been identified in natural coastal sediments, widely used mixing models have only two end-members, terrestrial and marine sediments (Ogrinc et al. 2005). Future research should focus on d15N content of the core OSOR 2 which could be used to track agricultural and urban point sources. In summary, terrigenous material has lower values for d15N and d13C than estuarine and marine organic matter (Ogrinc et al. 2005). The geochemical change through the OSOR 2 core reflect a complex history of environmental change generally caused by the anthropogenic influence of Osor.

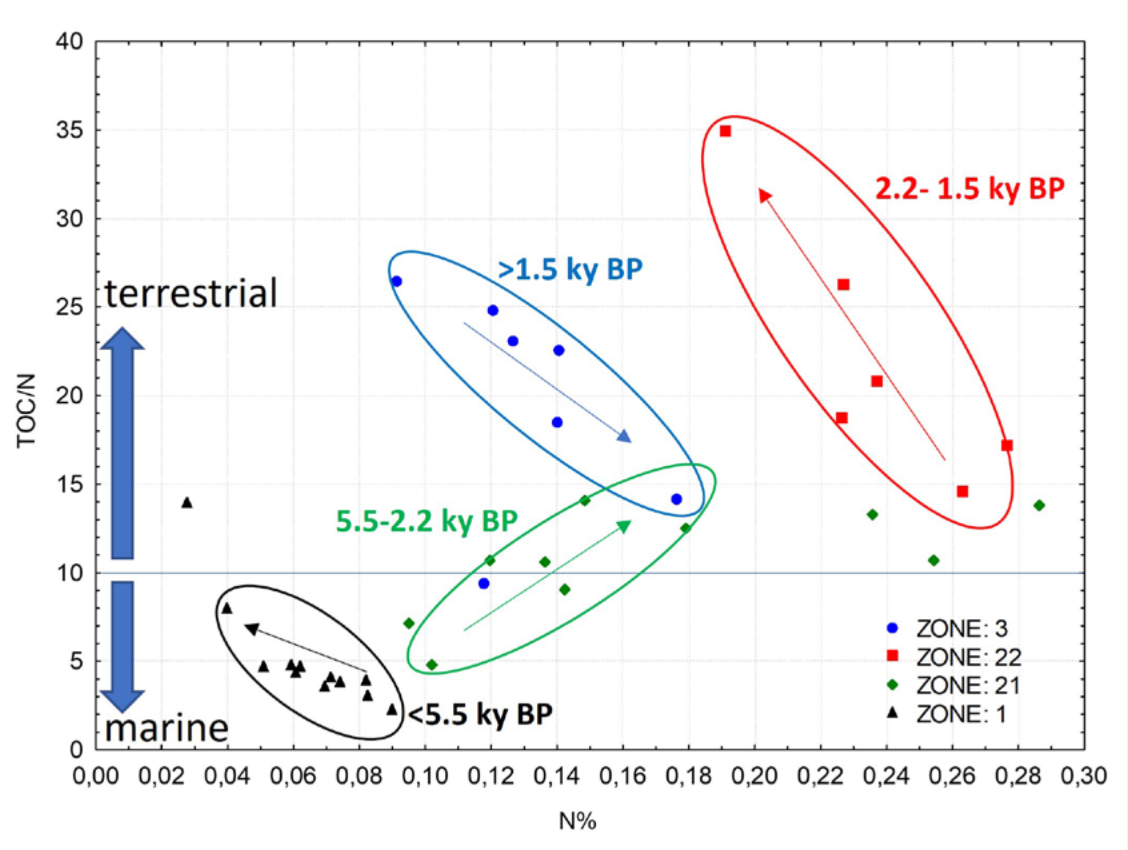

Figure 11: Changes in the Sources of Organic Carbon in the OSOR 2 Core Through Time. The Arrows Within the Ellipse Indicate General Trends of Change in Organic Carbon and Nitrogen (elaborated by HGI, 2025)

Osor Channel and the Town's Maritime Accessibility from Archaeological Perspective

The dating of the opening of the Osor Channel for maritime use is an important issue in all archaeological disputes concerning the maritime accessibility of Osor. As mentioned in the introduction, it is widely accepted that the channel was created by humans during the Iron Age or Roman period. However, the results obtained during the last two years of research contradict this archaeology-based interpretation.

Sediment core OSOR 2 has the potential to serve as a possible sedimentary record for determining the timing of the opening of the Osor Channel. However, geochemical and sedimentological analyses have not yet succeeded in establishing this event's precise timing. Material transported by currents from the Lošinj Channel shelf area could carry specific fossils (ostracods and foraminifera) or plant remains from the marshes on the southern side of the channel. Once the correct proxy has been identified, it may be possible to precisely date the opening of the Osor Channel.

Despite the lack of the precise timing, the gradual increase in terrestrial organic carbon and the initial 14C data (see chapter 5.1.1) suggest that, as early as 5621–5313 cal BP (3672–3364 cal BC), material from the Lošinj Channel was being transported by currents towards Osor Bay. This indicates that the Osor Channel did not evolve in the Iron or Roman periods, but rather before the Bronze Age. Given the steady rise in the sea level, which was reconstructed at around

–3 m for ca. 4600 BC (Brunović et al. 2019), this seems like a natural process. Current results cannot determine whether human intervention played a role in the formation of the Osor Channel. The sedimentary record (Subzone 21) partly coincides with the period of hillforts of the eastern Adriatic Bronze Age approx. 2200–900 cal BC (Blečić Kavur 2014), a topic covered in another article in this volume.

A further increase in terrestrial organic carbon in marine sediments, peaking between Iron Age and Late Antiquity (forthcoming publication, see also chapter 5.1.2), can be attributed to the growth of the city, agriculture activities as well as to the maintenance of the Osor Channel. From Roman times onwards, when quay walls and other maritime infrastructure elements were introduced to the northern Adriatic region (e.g. Koncani Uhač 2023), it is likely that the Osor Channel was also maintained accordingly. If a bridge was built between Cres and Lošinj, the waterway's banks had to be reinforced. However, no evidence of a Roman bridge has been found to date. A permanently installed bridge may have functioned similarly to those in the Middle Ages and the early modern period. Illustrated sources, like the one from 1500–1530 (Grafička zbirka HDA n. d.), show a permanent bridge with a narrow central section that could be raised to allow (sailing) boats to pass underneath.

It also seems impossible to determine the exact location of the channel in Roman times, as its position in relation to the Roman city wall is no longer traceable. The topography between the present-day Osor Channel and the city wall has changed significantly due to extensive filling in modern times. This is particularly evident when the first cadastral map of Osor from 1821 (Sušanj Protić 2015, fig. 11) is compared with the present-day one. Furthermore, strong currents require the channel to be repaired repeatedly, resulting in the loss of older traces. For example, during the construction works in 1894, the remains of an older 'riva antica' were found (Stato di Trieste n. d.). The southern end of the Osor Channel is particularly susceptible to erosion and requires regular repairs, as evidenced by the wooden pillars (dating in progress) detected during underwater excavations.

As the exact location of the Roman channel remains unknown, its depth cannot be determined. Today, the depth of the Osor Channel allows ships with a draft of up to 1.5 metres to pass through (Peljar 2012, 61). Hrvatski hidrografski institut (2003) states that the channel is 2.4 metres deep. However, ALB and underwater measurements show that the depth is actually around 3–3.5 m (the difference in measurements of up to 60 cm can be attributed to the ebb and flow of the tide). The shallow depth of the Osor Channel has obstructed shipping at least since the Late Middle Ages. According to Sušanj Protić (2015), the city's layout was reduced in size during the Venetian period. This appears to be partly linked to restrictions on maritime traffic, as the Osor Channel was too shallow for large Venetian ships due to natural sedimentation processes and a lack of maintenance (Klen 1957, 316–7). Ultimately, the Venetian government resolved this issue by relocating the island's administrative centre from Osor to Cres.

It is reasonable to assume that the bottom of the channel is limited by bedrock. This is evident from the seismic measurements taken prior to construction and underwater work commencing at the southern end of the channel (Geophysical study 2023). These measurements indicate that the bedrock lies 4–6 metres below the current sea level. The size of Roman ships has been reconstructed based on shipwrecks. For the Roman Portus, it is estimated that ships with a draught of between 1.9 and 7 metres could frequent the harbour (Boetto 2010, tab. 1). Given the shallow bottom of the Osor Channel and the lower sea level of 1–1.5 m in Roman times (Vacchi et al. 2016), large-draught vessels may have been restricted on the maritime route next to Osor. Stražičić (1995, 78–9) suggested that using the tidal current or the higher sea level during high tide, or unloading ships before crossing the canal, could have partially mitigated this issue. However, as it is not possible to ascertain whether shipping was feasible down to the bedrock in Roman times, any further calculations regarding maritime traffic are purely speculative.

The steep decline in terrestrial organic carbon in marine sediments after the Roman times makes a monocausal explanation unlikely. Such an approach would be inaccurate as both natural and human influences may have played a part in the history of the Osor Channel. From a historical perspective, there are numerous human-induced processes that could have contributed to lower sedimentation rates in the Osor Bay. Following two centuries of prosperity and continuous peace, Late Antiquity was marked by a series of radical changes. For example, large-scale agricultural production in southern Istria is believed to have ceased from Late Antiquity period onwards, with communities then cultivating a variety of products for personal consumption or sale within the region (Levak 2013). How the upheavals of the Late Antique period affected small regions like the Kvarner Islands in terms of land use and trade, and more specifically the maintenance of the Osor Channel, remains unclear.

Another possibility is the natural or deliberate closure of the Osor Channel to shipping. This would also explain the lower rate of sediment accumulation resulting from the short- or long-term destruction of the channel. In addition, a climatic influence cannot be ruled out and should be considered when analysing the data. So-called Late Antique Little Ice Age (LALIA from 536 to 660 AD) is considered to have been a period of turmoil in Europe, which caused human migrations and pandemics. The exact causes of the climate cooling are still not determined exactly but a possible cause could be a series of volcanic eruptions between 536 and 547 AD (Büntgen et al. 2016). The activities that were producing the specific organic carbon footprint in Osor during the period of Subzone 22 abruptly stopped after the Late Antique Little Ice Age. In order to confirm this, higher resolution dating in the transition from Subzone 22 to Zone 3 is needed.

Harbours and Anchoring in Jaz and Bijar Bay

Like many other parts of the Croatian coast, the Kvarner Bay is a challenging sailing passage on the route between Italy and Greece. The near-coastal Velebit massif is the area from which the notorious cold northeasterly wind (Croat. bura) originates, with gusts reaching almost 200 km/h. The 16th century insult 'damn the Kvarner having let you pass' (Kozličić 2006, 84) vividly describes the region. The region is also influenced by microtidal conditions with an average amplitude of ~30 cm but the influence of atmospheric pressure patterns together with predominant winds enables the sea level to rise to 1.6 m above mean sea level (Benac et al. 2008b). This illustrates the need for safe ports along the route between Istria and Dalmatia, and Osor was potentially one of them.

Most theories actually argued for two harbours, one in the north located in the bay of Bijar (Faber 1980; Ettinger Starčić 2012) and one south of the city walls in the bay of Jaz, now infilled (Faber 1980; Stražičić 1995). While the theory of a harbour in Bijar seems to be supported by underwater finds, no archaeological proof, like firm evidence of port facilities, could be found for the Jaz Bay to date. A geophysical survey of the coastal area between the Jaz Bay and the Lošinj Channel in spring 2024 discovered building remains (forthcoming publication), but it is currently unclear whether these are of Roman origin. However, the OSL-PD investigation provided some insight on marine transgression in Jaz Bay: the base of unit 7 (dark grey clayey silt, some iron straining, shells and shell fragments) marks inundation by the sea, as these are the first marine sediments preserved in core. These sit unconformably on unit 8, representing an erosional contact. Unit 8 is light olive-brown clayey silt, deposited in a terrestrial setting. By AD 170 ± 100, the marine transgression had reached the low-lying land to the south and east of Osor town. Unit 7's base is erosional and cut into terrestrial sediments with a depositional age of 6.89 ± 0.44 ka, meaning that only the last transgression can be dated.

In essence, the Jaz area was part of the coastal land up to AD 170 ± 100 when rising sea levels led to saltwater advancing inland. For this reason, today's Jaz Bay can be ruled out as the site of a (Roman) city harbour. After Roman times, as far as can be currently determined, the rise of the sea level, the natural sedimentation and erosion processes, as well as the anthropogenic interventions play the most important role in further changes of the Jaz Bay (Stražičić 1995, 74–88). Regarding the potential medieval saltworks in the Jaz area, the drill core sample offers limited insight as it was likely taken from outside the presumed location of the saltworks. The oldest historical sources date back to the time of the Venetian Republic. Despite the inaccuracies

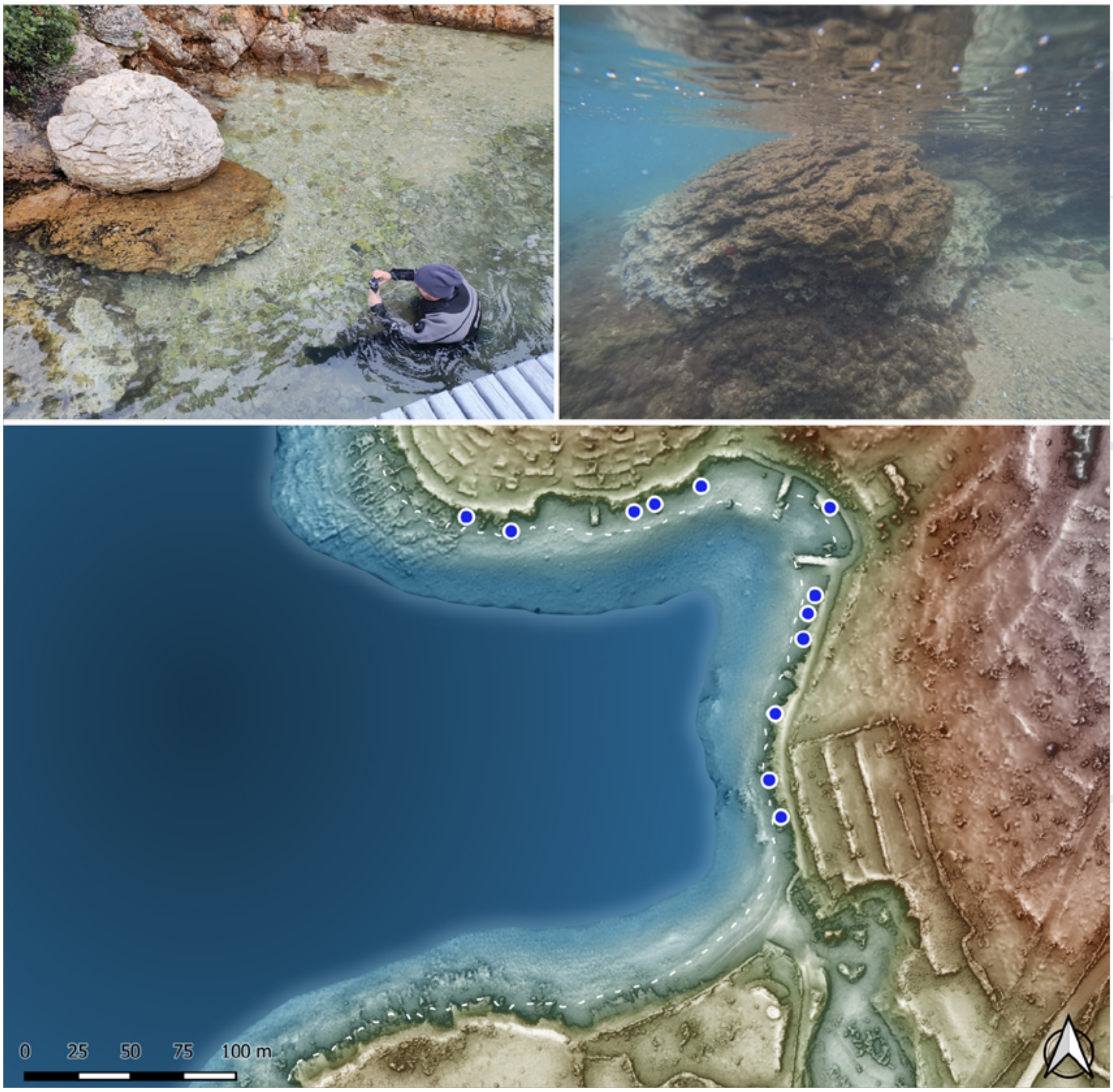

Figure 12: Documentation of the Boat Moorings in the Bijar Bay and a Comparison of Their Location and a Hypothetical Roman Sea Level (–1.5 m) Marked by a White Dashed Line (elaborated by Martin Fera, 2025 and Neno Starčić, 2024)

inherent in historical maps, they depict the Jaz area as a bay (e.g. Pavić 2000, fig. 6). The wetland contributed to the spread of malaria, leading to its gradual filling in by the 19th century. Stražičić (1995, fig. 3) suggests this occurred after 1821. Subsequently, dredged sediments from the Lošinj Channel were deposited there, and the creation of the L-shaped channel designed for fish farming through the middle of Jaz Bay was the last modern intervention (figs. 1 and 4). No archaeological finds have been discovered in the L-shaped channel in the bay (Ettinger Starčić 2012).

The suggestion by Faber (1980, fig. 4) that a section of the ancient harbour in Bijar was located in the waterlogged karst depression to the north-east and east of the city (fig. 4) can also be dismissed. The related question of whether Osor was ever located on an artificial island created by channels between Bijar and Jaz (Faber 1980, fig. 4) also does not seem to be correct, as the results of previous small-scale geoarchaeological research seem to contradict that theory (Draganits et al. 2019). Firstly, the waterlogged karst depression contains fresh water, not salt water, and is therefore unaffected by changes in sea level. Secondly, the study showed that the depression was almost completely filled with sediment around 6.000 years ago, and consequently cannot represent the harbour of Roman Osor, particularly given the lower sea levels of the past. An additional core was taken in the karst depression in spring 2024 to corroborate the 2019 results, and sediment analysis is ongoing.

Additionally, the Roman walls and (late) Roman graves were located at the edge of the depression in the area proposed by Faber (1980, fig. 4) as the northern harbour. The graves and building structures were excavated in the 1990ties (Majnarić Pandžić 1992, 270) next to the abandoned monastery from 15th century (Lemessi 1980, 148). While the archaeological excavation has never been published and the material been lost, some excavation documents remain in the Osor Archaeological Collection. Thus, in addition to precise geological dating, the archaeological evidence indicates that Osor was not naturally an island and that there was at no time a seawater link between Bijar and Jaz Bay.

Therefore, the only possible location for a city harbour is Bijar Bay. Evidence of anchoring has been found in the form of scattered ceramic material at the bottom of the bay (Ettinger-Starčić 2012). Although no remains of the harbour structure have been found, the Roman walls mentioned above in the area of the monastery may be the first indication of harbour infrastructure outside the city walls. The 12 mooring bollards that stretch along Bijar Bay and are carved from limestone have already been mapped by Faber (1980). They were re-recorded and documented during fieldwork (fig. 12). A comparison of the location of the bollards and the Roman sea level shows that they were indeed suitable for securing ships in Roman times. However, this does not necessarily mean that they were carved at that time, as local diver Neno Starčić sums up: 'People have been using the same places to anchor for centuries.'

Conclusion

The 'Osor beyond the myth' project emerged from the necessity to reinterpret the history of this regional trading port. Although the main focus is archaeology, it has become clear in recent decades that archaeology alone is incapable of capturing all the factors that have shaped the place's history. Given its location as a coastal city, it was particularly important to investigate the natural (topographic) conditions alongside other archaeological questions.

The results of the palaeoenvironmental reconstruction suggest a gradual increase in terrestrial organic carbon, indicating that material from the Lošinj Channel was being transported towards Osor Bay by currents as early as 5621–5313 cal BP (3672–3364 cal BC). This implies that the Osor Channel was not created by any human intervention during the Iron Age or Roman period but evolved naturally prior to the Bronze Age. There is a gradual increase in the amount of terrestrial organic carbon entering the bay from 5.5 to 2.2 cal ka BP (3500–200 BC), resulting from the significant input of charcoal caused by human activities in Osor. After 1.7 - 1.4 cal ka BP (270– 584 cal AD), the source of the organic carbon changes dramatically and abruptly. This indicates a gradual decline in the dominance of terrestrial-derived organic carbon in favour of primary marine production of organic matter.

The results presented in this paper provide deeper insights into questions concerning the coastal area and the maritime accessibility of Osor. While some of the new findings were expected, others came as a complete surprise. The results should encourage further archaeological investigations in the region and demonstrate the value of taking an interdisciplinary approach.

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Summary

Sea-level variability during the Late Pleistocene and Holocene profoundly shaped the Mediterranean region. During the Last Glacial Maximum, sea level was approximately 120–134 metres below its present position. The subsequent post-glacial rise led to the inundation of extensive coastal areas formerly inhabited by human populations, resulting in the submergence of numerous coastal archaeological sites that remain concealed beneath the sea surface today. Consequently, submerged landscapes have been the focus of many geoarchaeological investigations. However, until recently, the eastern Adriatic coast has remained relatively understudied in this respect.

This study focuses on the submerged landscapes surrounding Osor, an Iron Age and Roman town located on the northern Adriatic island of Cres. The *Osor beyond the myth* project arose from the need to reinterpret the history of this regional trading port. Given Osor’s coastal setting, particular emphasis was placed on reconstructing natural (topographic) conditions alongside broader archaeological questions. The results presented here offer new insights into Holocene relative sea-level rise, past environmental changes, and the coastal configuration and maritime accessibility of Osor.

A central research question concerns the construction of the Osor Channel, traditionally believed to have been excavated for maritime purposes. This narrow waterway, separating the islands of Lošinj and Cres, played a key role in maritime trade routes linking Istria and Dalmatia. Geoar-

chaeological investigations in the Osor area included geophysical surveys, sediment coring, and detailed geochemical and grain-size analyses of sediment cores. Radiocarbon and optically stimulated luminescence (OSL) dating were employed to establish a chronological framework. Integrated airborne laser scanning and multibeam sonar bathymetric data provided detailed insights into the submerged geomorphology of the area surrounding Osor.

A 2.9 m-thick sediment succession (core OSOR 2), recovered from Osor Bay, enabled the reconstruction of Holocene palaeoenvironmental changes driven by both natural processes in the wider region and anthropogenic activities in Osor. The OSOR 2 core did not yield unequivocal evidence of human intervention associated with the construction of the channel that would resolve the debate concerning its archaeological construction date. Instead, preliminary results suggest that the connection between Osor Bay and the Lošinj Channel via the Osor Channel was likely established as early as c. 5621–5313 cal BP (3672–3364 cal BC), implying that natural processes played a substantial role in its formation. Furthermore, the results indicate that the Jaz area remained part of the coastal land until AD 170 ± 100, when rising sea levels caused marine waters to advance inland. On this basis, present-day Jaz Bay can be excluded as a (Roman) city harbour.

Povzetek

Spremembe morske gladine v poznem pleistocenu in holocenu so pomembno oblikovale sredozemski prostor. Med zadnjim ledenim maksimumom je bila morska gladina približno 120–134 metrov nižja kot danes. Poznejši postglacialni dvig morske gladine je povzročil poplavljanje obsežnih obalnih območij, ki so jih naseljevale človeške skupnosti, kar je vodilo do potopitve številnih obalnih arheoloških najdišč, ki so še danes skrita pod morsko gladino. Posledično so potopljene krajine predmet številnih geoarheoloških raziskav, vendar je bila vzhodna obala Jadranskega morja do nedavnega v tem pogledu razmeroma slabo raziskana.

V tej raziskavi obravnavamo potopljene krajine v okolici Osorja, železnodobnega in rimskega mesta v severnem Jadranu, na otoku Cresu. Projekt Osor onkraj mitaF je nastal iz potrebe po ponovni interpretaciji zgodovine tega regionalnega trgovskega pristanišča. Zaradi obalne lege mesta je bila poleg drugih arheoloških vprašanj posebna pozornost namenjena tudi rekonstrukciji naravnih (topografskih) razmer. Predstavljeni rezultati prinašajo nova spoznanja o relativnem dvigu morske gladine v holocenu, okoljskih spremembah v preteklosti ter obalni konfiguraciji in pomorski dostopnosti Osorja.

Ena osrednjih raziskovalnih tem se nanaša na nastanek Osorskega kanala, za katerega se tradicionalno domneva, da je bil izkopan za pomorske namene. Ta ozek morski prehod med otokoma Lošinj in Cres je imel ključno vlogo v pomorskih trgovskih poteh med Istro ter Dalmacijo. Geoarheološke raziskave na območju Osorja so vključevale geofizikalne raziskave, vrtanje sedimentnih jeder ter podrobne geokemične in granulometrične analize sedimentov. Za vzpostavitev kronološkega okvira dogodkov so bile uporabljene radiokarbonske in OSL-datacije. Združeni podatki letalskega laserskega skeniranja in večsnopne sonarno-batimetrske meritve so omogočili vpogled v potopljeno geomorfologijo območja okoli Osorja.

Sedimentno zaporedje debeline 2,9 m (jedro OSOR 2), odvzeto v Osorskem zalivu, je omogočilo rekonstrukcijo holocenskih paleookoljskih sprememb, povezanih z naravnimi procesi v širšem prostoru in s človeškimi dejavnostmi v Osorju. Jedro OSOR 2 ni zagotovilo nedvoumnih dokazov o človeških posegih, povezanih z izgradnjo kanala, ki bi omogočili razrešitev razprave o njegovi arheološki starosti. Nasprotno pa preliminarni rezultati kažejo, da je bila povezava med Osorskim zalivom in Lošinjskim kanalom preko Osorskega kanala verjetno vzpostavljena že okoli 5621–5313 kal BP (3672–3364 pr. n. št.), kar nakazuje pomembno vlogo naravnih procesov pri njegovem nastanku. Poleg tega rezultati kažejo, da je območje Jaz ostalo del obalnega kopna vse do okoli leta 170 ± 100 n. št., ko je zaradi naraščanja morske gladine prišlo do vdora morske vode v notranjost. Na tej podlagi je današnji zaliv Jaz mogoče izključiti kot (rimsko) mestno pristanišče.