



University of Zagreb

Faculty of Mining, Geology and Petroleum Engineering

Ivona Ivkić Filipović

**ENVIRONMENTAL CHANGES IN
DALMATIAN KARST LAKES AND
PALEOLAKES DURING HOLOCENE
BASED ON SEDIMENTOLOGY,
GEOCHEMISTRY AND OSTRACOD
PROXIES IN LAKE SEDIMENTS**

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DOCTORAL THESIS

Supervisors:

Prof. Uroš Barudžija, PhD

Senior Research Assoc. Nikolina Ilijanić, PhD

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Sveučilište u Zagrebu

Rudarsko-geološko-naftni fakultet

Ivona Ivkić Filipović

**PALEOOKOLIŠNE PROMJENE U
KRŠKIM JEZERIMA I PALEOJEZERIMA
U DALMACIJI TIJEKOM HOLOCENA NA
OSNOVI SEDIMENTOLOŠKIH,
GEOKEMIJSKIH I OSTRAKODOLOŠKIH
POKAZATELJA U JEZERSKIM
SEDIMENTIMA**

DOKTORSKI RAD

Mentori:

Prof. dr. sc. Uroš Barudžija, redoviti profesor

dr. sc. Nikolina Ilijanić, viša znanstvena suradnica

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The doctoral thesis was prepared at the Croatian Geological Survey under the supervision of Nikolina Ilijanić, PhD, Senior Research Associate at the Department for Mineral Resources and Marine Geology, and Uroš Barudžija, PhD, Professor at the Department for Mineralogy, Petrology, and Mineral Resources, Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb.

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Za Evu, Mislava i našu malu koja nam tek stiže.

ABSTRACT

Karst lakes and paleolakes in Dinaric karst poljes represent favorable settings for paleolimnological studies of past environmental and climate changes, particularly during the Holocene, yet remain underexplored compared with other sites in the central Mediterranean. To fill this gap, three karst lakes and paleolakes were selected along a transect from the eastern Adriatic coast and the Ravni Kotari region to the high Dinaric karst, and were investigated by paleolimnological research methods to determine the timing of lake formation in Dalmatia, paleoenvironmental changes, the influence of geomorphological processes on their evolution, and hydroclimatic variations. The results of this extensive study point to the dynamic evolution of karst lakes, primarily controlled by Holocene climate changes and by sedimentological and geomorphological processes. Lake formation at the studied sites began roughly during the Late Pleistocene/Holocene transition. This initial phase was marked by dynamic environmental conditions and increased detrital input from the catchment, primarily from flysch deposits. At the same time, ostracod assemblages suggest the development of floodplains and wetlands. This is followed by basin deepening and formation of true lacustrine environments during the Early-Middle Holocene, characterized by carbonate sedimentation and abundant ostracods, gastropods, and Charophytes. Stable isotope analysis of lake carbonates and ostracod shells points to a generally wetter early Middle Holocene and progressive aridification toward the Late Holocene. This pattern agrees with other records in the Mediterranean region. However, discrepancies in paleoclimate records, such as lower lake levels in karst poljes during the wetter Early Holocene or hydrological disturbances during the generally arid Roman Warm Period, likely reflect geomorphological processes in karst that create high surface-to-subsurface connectivity, a key feature of Dinaric karst poljes. This dissertation provides new insights into paleoclimatic changes in the karst lakes and poljes in Dalmatia, emphasizes the influence of geomorphology on their evolution, and represents a key step toward recovering long sediment records of glacial-interglacial cycles in Dinaric karst poljes.

PROŠIRENI SAŽETAK

Uvod

Jezera predstavljaju povoljne taložne okoliše za proučavanje prošlih okolišnih i klimatskih promjena, dok jezerski sedimenti akumulirani na njihovom dnu omogućuju rekonstrukciju tih promjena primjenom različitih paleolimnoloških metoda. Jezerski sedimenti stoga imaju važnu ulogu u kvartarnim istraživanjima, osobito tijekom holocena, koji je obilježen relativno stabilnim klimatskim uvjetima u usporedbi s posljednjim glacijalnim periodom, ali i dalje vrlo značajnim za čovjeka i ekosustave. U kontekstu holocenskih istraživanja, posebno je značajno područje Sredozemlja zbog svoje osjetljivosti na hidroklimatske promjene, ali i zbog duge povijesti ljudskog utjecaja na okoliš, što jezerske sedimente čini vrijednim arhivima za proučavanje složenih interakcija između klimatskih i antropogenih signala. Jezera na području Sredozemlja su relativno dobro istražena te dosadašnje spoznaje upućuju na generalno vlažnije uvjete tijekom ranog holocena s dugotrajnom i postupnom aridifikacijom tijekom srednjeg i kasnog holocena. Međutim, novija istraživanja upućuju na značajnu prostorno-vremensku varijabilnost, posebno između sjevernog i južnog te zapadnog i istočnog dijela Sredozemlja. Stoga je paleoklimatska istraživanja potrebno provoditi na što većoj prostornoj rezoluciji, osobito u središnjem dijelu Sredozemlja, koje predstavlja sponu između njegova zapadnog i istočnog dijela. U tom kontekstu, krška jezera i paleojezera u krškim poljima u Dinaridima predstavljaju vrijedne arhive koji doprinose razumijevanju holocenske klimatske varijabilnosti na području središnjeg Sredozemlja. Kao jedan o glavnih tipova jezera na području Hrvatske i Sredozemlja, krška jezera su dodatno zanimljiva jer predstavljaju kompleksne arhive gdje sedimentni zapis ne odražava samo klimatske i okolišne promjene, već i hidrološke, hidrogeološke i geomorfološke procese karakteristične za osjetljive krške sustave. Međutim, kvartarni sedimenti u krškim jezerima, a posebno u krškim poljima su još uvijek nedovoljno istraženi te nedostaju kontinuirani zapisi koji bi nam omogućili uvid u paleoklimatske promjene tijekom prošlosti. To se naročito odnosi na paleoklimatska istraživanja temeljena na analizama stabilnih izotopa u jezerskim sedimentima i ljušturicama mikrofosila izgrađenih od karbonata, poput ostrakoda. Stoga su u sklopu ove disertacije odabrana tri krška jezera i paleojezera u krškim poljima Dalmacije, na potezu od istočne obale Jadranskog mora (Velo Blato na otoku Pagu), preko Ravnih kotara (Bribirsko-ostrovičko polje) do visokog dinarskog krša (Prološko Blato u Imotskom polju), koja su istraživana paleolimnološkim metodama s ciljem proučavanja navedenih procesa te paleookolišnih i paleoklimatskih promjena tijekom holocena.

Ciljevi i hipoteze

Osnovni cilj doktorskog rada je načiniti paleookolišnu i paleoklimatsku rekonstrukciju razvoja triju krških jezera u Dalmaciji tijekom holocena, na temelju sedimentoloških, geokemijskih i ostrakodoloških pokazatelja u jezerskim sedimentima.

Hipoteze doktorskog rada temelje se na sljedećim pretpostavkama:

- 1) Razvoj istraživanih krških jezera i paleojezera u Dalmaciji uvjetovan je geomorfološkim procesima i klimatskim promjenama, koje je moguće rekonstruirati pomoću posrednih pokazatelja u jezerskim sedimentima.
- 2) Promjene u ostrakodnoj fauni odraz su promjena u okolišu – hidroloških, geokemijskih i sedimentoloških.

Znanstveni doprinos

Paleolimnološka istraživanja u Dinaridima tijekom kvartara nisu brojna te nedostaju kontinuirani kopneni paleookolišni i paleoklimatski zapisi koji bi nam omogućili uvid u paleoklimatske promjene tijekom prošlosti. Ova disertacija, koja obuhvaća detaljne rekonstrukcije razvoja triju dinarskih krških jezera tijekom holocena, upotpunjuje prostornu prazninu u paleoklimatskim istraživanjima na području Sredozemlja te omogućuje povezivanje regionalnih zapisa s drugim kopnenim i morskim arhivima. Najveći metodološki iskorak u kontekstu paleoklimatskih istraživanja u Dinaridima je primjena metode stabilnih izotopa kisika i ugljika u jezerskim sedimentima i ljušturicama mikrofosila (ostrakoda), koji pružaju najbolji uvid u hidroklimatske varijacije tijekom prošlosti. Osim toga, korištenje različitih sedimentoloških, geokemijskih i ostrakodoloških pokazatelja u istraživanim jezerskim sedimentima, komplementarno s geofizičkim i geomorfološkim istraživanjima, omogućilo je nove spoznaje o procesima koji utječu na okolišne uvjete u krškim jezerima, poput geomorfoloških, što u konačnici utječe na interpretaciju paleoklimatskog signala na temelju stabilnih izotopa kisika i ugljika. Zaključno, disertacija je potvrdila da i krška polja u Dinaridima sadrže vrijedne paleoklimatske arhive tijekom holocena, što predstavlja ključan korak u istraživanju dugih kopnenih paleoklimatskih zapisa o glacijalno-interglacijalnim ciklusima.

Metode i postupci

Paleolimnološka istraživanja provedena su na tri područja duž transekta od istočne obale Jadranskog mora do područja visokog dinarskog krša, odnosno od Velog blata na otoku Pagu, preko Bribirsko-ostrovičkog polja u Ravnim Kotarima do Prološkog blata u Imotskom polju. Terenska istraživanja obuhvaćala su geofizička istraživanja geoakustičnim metodama i metodom georadara radi karakterizacije batimetrije i morfologije jezera te debljine i prostiranja jezerskih naslaga u krškim

poljima, zatim bušenje i uzorkovanje jezerskih sedimenata, kao i stijena sa slivnog područja (karbonata i fliša), te mjerenja fizičko-kemijskih parametara i uzorkovanje jezerskih voda. Geomorfološke značajke terena istraživane su prostornim analizama u GIS-u. Jezgre jezerskih sedimenata analizirane su u laboratoriju tzv. multiproxy pristupom. Sedimentološke metode sastojale su se od mjerenja boje i magnetskog susceptibiliteta, zatim strukturnih i teksturnih karakteristika sedimenata, određivanja veličine čestica laserskim difraktometrom, te određivanja ukupnog mineralnog sastava te minerala glina metodom rendgenske difrakcije na prahu (XRD). Geokemijske metode obuhvaćale su mjerenje ukupnog organskog i anorganskog ugljika (TOC, TIC) i dušika (TN) korištenjem CN analizatora. Od elementnih analiza određivani su glavni elementi i elementi u tragovima metodom masenog spektrometra s induktivno spregnutom plazmom (ICP-MS). Stabilni izotopi kisika i ugljika ($\delta^{18}\text{O}$ i $\delta^{13}\text{C}$) u jezerskim sedimentima i ljušturicama ostrakoda analizirani su metodom masene spektrometrije izotopnih omjera. Mikropaleontološke analize ostrakoda provedene su kvalitativno i kvantitativno koristeći lupu i skenirajući elektronski mikroskop (SEM). Starost sedimenata utvrđena je metodom radioaktivnog ugljika (^{14}C) i popratnim modeliranjem dubina-starost (age-depth modelling). U jezeru Velo Blato određivane su i koncentracije radioaktivnog cezija (^{137}Cs). Hidrokemijske analize u uzorcima jezerskih voda obuhvaćale su određivanje aniona i kationa te analizu stabilnih izotopa kisika i vodika u uzorcima jezerskih voda. Konačno, mikropaleontološki i geokemijski podaci obrađivani su statističkim metodama s naglaskom na primjenu metode kompozitnih podataka (CoDa) na ostrakodima u Velom Blatu te glavnim elementima i elementima u tragovima u Prološkom Blatu. Dobiveni paleoklimatski zapisi omogućili su usporedbu s drugim kopnenim i morskim zapisima na području Jadranskog mora i Sredozemlja, te evaluaciju geomorfoloških procesa koji utječu na interpretaciju stabilnih izotopa u krškim jezerima.

Rezultati i zaključci

Rezultati ovog opsežnog istraživanja ukazuju na dinamičan razvoj krških jezera, koji je prvenstveno bio uvjetovan klimatskim promjenama tijekom holocena, ali i sedimentološkim i geomorfološkim procesima. Početak formiranja jezera može se okvirno smjestiti na granicu kasnog pleistocena i holocena, a obilježen je dinamičnim okolišnim uvjetima i pojačanim donosom detritalnog materijala iz slivnog područja jezera, ponajprije iz fliških naslaga. Istovremeno, zajednice ostrakoda upućuju na razvoj poplavnih ravnica i močvarnih okoliša. Nakon toga slijedi produbljivanje bazena i formiranje pravih jezerskih okoliša tijekom ranog i srednjeg holocena, koje karakterizira taloženje jezerskog karbonata bogatog ostrakodima, gastropodima te ostacima algi Charophyta. Analize stabilnih izotopa u jezerskim karbonatima i ljušturicama ostrakoda ukazuju na generalno vlažnije uvjete u ranijem dijelu srednjeg holocena, s postupnim trendom aridifikacije prema kasnom holocenu, što je generalno u skladu s drugim zapisima s područja Sredozemlja. Međutim, utvrđena su značajna odstupanja u

paleoklimatskim zapisima. Primjerice, većina jezera s područja Sredozemlja bilježi relativno više razine jezera tijekom generalno vlažnijeg ranog holocena, u skladu s većom godišnjom količinom padalina, a time i većeg hidrološkog dotoka u jezero. Međutim, paleojezera u krškim poljima su u tom periodu obilježena relativno niskim razinama, odnosno poplavnim ravnicama koje označavaju tek začetak formiranja pravih jezera. Rezultati ovog istraživanja nude moguće objašnjenje ove kontradiktornosti, a koje leži u činjenici da se krška polja odlikuju velikom povezanošću između površinskih i podzemnih voda sve dok se ne stvori prirodna nepropusna barijera koja će spriječiti otjecanje površinskih voda u podzemlje. Istraživana jezera pokazuju da takve barijere, barem u dinarskim krškim poljima, najvjerojatnije predstavljaju glinovite naslage koje se nalaze u njihovom slivu, u ovom slučaju fliške naslage koje su pretaložene u jezero erozijskim procesima. S druge strane, hidrološki poremećaji evidentirani u zapisu stabilnih izotopa kisika i ugljika tijekom općenito sušnog i toplog rimskog perioda, vjerojatno su posljedica geomorfoloških procesa u kršu koji dovode do snažne povezanosti površinskih i podzemnih voda, što je jedno od glavnih obilježja dinarskih krških polja. Stoga je jedan od najvažnijih zaključaka disertacije da klimatske promjene i ljudska aktivnost nisu jedini faktori koji utječu na evoluciju krških jezera te da se i drugi lokalni procesi moraju evaluirati korištenjem geomorfoloških, geofizičkih i sedimentoloških metoda, posebno u kompleksnim područjima kao što su krška jezera i polja.

KEYWORDS

Paleolimnology

Karst lakes and paleolakes

Dinarides

Mediterranean

Holocene

Lake sediments

KLJUČNE RIJEČI

Paleolimnologija

Krška jezera i paleojezera

Dinaridi

Sredozemlje

Holocen

Jezerski sedimenti

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1. INTRODUCTION

1.1. Paleolimnology

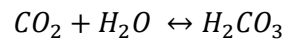
Paleolimnology is the scientific discipline that investigates past conditions and processes in lake basins and interprets their history through physical, chemical, and biological indicators preserved in lake sediments (Last & Smol, 2001). Lakes continuously accumulate sediment from their surroundings, and their life cycle typically ends with the formation of marshes and swamps (Löffler, 2004), a process known as lake ontogeny. Sedimentation rates in lakes are relatively rapid compared with those in oceans and other terrestrial systems, making lakes particularly sensitive to environmental changes driven by climatic variability, catchment processes, and human activity (Cohen, 2003). These changes can be well preserved in sediments at high temporal resolution, spanning seasonal to millennial and orbital timescales (Ruddiman, 2014; Bradley, 1999).

A lake's hydrological cycle describes the continuous circulation of water entering and leaving a lake system and determines its overall water balance. Water inputs include precipitation (rain and snow) falling directly onto the lake surface, surface inflow via rivers, and groundwater inflow. In contrast, outputs include evaporation, surface outflow via rivers, and groundwater outflow (Winter, 2004). Hydrologically open (exorheic) lakes are characterized by natural outflow, which eventually drains into the ocean (Löffler, 2004). Hence, an open lake is characterized by continuous water throughflow and relatively stable water levels, since inputs and outputs are equal (Cohen, 2003). In contrast, hydrologically closed (endorheic) lakes have no surface outflows and lose water mainly through evaporation. Here, the water budget is governed by the balance between precipitation and evaporation (effective moisture), resulting in frequent water-level fluctuations (Cohen, 2003; Löffler, 2004).

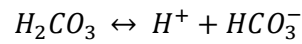
Lake waters can stratify into the warm upper epilimnion, the cold deep hypolimnion, and the middle metalimnion (Cohen, 2003). Lake mixing usually occurs twice a year, in spring and autumn, which regulates the distribution of oxygen and nutrients throughout the water column (Cohen, 2003). Dissolved oxygen (DO) is vital for aquatic life. It comes from the air via atmospheric diffusion and, as a byproduct of photosynthesis, from aquatic plants and algae. DO concentrations are influenced by productivity, respiration, temperature, and mixing.

Carbon cycles through lakes in complex pathways and in various organic and inorganic forms, and as particulate and dissolved organic matter (Cohen, 2003). Major sources of particulate organic carbon (POC) include dead plants, algae, and terrestrial runoff (e.g., leaves, soil), while dissolved organic carbon (DOC) comprises organic molecules dissolved in water, such as sugars, amino acids, and humic

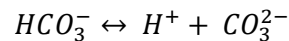
substances. Inorganic carbon is mainly dissolved carbon dioxide (CO₂) and bicarbonates from weathering and groundwater, while atmospheric CO₂ diffuses directly into the water surface. When dissolved in lake water, CO₂ reacts with water to form carbonic acid:



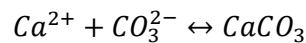
Subsequently, two dissociation reactions may occur:



and



The above equations describe the chemical equilibrium among dissolved forms of inorganic carbon in water, known as the carbonate equilibrium, which is pH-dependent. At low pH, most carbon is in the form of CO₂ and H₂CO₃. At neutral pH, bicarbonate (HCO₃⁻) dominates the system, and at high pH, carbonate (CO₃²⁻) becomes more abundant (Deocampo, 2010). The calcium in lake water combines with carbonate to form calcium carbonate:



Inorganic carbonate precipitation depends on the carbonate equilibrium and several environmental factors. In essence, any process that removes CO₂ from the system increases carbonate precipitation and decreases its solubility. Photosynthesis and CO₂ degassing remove CO₂, while respiration and organic matter decomposition add it, thus promoting CaCO₃ dissolution (Cohen, 2003). Evidently, for inorganic carbonates to precipitate at all, the concentrations of Ca²⁺ and CO₃²⁻ must be elevated to the point of supersaturation. This is achieved when the ion activity product of Ca²⁺ and CO₃²⁻ in a solution exceeds the mineral's solubility product constant (Kelts & Hsü, 1978). Such conditions are easily achieved in catchments comprised of carbonate bedrock or, for example, in summer when supersaturation is reached due to evaporative concentration (Deocampo, 2010).

Solutes and particulates are transported to the lake via rivers, groundwater, atmospheric gas exchange, airborne particulate matter, and precipitation (Cohen, 2003). Most lakes contain major ions such as Na⁺, K⁺, Ca²⁺, Mg²⁺, Cl⁻, HCO₃⁻, CO₃²⁻, and SO₄²⁻. Na⁺, K⁺, and Cl⁻ dominate coastal lakes, with Na⁺ and K⁺ also originating from feldspar hydrolysis. Mg²⁺ and Ca²⁺ can come from marine sources, chemical weathering of limestone and dolomite, or basic igneous rocks, while HCO₃⁻ and CO₃²⁻ mainly result from limestone weathering. Nutrients such as phosphorus and nitrogen are essential for the growth of autotrophic organisms in lakes, and thus for organic productivity (Cohen, 2003).

Salinity is the total concentration of dissolved ions in water, typically expressed in milligrams per liter (Cohen, 2003). Lake salinity is determined by the balance between salt inputs from various sources and their removal through outflow and mineral precipitation (Cohen, 2003). In general, hydrologically open lakes tend to have lower salinities because dissolved salts are washed out through outflow, while closed lakes are more prone to salt accumulation because dissolved ions are retained within the basin (Cohen, 2003; Löffler, 2004). The latter are especially important to paleolimnologists because salinity changes in closed basins provide valuable paleoclimate information, as they reflect changes in the balance between precipitation, runoff, and evaporation (Cohen, 2003).

The isotopic composition of lake waters provides crucial information on hydrological processes and past environmental and climatic conditions. The $\delta^{18}\text{O}$ of lake water is determined by the isotope composition of the precipitation received by the lake and any subsequent hydrological modification of the signal by catchment and within-lake processes (Leng & Marshall, 2004). In hydrologically closed lakes, the $\delta^{18}\text{O}$ of lake water is primarily determined by the balance between precipitation and evaporation (effective moisture). Evaporation is a kinetic process that removes the lighter oxygen isotope (^{16}O) from lake water at a rate controlled by wind speed, relative humidity, and temperature (Ito, 2001), resulting in elevated $\delta^{18}\text{O}$ values in the lake water above those of the background precipitation (Leng et al., 2006). In contrast, $\delta^{18}\text{O}$ values in waters from hydrologically closed lakes will primarily reflect the $\delta^{18}\text{O}$ of the background precipitation (Leng & Marshall, 2004). The $\delta^{13}\text{C}$ of lake water is essentially the isotopic composition of dissolved inorganic carbon ($\delta^{13}\text{C}_{\text{DIC}}$), which is controlled by the isotopic composition of the inflowing waters, CO_2 exchange with the atmosphere, and photosynthesis/respiration of aquatic plants within the lake (Leng & Marshall, 2004). Thus, interpreting sedimentary stable isotope records requires a good understanding of modern hydrological and biological conditions.

Biological processes provide a fundamental source of information for paleolimnologists, as aquatic organisms are sensitive to environmental variations, including pH, temperature, salinity, and the ionic composition of lake water. Shallow, littoral zones of the lake are usually rich in autotrophic and heterotrophic organisms, as light is not a limiting factor for growth (Cohen, 2003). This zone is inhabited by various aquatic plants (emergent and submerged macrophytes), which provide a substrate for many attached or crawling organisms such as ostracods and gastropods. In contrast, the deep, profundal zone lacks autotrophic organisms, and food resources primarily come from secondary productivity, consumption of settling organic detritus, and microbial activity (Cohen, 2003). The sublittoral zone refers to intermediate depths where photosynthesis is restricted to benthic algae and cyanobacteria (Cohen, 2003).

1.2. Defining karst: sinkholes, lakes, and poljes

Karst is a type of landscape formed by the dissolution of soluble rocks, typically limestone and dolomite, as well as marble and gypsum (Ford & Williams, 2007). It is characterized by well-developed secondary porosity from progressive aqueous dissolution, creating an extensive underground network of conduits and cave systems that redirect surface water into subsurface flow. Dissolution of carbonate rocks is the fundamental process in karst formation and a prerequisite for the formation of any karst feature or landform (Ford, 2004). Karst landscapes are characterized by features such as springs, swallow holes (ponors), sinking rivers and streams (ponornica), caves, sinkholes (dolines), and estavelles. These features were first systematically described in the Dinarides (Cvijić, 1893), a mountain range in Southeastern Europe with a long tradition of karst research, often regarded as the cradle of modern karst geomorphology. Karst landscapes cover about 10–15% of Earth's continental land surface, while roughly 20–25% of the global population depends on groundwater from karst aquifers (Ford & Williams, 2007). These systems are under increasing pressure driven by growing demand, intensifying land-use practices, and climate change, and thus require sustainable management (Ford & Williams, 2007). Karst is particularly sensitive to climate change because of its highly soluble lithology, limited natural filtration capacity, and rapid groundwater flow through conduits, which make hydrological systems highly responsive to changes in precipitation and temperature. Paleoenvironmental and paleoclimate studies in karst are therefore crucial, as they provide geological records of past climate variability, which can help us understand the hydrological responses of these vulnerable systems. Such studies are typically conducted on cave deposits (speleothems) and lake sediment cores obtained from karst lakes.

Sinkholes, or dolines, are enclosed depressions often regarded as diagnostic features of karst terrain (Williams, 2004; Waltham et al., 2005). They form through chemical dissolution of soluble bedrock, followed by collapse into an underground cavern. Ford & Williams (2007) distinguish two types of sinkholes: collapse sinkholes, formed by fracturing and collapse of a cave roof, and subsidence sinkholes, which involve a more gradual process of sagging and suffosion into an underground cavity. If the collapse reaches the groundwater level, a newly formed sinkhole can fill with water, forming a karst lake. A karst lake is therefore a surface accumulation of water directly connected to groundwater through its sides and bottom (Cohen, 2003). Surface-to-subsurface connectivity is a key feature of karst lakes. They are almost always associated with depressions, since they rely on a natural basin to collect and hold water. Besides sinkholes, karst lakes can also form in karst poljes, either as permanent (perennial) or seasonal (ephemeral) water bodies.

Karst poljes are one of the largest surface karst landforms, often defined as enclosed depressions in limestone terrain (Ford & Williams, 2007; Bonacci, 2013). They have a relatively flat floor, steeply rising marginal slopes, and karstic drainage (Ford & Williams, 2007). The origin of poljes is considered polygenetic (De Waele et al., 2009) and remains the subject of debate (Bonacci, 2013). Polje formation involves processes such as dissolution, tectonic activity, cave collapses, fluvial processes, and sediment infilling (Roglić, 1964). However, they are usually bounded by major faults, implying a strong control of tectonic movements on their origin. Poljes are characterized by complex hydrology and hydrogeology. They regularly experience seasonal flooding during the wet part of the year, when groundwater levels rise, or surface inflows exceed the drainage capacity of ponors (Bonacci, 2013). This flooding can create temporary, seasonal lakes, often referred to as karst wetlands (e.g., Cerknjško Polje in Slovenia, Livanjsko Polje in Bosnia and Herzegovina), where sedimentation occurs during the flooding period. Sediment can clog surrounding ponors, resulting in the formation of a permanent lake (Kindinger, 1999). Over time, ponors can reactivate, allowing sediment to be flushed into the conduits (Kindinger, 1999). Thus, poljes represent natural water reservoirs and sediment traps, which makes them important sedimentary archives within the otherwise barren karst terrain.

Some of the best examples of karst polje depressions can be found in the Dinarides, where they are distributed from the highest peaks (higher poljes) to the Adriatic Sea (lower poljes) (Mijatović, 1984), and aligned along the tectonic boundaries in the NW–SE direction known as the “Dinaric strike”. A combination of tectonic movements and paleoclimatic changes in the Neogene and Quaternary resulted in various depositional environments, the best known of which is the Dinaride Lake System (DLS) (e.g., Đujić, 1997; Krstić et al., 2003; Harzhauser & Mandić, 2008; de Leeuw et al., 2011, 2012; Sant et al., 2018). However, Quaternary deposits in Dinaric karst poljes represent a crucial yet underexplored sedimentary archive, offering valuable insights into past environmental and climatic changes through their physical, biological, and geochemical records.

1.3. The Holocene

The Quaternary period, which began approximately 2.6 million years ago and continues to the present, is characterized by repeated glacial-interglacial cycles that caused major fluctuations in global climate, ice-cap volume, and sea level. These oscillations were primarily driven by variations in Earth's orbital parameters, known as Milankovitch cycles, which control the distribution of solar radiation in the Northern Hemisphere (Cronin, 2010). The most recent period in Earth's history when ice sheets reached their greatest extent is the Last Glacial Maximum (LGM), which lasted between ca. 26.5 ka and 19 ka BP (Clark et al., 2009). Following the LGM, Earth began to warm as a gradual increase in solar energy reached northern latitudes during the Last Deglaciation, characterized by ice melting and global sea-level rise (Clark et al., 2012).

The Holocene is the current interglacial period, which began around 11.7 ka BP. It is characterized by the stabilization of global temperatures following the cold, variable climate of the Late Pleistocene. This enabled environmental reorganization, vegetation expansion, and the rise of complex human societies (Roberts, 2014). The Holocene is subdivided into three stages: Early Holocene - Greenlandian (11.7–8.2 ka), Middle Holocene - Northgrippian (8.2–4.2 ka), and Late Holocene – Meghalayan (4.2 ka–present) (Walker et al., 2018). These subdivisions are based on the prominent climatic anomalies known as the “8.2 ka event”, an abrupt cooling event recorded in Greenland ice cores and elsewhere in the world (e.g., cave speleothems in Brazil and India), and the “4.2 ka event”, an abrupt arid event recorded primarily in South and Southeastern Asia. However, a recent study questions the interpretation of the “4.2 ka event” as a globally significant climatic anomaly (McKay et al., 2024), while a recent review of the Holocene subdivisions finds no evidence for a global climatic event and argues that the decision of the International Commission on Stratigraphy to define the Meghalayan Stage should be rescinded (Bradley, 2025). Global temperature reconstructions at the millennial timescale indicate a rise of approximately 0.6°C from the Early Holocene, culminating in a prolonged interval of relatively stable warmth between 9.5–5.5 ka, a period known as the Holocene Climatic Optimum, which was followed by a cooling of 0.7°C until around 100 years ago (Lowe & Walker, 2014). The general tripartite nature of Holocene climate evolution is largely governed by millennial changes in summer insolation, from high summer insolation in the Northern Hemisphere between approximately 11.7 and 7.0 ka, to its gradual decline towards the modern period (Wanner et al., 2011).

On sub-millennial timescales, Holocene climate variability becomes far more complex, driven by interactions among solar and volcanic activity, greenhouse gases, ocean circulation variability, and feedbacks from sea ice, vegetation, and land cover, resulting in great heterogeneity and asynchrony (Cronin, 2010). From a geological perspective, decadal-to-centennial climate changes are considered

very short-term fluctuations, yet they remain significant for humans and ecosystems. Of particular interest are the climate epochs of the Common Era (last 2000 years), including the Roman Warm Period (RWP) (~1–300 AD), the Dark Age Cold Period (DACP) (~300–800 AD), the Medieval Warm Period (MWP) (~800–1300 AD), and the Little Ice Age (LIA) (~1300–1900 AD) (Ljungqvist, 2010). The MWP and the LIA represent the most notable climate shifts of the Late Holocene, transitioning from the relatively warm conditions of the MWP, which in some regions matched or even exceeded temperatures of the past decade (Mann et al., 2009), to the markedly cooler temperatures of the LIA, likely the coldest period in the last 8000 years (Wanner et al., 2022). Although the drop in mean temperature (~0.6°C) was incomparable to that of the Last Ice Age (4–6°C, even more than 10°C in some regions), it nonetheless triggered significant environmental changes, such as glacier advances, altered precipitation patterns, and increased frequency of crop failures and famine (Lowe & Walker, 2014; Roberts, 2014; Wanner et al., 2022). The climate epochs of the Common Era, however, show a strong regional character and do not appear to represent globally synchronous climate events (PAGES 2k Consortium, 2013; Neukom et al., 2019).

In contrast to the predominantly regional and spatially heterogeneous temperature variability of the preindustrial Common Era, the last ca. 150 years are characterized by unprecedented, near-global warming (PAGES 2k Consortium, 2013; Neukom et al., 2019). The pioneering reconstructions of Mann et al. (1998, 1999) indicated relatively modest variability in Northern Hemisphere mean temperature before the twentieth century, but recent warming that strongly contrasts with the preceding millennium. Subsequent reconstructions based on more extensive proxy databases and alternative methodologies found greater regional climatic variability in the preindustrial Common Era, but nevertheless indicated the unusual character and spatial extent of recent Northern Hemisphere warming (Moberg et al., 2005; Hegerl et al., 2007; Mann et al., 2008, 2009; Ljungqvist, 2010; PAGES 2k Consortium, 2013, 2019), consistent with anthropogenic greenhouse-gas forcing (Hegerl et al., 2007; Summerhays et al., 2024). Studies of Holocene climate variability are therefore crucial for understanding the balance between natural and anthropogenic influences and provide a baseline for future climate predictions.

2. THESIS RATIONALE

The Mediterranean region is highly sensitive to global-scale climate patterns due to its unique position between mid-latitude and tropical climates and its semi-enclosed nature (Lionello et al., 2012). The hallmark of a typical Mediterranean climate is the pronounced contrast between the wet (winter) and dry (summer) seasons. During summer, the Mediterranean Sea stores large amounts of heat and releases it into the atmosphere in autumn and winter, enhancing storm activity and heavy precipitation in adjacent regions. This pronounced seasonality amplifies hydrological extremes (droughts and floods), which can have a profound impact on human societies, infrastructure, and agriculture. Thus, the Mediterranean region is considered a hotspot for paleoclimate and paleoenvironmental research due to its climatic sensitivity and long history of human occupation, which enable insights into both natural climate variability and human-climate interactions. In general, the Holocene climate evolution in the Mediterranean region began with a humid Early Holocene, followed by a gradual drying trend during the Middle and Late Holocene (Roberts et al., 2008; Peyron et al., 2011; Finné et al., 2019). However, spatiotemporal incoherencies in climate variability are a well-known feature of the Mediterranean climate (Finné et al., 2019), and different patterns have been proposed, including east-west (Roberts et al., 2011; Finné et al., 2019) and north-south (Magny et al., 2012, 2013) divisions, suggesting different influences on Holocene climate evolution in the Mediterranean. To better understand these regional differences and their underlying drivers, more high-resolution paleoclimatic and paleoenvironmental records are needed, particularly from the central Mediterranean, a crucial link between the western and eastern sectors (Finné et al., 2019).

Paleolimnological records of Holocene climate and environmental changes in the central Mediterranean are numerous, with most studies conducted in Italy and southeastern Europe. These records provide insights into Holocene climate variability based on geochemical, mineralogical, sedimentological, and micropaleontological indicators in lake sediments: Lake Shkodra (Mazzini et al., 2016; Zanchetta et al., 2012), Ohrid (Lacey et al., 2015), Prespa (Leng et al., 2013), Butrint (Morellón et al., 2016), Dojran (Francke et al., 2013), Trichonida (Seguin et al., 2020), Lake Accesa (Magny et al., 2007), Trasimeno (Marchegiano et al., 2018), Preola and Gorgo Basso (Curry et al., 2016), Pergusa (Sadori & Narcisi, 2001; Zanchetta et al., 2007, 2022), among others. Studies in karst poljes have traditionally focused on hydrogeology, geomorphology, tectonics, glacial and fluvio-glacial processes (e.g., Gracia et al., 2003; Jiménez-Sánchez et al., 2013; Žebre et al., 2016). In paleolimnological research, karst poljes have received little attention and do not yet appear to be recognized as valuable terrestrial archives of paleoenvironmental and paleoclimatic change. For example, researchers have studied socio-environmental changes during the Holocene in Greece by combining multiproxy core

analysis with historical records of human settlement and interventions in poljes, such as Lake Symphalia (Seguin et al., 2019) and the poljes of Assea, Pheneos, and Kaisari (Seguin et al., 2020).

Karst lakes are the primary lake type in Croatia and are mostly found along the eastern Adriatic Coast (EAC). Paleolimnological studies during the Holocene were conducted at Lake Vrana on the island of Cres (Hajek-Tadesse et al., 2011; Ilijanić, 2024), at Lake Vrana near Biograd na Moru (Hajek-Tadesse et al., 2015, 2018a; Ilijanić, 2014), and at Lake Crniševu within the Baćina Lakes (Ilijanić, 2014; Hajek-Tadesse et al., 2019). Furthermore, research on drowned karst landscapes along the EAC included multiproxy sediment core analysis and geophysical methods (Brunović et al., 2020; 2024; Hasan, 2017, 2024; Ilijanić, 2014, 2025; Razum, 2018, 2021; Smrkulj et al., 2024, 2025, 2026). These records provide excellent insight into terrestrial paleoenvironmental variations in closed karst depressions, particularly those associated with the post-glacial and Holocene sea-level rise. In contrast to the research on the EAC, Holocene paleoenvironmental studies in karst poljes are rare and have been conducted so far only in Bokanjačko Blato near the city of Zadar (Ilijanić et al., 2018), Čepić Polje in Istria (Balbo et al., 2006), and Vrgoračko Polje in southern Dalmatia (Posilović et al., 2018), as well as earlier investigations of marl deposits of uncertain age based on ostracod fauna (Jurišić-Polšak et al., 1993; Sokač, 1975). These karst poljes contain paleolakes that no longer exist because they were drained artificially. A possible explanation for the limited study of karst poljes could be seasonal flooding, which complicates geological fieldwork (e.g., paleolake determination using geophysical methods). However, past geological explorations often overlooked Quaternary lake sediments in karst poljes or misinterpreted them as alluvial, paludal, or wetland sediments.

To fill this gap, three karst lakes and paleolakes were investigated along a NW-SE transect extending from the eastern Adriatic coast to the high Dinaric karst: from Lake Velo Blato on Pag Island across Bribir-Ostrovica karst polje in Ravni Kotari to Prološko Blato in Imotsko Polje (Fig. 1). The main objective of this thesis is to reconstruct the paleoenvironment and paleoclimate in these three karst lakes based on sedimentological, geochemical, and ostracod proxies in lake sediments. These changes were first investigated in individual lakes and paleolakes, as presented in five original scientific papers in Chapter 7 (Appendix), while Chapter 4 (Discussion) presents an integrated discussion of the three study sites to assess the paleoenvironmental and paleoclimatic changes, including the timing of lake formation, hydroclimatic variations, and paleoenvironmental and geomorphological aspects of lake formation during the Holocene. These objectives are derived from the following hypotheses, which are tested in the final Chapter 5 (Conclusion):

1) It is assumed that the evolution of karst lakes and paleolakes in Dalmatia is controlled by geomorphological processes and climate changes, which can be reconstructed using the multiproxy study of lake sediments.

2) It is assumed that changes in the ostracod record reflect environmental changes in the investigated lakes, including hydrological, geochemical, and sedimentological changes.

Paleolimnological research on selected karst lakes and paleolakes provides a new contribution to our understanding of Holocene climate variability in Dalmatia, particularly in the Dinaric high karst zone, where such data are critically lacking. The results published in scientific papers are readily accessible for regional comparisons with other paleoclimate records derived from marine sediments, speleothems, and other lake sediments. Such comparisons are crucial for understanding both past and future climate changes and their impacts on human societies.

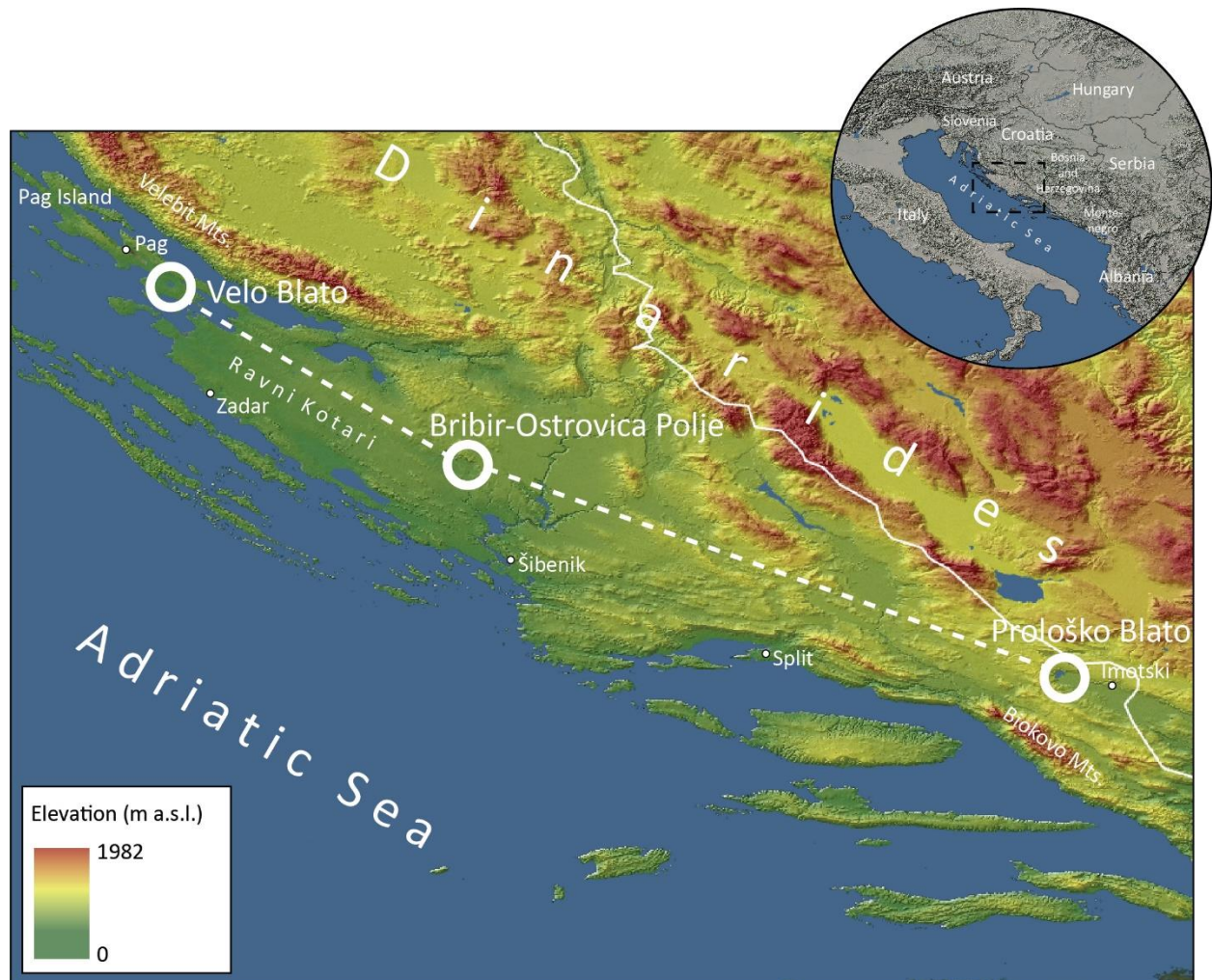


Figure 1. (A) Geographical position of the study area, and B) a transect of study sites extending from Lake Velo Blato on Pag Island across Bribir-Ostrovica Polje in Ravni Kotari to Prološko Blato in Imotsko Polje.

3. METHODOLOGY

3.1. Study sites

Lake Velo Blato is a shallow (less than 3 m deep) coastal karst lake situated in the southern part of the Island of Pag along the eastern Adriatic Coast (Croatia) (Fig. 1). It is a protected ornithological reserve, along with other wetlands on the island (Kolanjsko Blato, Malo Blato). The lake is a cryptodepression, with an average water depth of 0.5-2.4 m above sea level (a.s.l.), while the deepest point is at -1.8 m (Magdalenić, 1984). Due to its endorheic nature, lake levels (and salinity) are strongly controlled by the amount of precipitation received during the wet season (Fig. 2) (Magdalenić, 1984). Wetland vegetation is particularly well-developed along the northeastern margin of the lake and in the central part perpendicular to the NW-SE direction of the lake (Fig. 2).

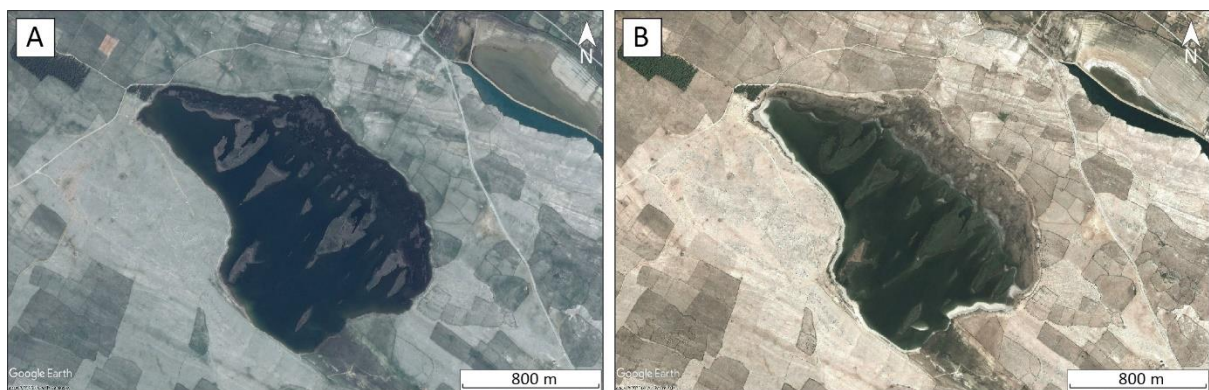


Figure 2. Google Earth satellite images of Lake Velo Blato: (A) high lake level in spring and (B) low lake level in summer.

The lake lies mostly on Cretaceous rudist and Eocene foraminiferal limestones, and only partly on Eocene flysch deposits (marls, sandstones) found in the southeastern part (Fig. 3) (Sokač et al., 1974, 1976). The relief is in accordance with geological structures: anticlines correspond to the island's highest parts, while synclines correspond to shallow depressions. Lake Velo Blato lies in such a depression. The landscape is generally characterized by poor vegetation cover due to sea salt aerosols spread across the island during strong Bora winds blowing from the Velebit Mts. The climate is typical Mediterranean (Csa, according to the Köppen climate classification) with high evaporation rates (Magdalenić, 1984), conditions favorable for salt production in coastal salt pans, possibly since Roman times.



Figure 3. (A) Field image of the southeastern shore of Lake Velo Blato showing a contact between (B) Eocene flysch deposits and (C) Eocene foraminiferal limestones.

Bribir-Ostrovica karst polje is one in a series of karst poljes in Ravni Kotari, a karstic lowland region in northern Dalmatia situated between the Adriatic coast and the hinterland (Fig. 1). The wider area is built of Cretaceous rudist limestones and alternating layers of limestones and dolomites, followed by the Eocene foraminiferal limestones, flysch deposits, and conglomerates and limestones (Mamužić, 1971, 1975). The Quaternary sediments are mostly found within the karst poljes and consist of slope-wash deposits (including clays, sands, and gravels) and lake sediments (Mamužić, 1971). Lake sediments are found in the central part of the polje (Fig. 4). The polje is seasonally flooded due to rising groundwater levels. The largest natural stream is the Bribirčica River in the southeastern part, while drainage canals intersect the rest of the polje. The wider area is rich in archeological heritage, including the Middle Neolithic site of Krivače in the southern part of the polje, Bribirska Glavica hill, colloquially known as the Croatian Troy, and the Medieval Ostrovica fortification. The Middle Neolithic site Krivače is particularly interesting, as it provides insights into early farming, animal domestication, development of permanent villages, pottery styles, and social organization (McClure et al., 2014, 2022). However, the evolution of the Bribir-Ostrovica polje has not been investigated in detail, beyond the initial geoarcheological studies (Podrug et al., in press).

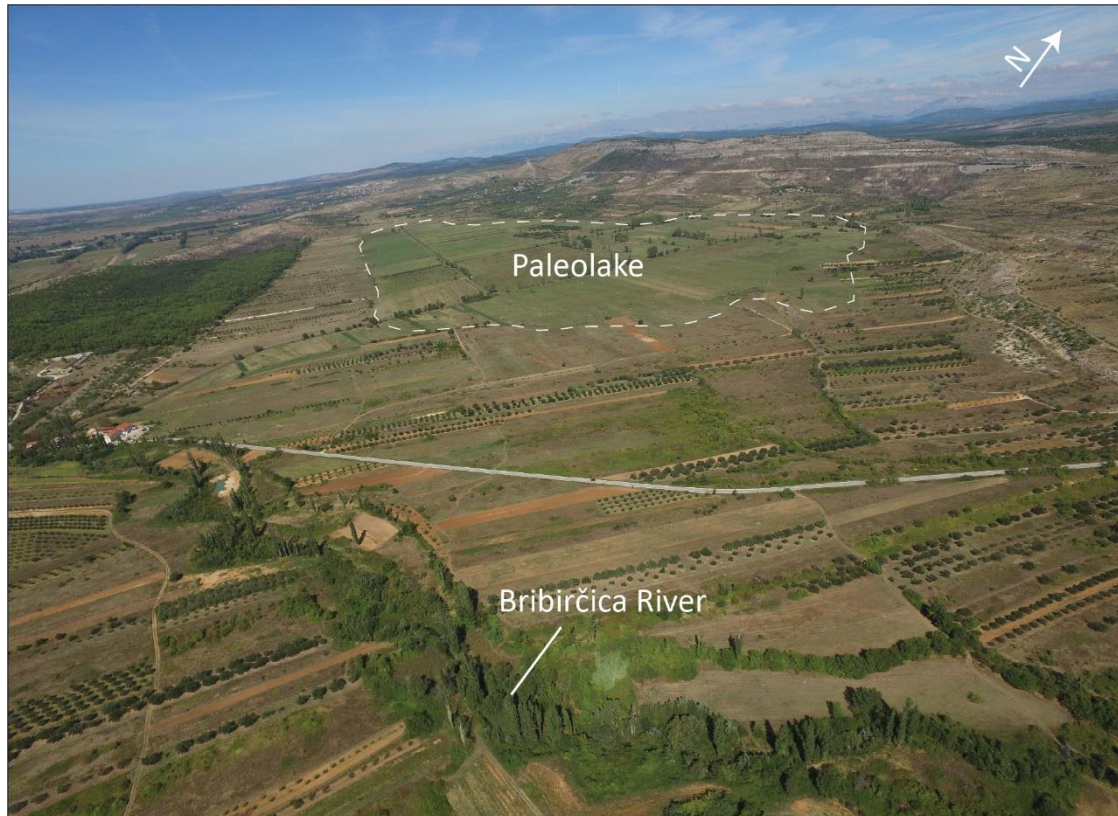


Figure 4. Drone image of the Bribir-Ostrovica karst polje showing the assumed paleolake extent in its central part and the Bribirčica River in the southeastern part.

Prološko Blato is a seasonally flooded karst wetland situated in the northwestern part of the Imotsko Polje (Fig. 1), one of the largest karst poljes in the Dinarides. It is a typical karst landscape with numerous geomorphological features, including springs, ponors, ponornica rivers, estavelles, and caves. However, the region is best known for its sinkholes, including Red Lake and Blue Lake near the city of Imotski. A less famous but still impressive group of sinkholes lies in the northwestern part of the Imotsko Polje and is called the Lokvičići Lake System, which includes Galipovac Lake, Knezovića Lake, Mamića Lake, and Prološko Lake.

The polje is surrounded by Cretaceous carbonates (limestones and dolomites), Paleogene flysch and Promina deposits, and Miocene marls, while the depression is filled with various Quaternary sediments (gravels, sands, clays) (Raić et al., 1976; Raić & Papeš, 1978). The region is seismically very active due to compressional tectonic movements between the Adriatic microplate and the Dinarides (Dragičević et al., 1999; Kuk et al., 2000). The hydrological conditions depend on precipitation rates in the Herzegovinian mountains, where larger surface rivers emerge and flow downstream through many poljes in a cascading drainage pattern, including the Suvaja River in Imotsko Polje.

Seasonal flooding in the Prološko Blato transforms the entire area into a shallow lake, and only a small, isolated hill (Manastir) remains above water, forming a small island (Fig. 5). The Manastir contains the ruins of a 16th-century Franciscan monastery. In the dry season, the water retreats into ponors along the edges of the polje and into the Prološko Lake and Krenica Lake (Fig. 5). Seasonal flooding is the main erosional process in the area, creating distinctive erosional channels with exposed paleolake sediments, which are then suitable for field sampling and mapping (Figs. 5 and 6).

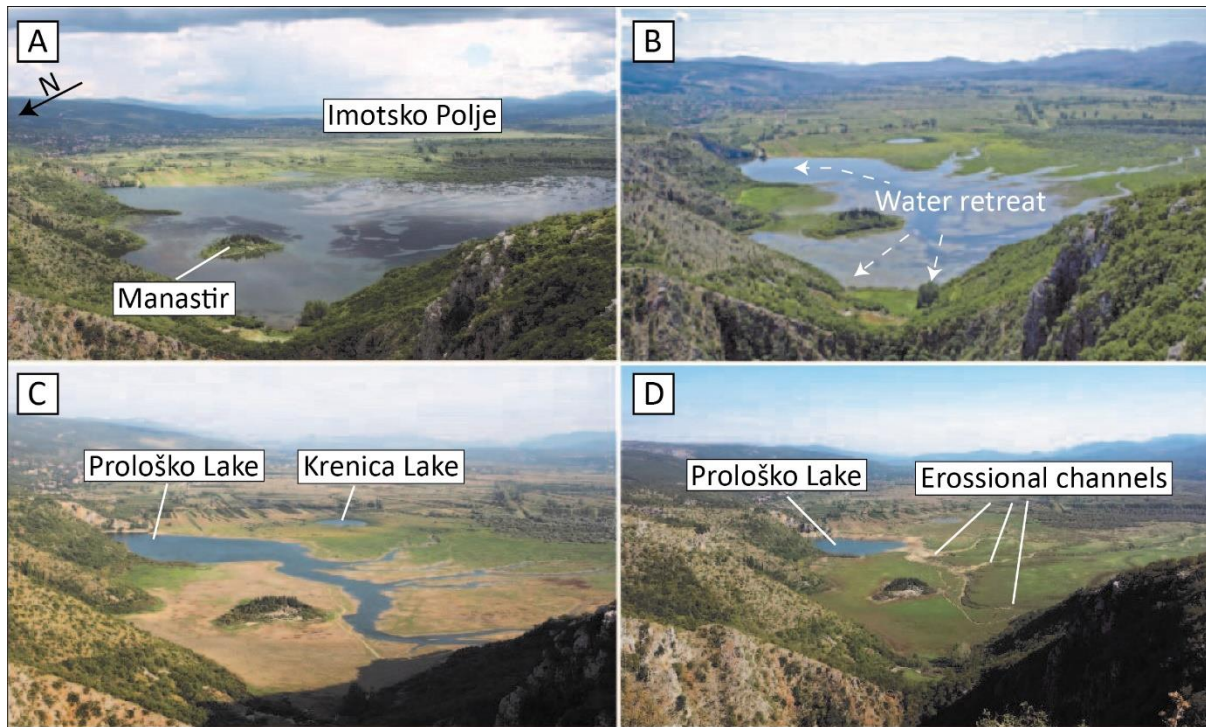


Figure 5. Field images of the Prološko Blato research area showing lake level changes due to seasonal flooding: (A) high lake levels in the wet season (winter-spring), when only a small hill, Manastir, remains above water, (B) the retreat of water into ponors, (C) further water retreat through erosional channels into the Prološko Lake sinkhole in late spring-early summer, (D) dry karst polje with exposed erosional channels in late summer.

Prološko Lake is the most significant estavelle in the Prološko Blato, functioning as a karst spring in wet periods and as a ponor during dry periods. It is actually a sinkhole filled with water, which never dries out. It is characterized by steep limestone slopes on one side and a sharp contact with Quaternary sediments on the other (Fig. 7). The steep slopes resemble those of other sinkholes in the Imotsko Polje (e.g., Red Lake), implying a collapsed nature (Roglić, 1938).



Figure 6. Erosional channels in the Proložsko Blato research area with exposed paleolake sediments.

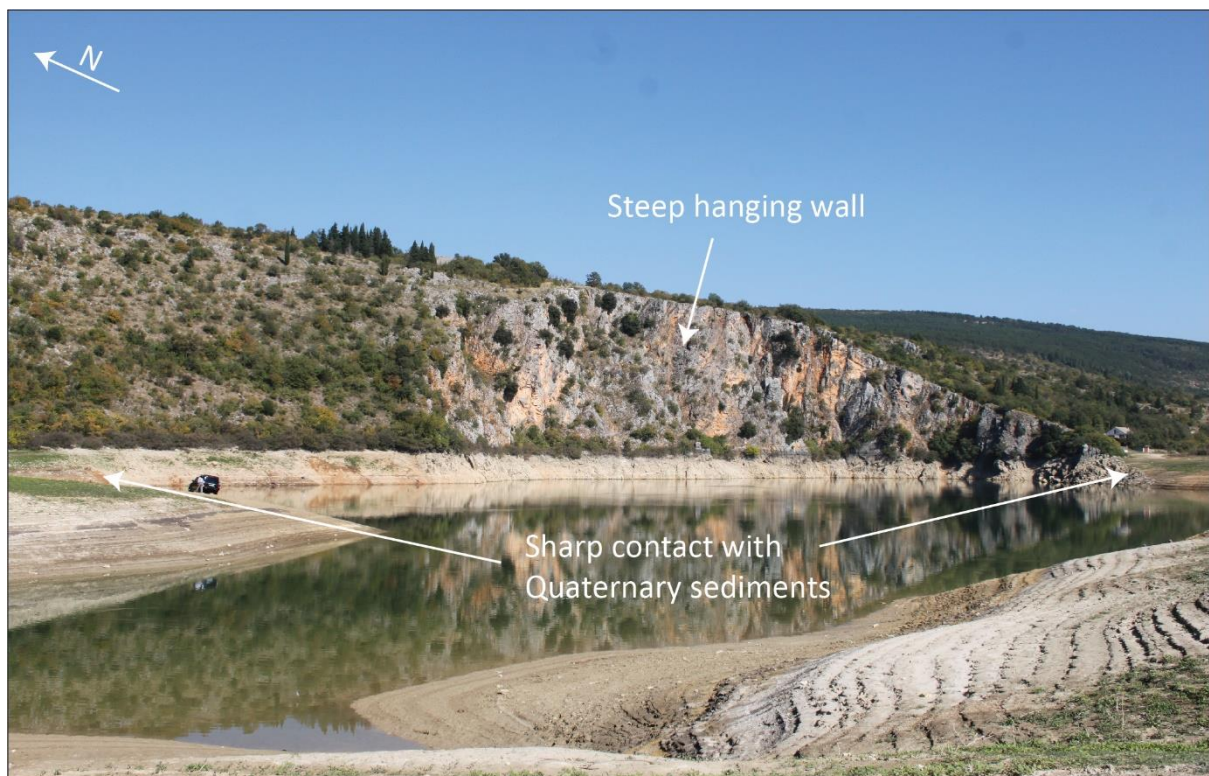


Figure 7. The Proložsko Lake sinkhole at the contact between karst polje sediments and Cretaceous limestone.

3.2. Field methods

Field methods in this study included geophysical methods, sediment coring, and sampling of water, outcrop sediments, and rocks in the studied lakes, karst poljes, and their catchments. The morphology and bathymetry of Lake Velo Blato and Prološko Lake sinkhole within the Prološko Blato wetland were investigated using acoustic geophysical methods. This included using side-scan sonar (SSS, Humminbird 999 HD SI) mounted on a rubber boat, in lakes Velo Blato and Prološko Lake. A sub-bottom profiler (SBP, Innomar SES-2000) was used to assess sediment architecture across the entire Prološko Lake area, with 32 seismic profiles collected. For land surfaces in the karst polje of the Prološko Blato wetland and the Bribir-Ostrovica karst polje, ground-penetrating radar (GPR) was used during the dry seasons, in collaboration with Geoda LLC Consulting from Zagreb, Croatia. In addition to geophysical methods, the main geomorphological features were examined using spatial analyses in ArcGIS (e.g., digital elevation models (DEM), LiDAR data (DGU Geoportal), and unmanned aircraft survey (UAS) data) in the Prološko Blato wetland.

For drilling of lake sediments in karst poljes Bribir-Ostrovica and Prološko Blato, the percussion drilling set Eijkelkamp Cobra TT was used, which collects sediments in a 1-meter-long metal corer 100 mm in diameter (Fig. 8A). This allows the recovery of undisturbed sediment cores up to 5-8 m long, using additional metal rods. The sediment cores were photo-documented prior to extraction from the metal corer and subsampling on site. Three sediment cores in the Bribir-Ostrovica karst polje (and adjacent Žažvić polje) were collected: OSP-2 (460 cm), OSP-3 (472 cm), and ZAZ-1 (450 cm). In Prološko Blato karst polje, the composite sediment cores PB-1 (650 cm) and PB-2 (920 m) were used for analyses, combined with sediment profiles (PBK1-PK, PBK3) from exposed outcrops in erosional channels. Surface sediments across Prološko Lake were sampled using Van Veen grab sampler and winch from a rubber boat. Sediment samples were transported to the Croatian Geological Survey and stored in cold storage at 4°C. Lake sediment cores in Lake Velo Blato were retrieved using a Uwitec piston corer mounted on a tripod tower on a floating platform (Fig. 8B). The sediment cores were collected in plastic PVC liners 3 meters in length, 60 mm in diameter. A 568 cm-long lake sediment core VB-2 was recovered from Velo Blato at 2.7 m water depth. In addition, several short sediment cores (<50 cm long) were collected in Velo Blato using a Uwitec gravity corer and winch from a rubber boat. The short cores were sliced in 1-cm intervals in the laboratory using a Uwitec core extruder. Sediment cores were also taken from other wetlands on Pag Island, Malo Blato, and Kolanjsko Blato. Core extraction was conducted manually using a plastic liner and a piston corer. In Kolanjsko Blato, two connected rubber boats were used for stabilization during core extraction. All sediment cores were transported to the Croatian Geological Survey and stored in cold storage at 4°C.

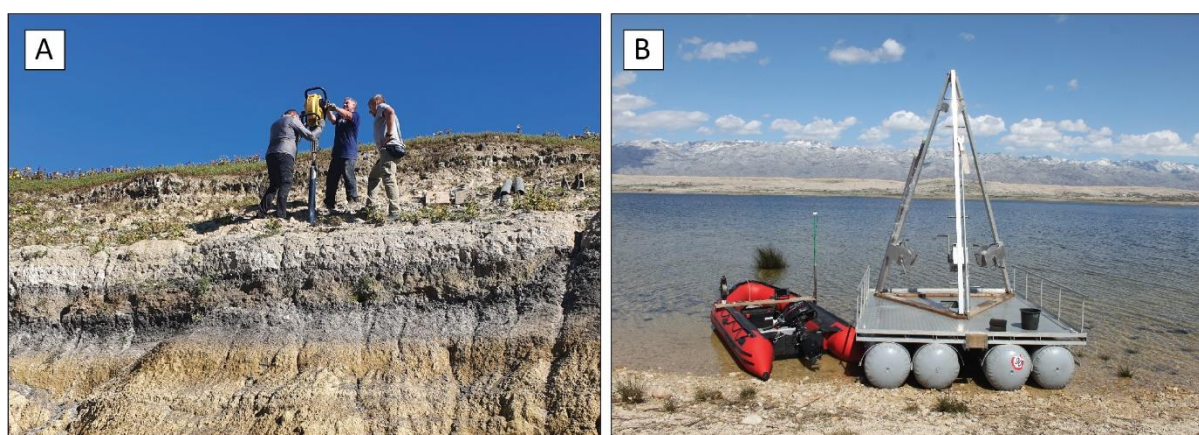


Figure 8. Percussion drilling of paleolake sediments in Prološko Blato using Eijkamp Cobra TT (A) and a floating platform for sediment coring with Uwitec piston corer in Lake Velo Blato (B).

Table 1. Overview of sediment cores used in this study.

Coring site	Core name	GPS coordinates	Core length	Coring date	Coring equipment
Velo Blato	VB-2	44°21'17" N, 15°09'18" E	0-568 cm	9.4.2021.	Piston corer + platform
Malo Blato	MB-1/2	44°21'13" N, 15°07'26" E	0-107 cm	19.3.2021.	Piston corer, manually
Kolanjsko Blato	KB-1/1	44°31'26" N, 14°54'40" E	0-35 cm	19.3.2021.	Piston corer, manually
Bribir-Ostrovica polje	OSP-2	43°56'17" N, 15°48'47" E	0-460 cm	18.- 21.10.2016.	Eijkamp Cobra TT
	OSP-3	43°56'09" N, 15°49'00" E	0-472 cm		
Žažvić polje	ZAZ-1	43°55'40" N, 15°49'25" E	0-450 cm		
Prološko Blato	PB-1	43°28'23" N, 17°07'05" E	0-310 cm	10.10.2018.	Eijkamp Cobra TT + exposed outcrops
	PB-2	43°28'30" N, 17°06'54" E	0-520 cm	6.10.2020.	
	PBK1-PK	43°28'19" N, 17°07'00" E	0-632 cm	11.10.2018.	

3.3. Laboratory methods

The lake sediment cores were analyzed in the laboratory of the Croatian Geological Survey (CGS). The sediment cores from Lake Velo Blato were split lengthwise into two halves, with the archive halves stored in the core repository cold chamber (at 4°C) for future analyses. Working halves were cleaned and photographed. The sediment cores from Prološko Blato were transported to the laboratory in plastic boxes in 10-cm and photographed. All the sediment cores were covered with thin transparent plastic film prior to surface measurements. The color of lake sediments was measured at 1-cm intervals using an X-Rite spectrophotometer, and results are expressed in CIE L*a*b* color space. The magnetic susceptibility (MS) was generally measured at 1-cm resolution along the core axis using a Bartington MS2E surface-scanning sensor, and results are expressed in SI units for volume (κ_{f}) MS (10^{-}

⁵). Initial sediment core description was performed prior to sediment sub-sampling, followed by the determination of sediment color using the Munsell color chart. The same procedure was applied to sediments from the Bribir-Ostrovica karst polje, which were subsampled on-site and stored in plastic bags. The sub-sampled sediments from all sediment cores were used for further analyses.

The wet/dry bulk densities and water content in the lake sediment core from Lake Velo Blato were calculated for a 1 cm³ volume of sediment after weighing and drying overnight at 105 °C. In addition, smear slides were prepared on glass slides using Norland 61 optical adhesive and a UV lamp. The selected samples from all sediment cores were either dried in an oven at 40°C or freeze-dried. Dry sediments were crushed into a fine powder using an agate mortar and pestle for geochemical and mineralogical analyses.

Grain size analysis was performed using a Shimadzu SALD-2300 laser diffractometer for particle sizes ranging from 0.17 mm to 2 mm. Sample pretreatment included removing organic matter with 30% hydrogen peroxide (H₂O₂) and dispersing particles with sodium hexametaphosphate ((NaPO₃)₆). The data were processed statistically using the GRADISTAT software package (Blott and Pye, 2001), which calculates key grain-size parameters, such as mean, median, sorting, skewness and kurtosis, using Folk & Ward (1957), and provides a physical description of the textural groups (e.g., sandy mud) and sediment name (e.g., fine silt) for each sample after Folk (1954), as well as volume percentage (vol%) of grains falling into each size fraction, modified from Udden (1914) and Wentworth (1922). Gravels, if present, were described visually (e.g., in Prološko Blato, paper 4).

In addition to surface magnetic susceptibility (MS) measurements, the Bartington MS2B sensor was used to measure mass-specific MS (χ_{fr}) and dual-frequency mass MS (χ_{fd}). For that purpose, finely powdered samples were packed in 10 cm³ plastic pots and weighed before measurement at low (0.46 kHz) and high (4.6 kHz) frequencies.

Bulk mineralogical and clay mineral analyses were conducted at CGS laboratories on finely powdered samples. In addition, marl samples were collected from Eocene flysch deposits found in the catchment at all three study sites to determine the sediment source using clay mineral composition. Mineralogical analyses were performed on a PANalytical X'Pert Powder diffractometer (XRD) with Ni-filtered CuK α radiation generated at 45 kV and 40 mA, and equipped with a vertical goniometer of θ/θ geometry and a PIXcel detector. Processing and interpretation of data were done using X'Pert Highscore Plus software and the associated International Center for Diffraction Data (ICDD) mineral database (PDF-4/Minerals). The clay mineral analysis was conducted using oriented glass slides of the separated clay fraction (<2 μ m) by centrifugation after carbonate removal with buffered sodium acetate (NaOAc) solution, in air-dried and ethylene glycolated states, and after heating at 400 °C and

550 °C. The identification of clay minerals followed standard procedures by Moore & Reynolds (1997) (for more details, see papers 1, 3, and 4).

For the analyses of total organic carbon (TOC), total inorganic carbon (TIC), and total nitrogen (TN), selected powdered samples were weighed to about 2 g, and TOC-TN analyses were carried out using a Thermo Scientific™ Flash 2000 NC Analyzer at the CGS. The instrument measures total carbon (TC) and total nitrogen (TN), whereas total organic carbon (TOC) is determined after carbonate removal with 8 ml of 4.2 M HCl. Then, total inorganic carbon (TIC) is calculated as the difference between TC and TOC. The TOC-TN analyses were applied at all three study sites.

For stable isotope analyses, samples were generally prepared at CGS, while the measurements were conducted at the British Geological Survey (BGS). Lake carbonates were analyzed in Lake Velo Blato and Proložko Blato (papers 2 and 5), while organic matter and ostracod shells were analyzed in Lake Velo Blato (paper 2). For stable isotope analyses of lake carbonates ($\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$), about 1 g of freeze-dried sample was treated with 5% sodium hypochlorite for 24 h to remove organic matter. Following this, the samples were sieved at 80 μm using deionized water, air-dried on filter paper, powdered, and stored in plastic bags for transportation to BGS. There, 30 mg of sample material, along with 15 mg of laboratory standards, was reacted overnight with anhydrous phosphoric acid at 25 °C to release CO_2 , which was then analyzed using a Sercon Geo HS2022 dual-inlet isotope ratio mass spectrometer (IRMS). $\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$ are reported as per mille (‰) deviations of the isotopic ratios relative to the Vienna Pee Dee Belemnite (VPDB) international standard. For stable isotope analysis of organic matter ($\delta^{13}\text{C}_{\text{OM}}$), 1 g of freeze-dried sample was treated with 8 ml of 4 M HCl for 24 h at room temperature to remove carbonates. Following this, samples were rinsed twice with distilled water, dried, powdered, and stored in plastic bags for transport to BGS, where carbon isotope analysis was performed using an Elementar vario ISOTOPE cube elemental analyzer coupled to an isoprime precisiON IRMS. Stable isotope data are reported in delta (δ) notation in per mille (‰) relative to the international reference scale (VPDB). For stable isotope analyses of ostracod shells ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$), between 1 and 3 well-preserved valves were picked, cleaned with ethanol using a fine brush, and transferred to glass vials. Then, the picked ostracod valves were treated with plasma ashing to remove any residual organic matter, particularly from the valve inner lamella, which is difficult to clean with a brush. Stable isotope analysis was conducted using an IsoPrime100 dual-inlet IRMS, and results are reported in delta notation per mille relative to VPDB. More details on the stable isotope measurements are provided in related papers 2 and 5.

For major- and trace-element analyses, samples were prepared at CGS laboratories, while formal analyses were conducted at the Bureau Veritas (BV) commercial laboratory in Vancouver, Canada.

Selected samples from Velo Blato and Proložko Blato lake sediments were stored in plastic bags for transportation to BV. There, approximately 1 g of each sample was digested with a four-acid mixture (HCl-HNO₃-HClO₄-HF) at 200°C (MA200 method). In addition, mercury (Hg) concentrations in the Velo Blato lake sediment core were determined by aqua regia digestion (AQ200-HG). Major and trace elements were measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The method allows a “near-total” analysis of 45 elements, with major elements reported as mass percent (%) and trace elements as mg/kg. The accuracy of the analyses was controlled by certified geological reference materials (STD OREAS25A-4A, STD OREAS45H; ACME laboratory, n=5) and was mostly within ±5% of the certified values. More information can be found in related papers 1 and 5.

Biological proxies used in this study included micropaleontological analyses of ostracods. Qualitative and quantitative analyses were conducted using a light microscope (stereomicroscope), while fine morphological features of ostracod shells were analyzed using a scanning electron microscope (SEM JEOL JSM-35CF). Ostracod analyses were conducted at the CGS. Statistical analyses of ostracod assemblages were performed only for the site with the highest species richness, that is, Lake Velo Blato (paper 2). For the other two sites, ostracod assemblages were typically dominated by one or two species, and therefore, statistical analyses were unlikely to provide additional insights. In that case, ostracod biozonation was determined visually based on variations in species relative abundances (papers 3 and 5).

Age determinations in this study were performed using radiocarbon accelerator mass spectrometry (¹⁴C AMS) at a commercial Beta Analytics Laboratory (Miami, USA) (papers 1, 4, and 5), at the Radiocarbon Laboratory of the Institute of Physics, Center for Science and Education, Silesian University of Technology (Gliwice, Poland) (papers 4 and 5), and at the AMS 14C facility of the Institute of Energy and the Environment, Penn State University (USA) (paper 3). Age-depth modeling was performed at all three study sites to obtain a continuous chronological framework for the studied lake sediments. More details on the age-depth modeling are provided in papers (papers 1, 2, 3, and 5).

The gamma spectrometry was performed on short sediment core samples from Velo and Kolanjsko Blato at the Institute for Medical Research and Occupational Health in Zagreb, using ORTEC p-type coaxial high-purity germanium (HPGe) detectors. Samples were packed in a 100-cm³ volume geometry, sealed, and left for 4 weeks to reach radiochemical equilibrium before determining radionuclide activities. The data acquisition was performed using a computerized system (GammaVision software). Activity concentrations of ¹³⁷Cs were used to determine the sedimentation rate on the analyzed sediment cores (paper 1).

Modern water chemistry was assessed at study sites where stable isotope analyses were performed in lake sediments (papers 1, 2, and 5). These included measurements of the stable isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and the chemical composition (cations and anions) of lake water samples at the CGS hydrochemical laboratory. In Lake Velo Blato, a closed-lake system, lake water samples were collected in the summer of 2022 and in the winter of 2023 to characterize seasonal variations in lake water chemistry, including kinetic effects (evaporation) on stable-isotope hydrology. In Prološko Blato, an open-lake system, water samples from Prološko Lake were collected in the autumn of 2018 every 5 m to characterize lake water stratification and modern isotope hydrology. These analyses were crucial for paleoclimatic and paleoenvironmental interpretation, particularly the stable isotope composition of lake carbonates. At both sites, modern isotope hydrology was characterized by constructing the local meteoric water line (LMWL) using published modern precipitation data from the closest available station in Zadar (Vreča et al., 2006), situated on the eastern Adriatic Coast. However, the Prološko Blato is situated in the Dalmatian hinterland, where the climate is characterized by greater continental influence and modern precipitation data from the Zadar station may not fully reflect climate conditions at this study site. Thus, the Online Isotopes in Precipitation Calculator (OIPC) (<https://wateriso.utah.edu/waterisotopes>) was used here to estimate the stable isotope ratios of precipitation (Bowen & Wilkinson, 2002; Bowen & Revenaugh, 2003; Bowen et al., 2005).

3.4. Statistical analyses

Statistical analysis was performed on micropaleontological (ostracod) data from Lake Velo Blato (paper 2) and geochemical data from Prološko Blato (paper 5) using the Compositional Data Analysis (CoDA) approach. In micropaleontological analysis, Principal Component Analysis (PCA) reduces the complexity of multivariate biological datasets and identifies the main gradients of environmental change. Another commonly used method is Cluster Analysis (CA), which groups samples by similarity, allowing identification of ostracod biozones in the lake sediment record. Similarly, PCA is often applied to geochemical datasets (major and trace elements) to reduce dimensionality and to discriminate element groupings associated with sedimentary processes. However, these multivariate statistical analyses often apply to relative ostracod abundances or element concentrations without accounting for the compositional nature of the data (Razum, 2018). Compositional data (CoDa) are often characterized by a constant sum; although this is not a necessary condition, it is a particular representation of an equivalence class (Barceló-Vidal & Martín-Fernández, 2016). As a result, the variables are not independent, meaning that an increase in one component must be accompanied by a decrease in the others (Aitchison, 1986). However, ordinary statistical methods (PCA, CA) assume that variables can vary independently in Euclidean space. Thus, applying these methods directly to

CoDa can produce misleading distances, correlations, and patterns. Therefore, CoDa requires specific transformations prior to statistical analysis.

CoDa transformations are log transformations. Thus, the ostracod (or geochemical) dataset cannot contain zero values. One way to handle this is to use the geometric Bayesian multiplicative replacement method, which is implemented in the *zCompositions* R package for multivariate analysis (Palarea-Albaladejo & Martín-Fernández, 2015). The method essentially replaces zero values with a very small number while preserving the overall composition of a sample. Accordingly, all zero values are treated as “counting zeros”, assuming that the species were present in the environment but remained undetected during the analysis because of their low abundance. However, micropaleontological datasets often contain species with zero values that may represent true absences (“true zeros”), thereby providing meaningful paleoecological information. Thus, to avoid bias introduced by zero-replacement methods, it is best to exclude rare and scattered species from the dataset.

After handling zeros, isometric-log-ratio (ILR) and centered-log-ratio (CLR) transformations were applied to the ostracod dataset, while CLR transformations were applied to geochemical datasets using the *compositions* package in R (van den Boogaart & Tolosana-Delgado, 2008), enabling valid multivariate statistical analyses. Further statistical analyses were performed in the PAST program (Hammer et al., 2001). More details on CoDa are provided in the related paper 2.

4. DISCUSSION

The main objective of this thesis was to provide Holocene paleoenvironmental and paleoclimatic reconstructions of three karst lakes and paleolakes in Dalmatia, based on sedimentological, geochemical, and ostracod proxies preserved in the lake sediment records. These reconstructions aimed to provide new information on the timing of lake formation, paleoenvironmental and geomorphological aspects of lake formation, and hydroclimatic variations in Dalmatia during the Holocene. These long-term reconstructions provide an important context for assessing the potential response of karst lake systems to ongoing and future climate change, particularly changes in temperature, precipitation, and hydrological variability.

4.1. The timing of lake formation in Dalmatia

The evolution of karst lakes and paleolakes in Dalmatia can be traced back to the Late Pleistocene/Holocene transition, although true lake sedimentation in some lakes began later. For example, the evolution of the coastal Lake Velo Blato on Pag Island can be traced back to the Early Holocene (10.000 cal yr BP), when sea level was approximately 40 m lower than today (Lambeck et al., 2014) and the coastline was farther from the island. During that time, the true lake in Velo Blato was not yet established, but the basin already existed as a karst polje depression (Ilijanić et al., 2022). A further rise in sea level raised the groundwater level, and at approximately 8100 cal yr BP (Middle Holocene), a lake environment was established (Ilijanić et al., 2022). In the Bribir-Ostrovica karst polje, floodplain/wetland sedimentation began at ca. 13.200 cal yr BP, followed by basin deepening and the establishment of a stable lake environment at ca. 9600 cal yr BP (Ilijanić et al., 2026). Here, the formation of a permanent lake environment between 9600 and 7200 cal yr BP coincides with the human occupation of the nearby Neolithic settlement of Krivače, thus providing a valuable context for human-environment interactions in Dalmatia (Ilijanić et al., 2026). In Prološko Blato, alluvial fan sedimentation ceased at the Late Pleistocene/Holocene transition, which enabled basin deepening and the formation of a shallow lake/wetland at approximately 9000 cal yr BP (Ivkić Filipović et al., 2025a). The timing of lake formation in this study generally corresponds with that of other lakes along the eastern Adriatic Coast (Ilijanić, 2014). For example, in Bokanjačko Blato near the city of Zadar, a shallow lake formed during the Early Holocene around 10.300 cal yr BP (Ilijanić et al., 2018). In Čepić Polje on the Istrian Peninsula (Northern Adriatic), the Late Pleistocene/Holocene transition is characterized by colluvial sedimentation, followed by the development of a lake fed by intermittent (periodic) streams (Balbo et al., 2006). Similarly, at Vrana Lake near Biograd na Moru, a floodplain environment prevailed during the Late Pleistocene/Holocene transition, followed by the development of a low-energy wetland, with a permanent freshwater lake forming around 8130 cal yr BP (Hajek-

Tadesse et al., 2018a). The nearly coherent timing of lake formation in Dalmatia suggests a clear environmental reorganization at the Late Pleistocene/Holocene transition, particularly in karst poljes. Whereas Holocene sea-level rise clearly influenced lake development along the eastern Adriatic Coast, lake formation in the studied karst poljes was also controlled by sedimentological and geomorphological processes coupled with hydroclimatic changes (see further discussion).

4.2. Paleoenvironmental reconstruction of Dalmatian karst lakes and paleolakes

The multiproxy core analysis of Dalmatian karst lakes and paleolakes enabled paleoenvironmental reconstruction at individual study sites, characterized by transitions between floodplain/wetland and shallow-lake environments. Particularly evident are periods of dynamic environmental conditions characterized by higher siliciclastic input, in contrast to periods of relatively stable conditions and endogenic carbonate precipitation. For example, in Prološko Blato lake sediments, compositional analysis of geochemical data clearly discriminated elemental groupings by sedimentary processes, i.e., endogenic carbonate precipitation (Ca, Sr, partly Mg) versus detrital input of siliciclastic material (Al, Fe, Ti, Zr, partly Mg) (Ivkić Filipović et al., 2026). Furthermore, sedimentation in Lake Velo Blato began with enhanced detrital input from flysch deposits, especially clays, during the early Middle Holocene. In the lowermost part of the sediment core, ostracods exhibit the lowest adult-to-juvenile ratio, and gastropods are mostly fragmented, suggesting dynamic environmental conditions at the onset of lake sedimentation (Ivkić Filipović et al., 2026a). This is further supported by the elevated abundances of lithogenic elements (Al, Ti, Fe, K, and Na) bound to the siliciclastic component, as well as the presence of dolomite alongside calcite and aragonite and associated elevated Mg concentrations in the lower part of the VB-2 sediment core (Ilijanić et al., 2022). These mineralogical and geochemical characteristics indicate increased erosion and detrital input from the catchment (Ilijanić et al., 2022). Similar conditions were identified at the onset of lake sedimentation in Bribir Ostrovica karst polje (Ilijanić et al., 2026) and Prološko Blato (Ivkić Filipović et al., 2026b). However, increased detrital input in the Bribir-Ostrovica karst polje may also reflect intensifying human activity within the catchment, including agriculture, settlement expansion, and slope destabilization (Ilijanić et al., 2026). Previous biomarker analyses of sediment core OSP-2 showed elevated levels of N-alkanes and polycyclic aromatic hydrocarbons (PAHs, fire-indicator compounds) between 8000 and 6000 cal yr BP, which could result from both human and climate-driven activity (Hartke, 2022). Thus, human activity should also be considered here as a possible driver of environmental change. Regardless, it is clear that true lacustrine conditions were preceded by detrital sedimentation of clayey material associated with flysch deposits at all three study sites.

The initial detrital phase of lake sedimentation was followed by lake deepening and sedimentation of predominantly lacustrine carbonates, rich in ostracods, gastropods, and *Chara* gyrogonites, with limited siliciclastic input from the catchment. This suggests favorable environmental conditions for carbonate precipitation, such as lake hydrology, sedimentology, and climate (Gierlowski-Kordesch, 2010). Several proxies imply more stable environmental conditions, including lower magnetic susceptibility (MS), decreased abundances of lithogenic elements and minerals bound to the siliciclastic component (e.g., feldspars, dolomite, clay minerals), and higher Ca/Al ratios. Such conditions are encountered at ca. 7100 cal yr BP in Lake Velo Blato (Ilijanić et al., 2022), at ca. 9600 cal yr BP in Bribir-Ostrovica polje (Ilijanić et al., 2026), and at ca. 8000 cal yr BP in Prološko Blato (Ivkić Filipović et al., 2025, 2026b). Lake hydrology is the dominant factor in carbonate mineral precipitation (Platt & Wright, 1991). In hydrologically open lakes, where meteoric inputs dilute lake water chemistry, the dominant carbonate mineral phase is low-Mg calcite (Platt & Wright, 1991), as seen in paleolakes in Prološko Blato and Bribir-Ostrovica polje (Ivkić Filipović et al., 2025; Ilijanić et al., 2026). In hydrologically closed lakes, where solutes accumulate through evaporative concentration, high-Mg calcite and aragonite may form, as seen in Lake Velo Blato (Ilijanić et al., 2022). Fossil remains of ostracods, gastropods (primarily *Bithynia tentaculata*), and encrusted Charophyte remains in lacustrine carbonates suggest a relatively shallow (up to 10 m deep) lake environment at all three study sites. Lacustrine carbonates from Velo Blato are mostly laminated sandy silt, except for the topmost part, which consists of an organic-rich layer (Ilijanić et al., 2022). This implies variable detrital/endogenic/organic sedimentation and sediment preservation with minimal disturbance by bioturbation and erosion (Gierlowski-Kordesch, 2010). In contrast, lacustrine carbonates in karst poljes are mostly massive, homogeneous sandy silts (Ilijanić et al., 2026; Ivkić Filipović et al., 2025), indicating intense bioturbation at the lake bottom (Gierlowski-Kordesch, 2010). Particularly interesting is the occurrence of spherulitic aragonites at the bottom of the lake sediment core from Velo Blato (Ivkić Filipović et al., 2026a) and throughout the lake sediment core from Prološko Blato (Ivkić Filipović et al., 2026b). Although their origin remains unclear, the spherulitic morphology may indicate microbially induced precipitates (Ivkić Filipović et al., 2026b).

Carbonate bedrock is a prerequisite for lacustrine carbonate precipitation, independent of climate (Gierlowski-Kordesch, 2010), because it provides particulate (detrital) carbonates and dissolved calcium and carbonate ions through groundwater and surface waters. However, climate undoubtedly regulates internal and external lake processes, such as the dissolution of carbonate rocks, detrital input from the catchment, lake productivity, and concentration through evaporation. As discussed in section 1.1, carbonate precipitation is pH-dependent, and any process that removes CO₂ from the system can promote its precipitation. These processes include increased CO₂ exchange with the

atmosphere (e.g., due to higher temperature) and increased photosynthetic activity by lake algae. Therefore, a combination of carbonate bedrock and climate stabilization in the Holocene clearly influenced lacustrine carbonate precipitation at all three study sites.

Organic matter (OM) in lake sediments reflects changes in past lake productivity (endogenic OM) and vegetation changes in the catchment (allogenic OM). In Lake Velo Blato, an endorheic lake surrounded by barren karst, OM is primarily derived from lake productivity (Ivkić Filipović et al., 2026a). Here, the average TOC/TN ratio is 12, indicating mixed algal and macrophyte sources, while the stable carbon isotope of organic matter ($\delta^{13}\text{C}_{\text{om}}$) varies between -26.2‰ and -17.1‰ , reflecting variations in carbon cycling associated with progressive encroachment of emergent aquatic (macrophytes) and palustrine plants (reeds) (Ivkić Filipović et al., 2026a). In contrast, lake sediments from the Bribir-Ostrovica karst polje have TOC/TN ratios ranging from 15.7 to 4.1 (Ilijanić et al., 2026), reflecting the mixed terrestrial and aquatic origin of organic matter (Meyers & Teranes, 2001). Similarly, the TOC/TN ratio in Prološko Blato in Imotsko polje varies between 3.9 and 29.0, where higher values indicate terrestrially derived OM (land plants) during the initial phase of lake/wetland formation, while lower values suggest predominantly endogenic (algal) OM during the more stable, paleolake phase (Ivkić Filipović et al., 2026b). In addition, the TOC and TN values in the Prološko Blato paleolake are very low, below 2% and 1%, respectively (Ivkić Filipović et al., 2026b). Such low values indicate that the lake was likely nutrient-poor (oligotrophic) due to low productivity and had minimal OM input from the catchment (Meyers & Teranes, 2001).

The ostracod fauna identified in all three study sites reflects a broad range of freshwater and brackish lacustrine environments, ranging from deeper, oligotrophic lakes associated with karst springs to shallow, well-vegetated and occasionally flooded karst poljes (Table 2). Ostracod assemblages in Lake Velo Blato reflect primarily changes in salinity, associated with the transition from freshwater to brackish lake between 7500 and 6300 cal yr BP, and secondarily changes related to lake ontogeny (shallowing, vegetation encroachment, eutrophication) due to the transition from brackish lake to brackish wetland from ca. 2100 cal yr BP onwards (Ivkić Filipović et al., 2026a). In paleolakes in karst poljes, ostracod assemblages seem to reflect changes in lake hydrology and productivity. For example, in the Bribir-Ostrovica karst polje, ostracods are dominated by *Candona neglecta* and *Metacypris cordata*, the latter typically associated with littoral vegetation in mesotrophic to eutrophic standing water bodies (ponds and lakes) (Meisch, 2000). This suggests the development of a permanent, shallow lake rich in aquatic vegetation (Ilijanić et al., 2026). On the other hand, in the Prološko Blato paleolake, the ostracod community is characterized by the almost exclusive presence of one species, *C. neglecta*, which might be related to extremely oligotrophic conditions (low TOC and TN) and water temperatures balanced by numerous karst springs in the area (Ivkić Filipović et al., 2026b). However,

in the final stages of paleolakes in both karst poljes, the ostracod community is dominated by Ilyocyprididae, such as *Ilyocypris bradyi*, which is often associated with karst springs (Meisch, 2000). In these final stages, other species also occur, including *Limnocythere* cf. *sanctipatricii*, *Paralimnocythere psammophila*, *Pseudocandona marchica*, *Mixtacandona* sp., etc., but they are mostly scattered, while the total number of ostracods is clearly decreased (Ilijanić et al., 2026; Ivkić Filipović et al., 2026b). Thus, ostracod assemblages in these final stages of paleolakes in karst poljes suggest a clear environmental change, likely reflecting the transition from permanent lakes to seasonally flooded water bodies, conditions characteristic of karst poljes today. A particularly unusual finding is the *Juxilyocypris kempfi* in the topmost sediments of Prološko Blato (Ivkić Filipović et al., 2026b), a cold-climate indicator species previously thought to have become extinct at the Late Pleistocene/Holocene transition (Hajek-Tadesse, 2018b). Although sampling living ostracods is needed to confirm its presence in the present-day karst wetland, a confirmed finding may raise new questions about species survival in karst refugia (Ivkić Filipović et al., 2026b).

Later stages of lakes at all three study sites are characterized by again elevated MS and abundances of elements and minerals associated with the siliciclastic component. In Lake Velo Blato, lithogenic elements (Al, Fe, Ti, K, and Na), nutrient elements (P and N), TOC, and sulfur (S) display an increase from 500 cal yr BP and reach the highest values during the last 200 cal yr BP, indicating significant environmental changes such as higher lake productivity and eutrophication (Ilijanić et al., 2022). The assessment of heavy metal pollution using enrichment factors (EF) throughout the sediment core indicated predominantly geogenic (background) metal concentrations, with only occasional increases in EF values for Cd, Cr, Cu, Pb, and Zn during the Late Holocene, potentially reflecting limited anthropogenic influence, particularly during the Roman and Medieval times (Ilijanić et al., 2022). Similarly, Prološko Blato lake sediments are characterized by the highest MS, low Ca/Al ratio, and elevated concentrations of TOC, TN, Pb, Zn, Cu, and P over the last ca. 500 years (Ivkić Filipović et al., 2026). These changes coincide with increased fluvial activity in the karst polje, as well as intensified agricultural activity during the Medieval period (Ivkić Filipović et al., 2026). Although major and trace elements were not analyzed in Bribir-Ostrovica karst polje, the topmost sediments are characterized by elevated MS, N, and TOC, indicating higher siliciclastic input, possibly related to soil erosion as indirect evidence of human occupation (Ilijanić et al., 2026). Therefore, lake sedimentation over the last ca. 500 years at all three study sites likely reflects mixed natural and anthropogenic influences.

Table 2. Ostracod fauna found in this study and associated paleoenvironments. Juveniles are excluded. VB = Velo Blato, BO = Bribir-Ostrovica polje, PB = Prološko Blato.

Species	Study site	Paleoenvironment
<i>Candona neglecta</i> G.O. Sars, 1887	VB, BO, PB	Deeper, freshwater oligotrophic lakes connected to karst springs
<i>Candona angulata</i> G.W. Müller, 1900	VB	Brackish oligotrophic coastal lake
<i>Pseudocandona marchica</i> (Hartwig, 1899)	VB, BO, PB	Shallow oligotrophic to mesotrophic lake, OM-rich sediments
<i>Pseudocandona compressa</i> (Koch, 1838)	PB	Shallow oligotrophic lake
<i>Mixtacandona</i> sp.	BO	Karst-fed shallow lacustrine-fluvial environment (flooded karst polje)
<i>Fabaeformiscandona fabaeformis</i> (Fischer, 1851)	BO	Very shallow (marginal) oligotrophic lake
<i>Candonopsis kingsleii</i> (Brady & Robertson, 1870)	VB, BO	Shallow, freshwater to brackish oligotrophic lake
<i>Cyprideis torosa</i> (Jones, 1850)	VB	Brackish oligotrophic to mesotrophic coastal lake
<i>Darwinula stevensoni</i> (Brady & Robertson, 1870)	VB, PB	Shallow, oligotrophic, well-oxygenated lakes
<i>Heterocypris salina</i> (Brady, 1868)	VB	Brackish oligotrophic coastal lake
<i>Cypria ophtalmica</i> (Jurine, 1820)	VB, BO	Freshwater to brackish, oligotrophic to mesotrophic lake, OM-rich sediments
<i>Metacypris cordata</i> Brady & Robertson, 1870	VB, BO	Shallow, warm, well-vegetated freshwater environment
<i>Cyclocypris ovum</i> (Jurine, 1820)	VB, BO	Shallow, warm, well-vegetated freshwater environment
<i>Ilyocypris gibba</i> (Ramdohr, 1808)	VB, PB	Freshwater to slightly brackish (oligohaline) lakes
<i>Ilyocypris salebrosa</i> Stepanaitys, 1960	PB	Rare species found in clayey sediments associated with higher detrital input
<i>Ilyocypris inermis</i> Kaufmann, 1900	BO	Karst-fed shallow lacustrine-fluvial environment (flooded karst polje)
<i>Ilyocypris bradyi</i> Sars, 1890	VB, BO, PB	Karst-fed shallow lacustrine-fluvial environment (flooded karst polje)
<i>Juxilyocypris kempfi</i> Hajek-Tadesse, 2018	PB	Cold, freshwater flooded karst polje habitats
<i>Cypridopsis vidua</i> (O.F. Müller, 1776)	VB, BO, PB	Freshwater oligotrophic lakes (PB) and lakes with rich vegetation (VB, BO)
<i>Limnocythere inopinata</i> (Baird, 1843)	VB, PB	Shallow, oligotrophic, well-oxygenated lakes
<i>Limnocytherina</i> cf. <i>sanctipatricii</i> Brady & Robertson, 1869	PB	Oligotrophic lake environments
<i>Paralimnocythere psammophila</i> (Flössner, 1965)	VB, BO	Freshwater, oligotrophic, permanent to temporary (seasonal) lake environments
<i>Paralimnocythere</i> cf. <i>relicta</i> (Lilljeborg, 1863)	BO	Freshwater, oligotrophic, permanent to temporary (seasonal) lake environments
<i>Cypris bispinosa</i> Lucas, 1849	VB, BO	Freshwater oligotrophic permanent (VB) or temporary (BO) lake environments
<i>Hungarocypris madaraszii</i> (Örley, 1886)	VB, BO	Freshwater (VB, BO) to brackish (VB) oligotrophic lake environments
<i>Herpetocypris chevreuxi</i> (Sars, 1896)	VB	Freshwater to brackish oligotrophic lake environments
<i>Notodromas monacha</i> (O.F. Müller, 1776)	VB, BO	Shallow freshwater (BO) to brackish (VB) lake rich in aquatic vegetation
<i>Heterocypris reptans</i> (Kaufmann, 1900)	BO	Karst-fed shallow lacustrine-fluvial environment (flooded karst polje)

4.3. Geomorphological aspects of lake formation

Geomorphological processes in karst, such as dissolution, subsidence, and cavern collapses, influence the evolution of karst lakes (Cohen, 2003; Ford & Williams, 2007), while tectonic activity, planation by karst dissolution, and position of the water table are important factors in the development of karst poljes (Ford & Williams, 2007). Coastal Lake Velo Blato is situated in a tectonic depression (syncline) made of flysch deposits, and the initial phase of its development can be approximated as a karst polje (Ilijanić et al., 2022). Here, lake formation is associated with the Holocene sea-level rise and concomitant rise in groundwater level, which enabled the impoundment of a water body (Ilijanić et al., 2022). In the Bribir-Ostrovica karst polje, paleolake sediments lie on top of greyish clays, which originate from surrounding flysch deposits and are transported in the karst polje depression via fluvial/colluvial processes (Ilijanić et al., 2026). In Prološko Blato, a paleolake developed in the distal part of the alluvial fan due to the cessation of alluvial sedimentation or migration of the active channels away from the basin (Ivkić Filipović et al., 2025). However, the hallmark of karst polje hydrology is the high surface-to-subsurface connectivity (Bonacci, 2013), meaning that any surface waters entering the karst polje are quickly drained in the subsurface through ponors, usually at the contact between Quaternary sediments and limestone bedrock. Flooding in poljes occurs as a result of rising groundwater levels and/or when the surface inflow exceeds the maximum capacity of ponors (Bonacci, 2013). Therefore, it is safe to presume that the development of a permanent lake in a karst polje may occur when: 1) accommodation space (basin) is formed, 2) enough water (surface and groundwater) is available in the system, 3) impermeable material (e.g., clays from flysch deposits, organic material) is deposited at the bottom of a basin, and 4) impermeable material blocks the surrounding ponors (Fig. 9). If these criteria are not met, we can expect either simple surface-to-subsurface flow (ponornica river) or seasonal flooding (Fig. 9).

Dissolution processes and sinkhole formation are of great importance in Imotsko Polje, while tectonic activity is known to affect karst hydrology, for example, by altering groundwater pathways and desiccation of karst springs (Brčić et al., 2019). Geomorphological, geophysical, and sedimentological research in Prološko Blato has shown that the Holocene paleolake may have been desiccated by the dissolution and collapse of a sinkhole in its marginal part, which is now known as Prološko Lake (Ivkić Filipović et al., 2025). Here, a sharp contact between the sinkhole and Quaternary alluvial sediments, as well as the absence of coarse-grained alluvial sediments on seismic profiles, suggests that a portion of the polje sedimentary infill might have collapsed in the underground cavern (Ivkić Filipović et al., 2025). Although the timing of the collapse event remained unclear, it is suggested that the existence of such a sinkhole in the paleolake's marginal part would have led to its seasonal desiccation, as it does today (Ivkić Filipović et al., 2025). However, no signs of seasonal desiccation (e.g., desiccation

cracks) were detected in paleolake sediments during its permanent phase, suggesting that this lake was a permanent water body (Ivkić Filipović et al., 2025). Moreover, the UAS survey conducted at the onset of the flooding period confirmed that seasonal flooding is the primary erosional process through which paleolake sediments are eroded from erosional channels and transported to the Prološko Lake bottom (Ivkić Filipović et al., 2025). Thus, the presence of erosional channels suggests that seasonal flooding was established during the post-paleolake phase, possibly linked to the collapse sinkhole or the unblocking of the ponors (Ivkić Filipović et al., 2025). Therefore, geomorphological processes have clear implications for paleoclimate and paleohydrological studies of karst lakes, a dominant lake type in Croatia and the Mediterranean region.

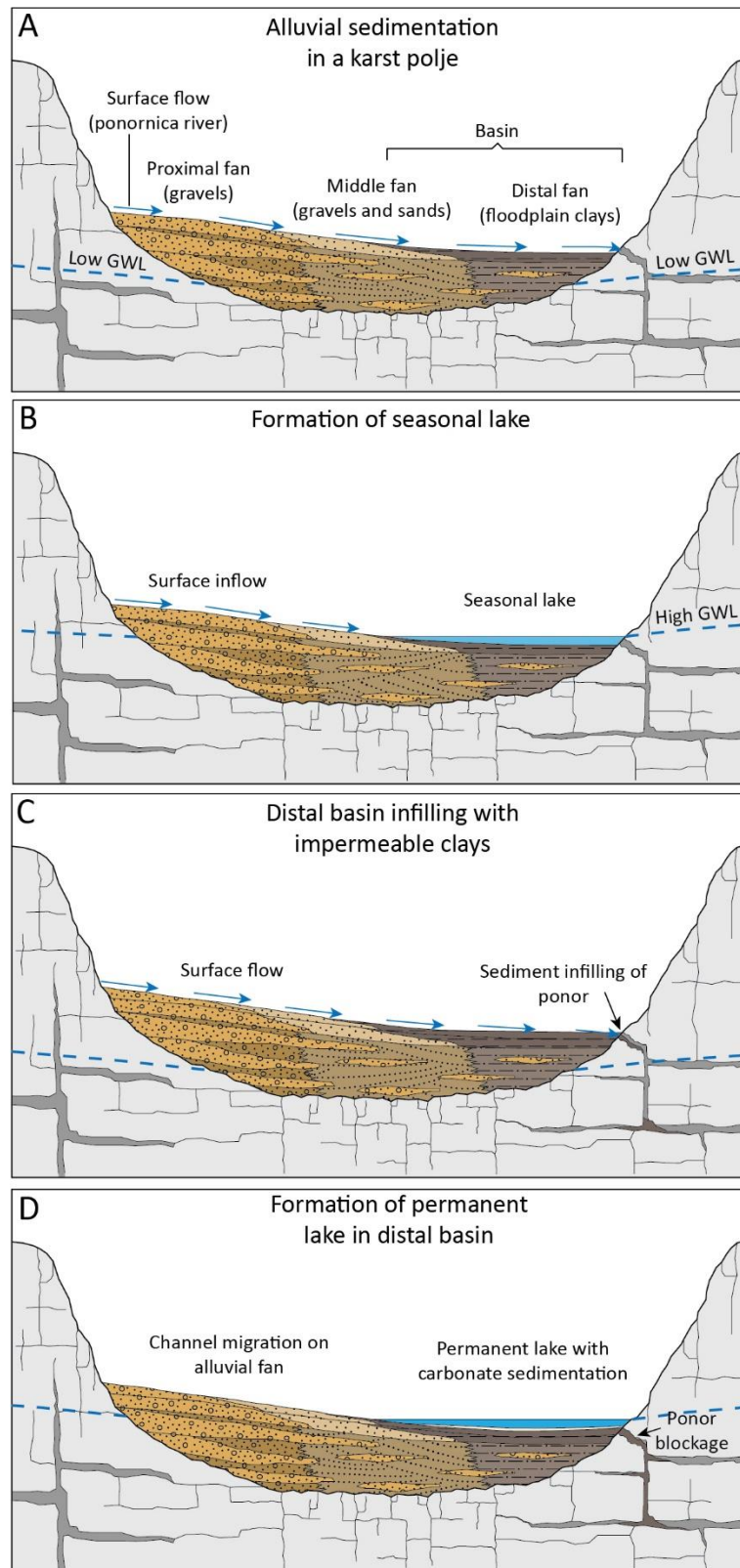


Figure 9. Model of lake formation in a karst polje: (A) alluvial fan sedimentation in karst polje depression, (B) formation of seasonal lake in the distal fan (basin) during the wet period due to high surface inflow and groundwater level (GWL) rise, (C) further basin infilling with floodplain clays in the distal part, which are also washed into the ponors, (D) sediment infilling leads to blockage of the ponors, limiting the surface to subsurface connectivity, which can lead to the formation of a permanent lake.

4.4. Hydroclimatic variations in Dalmatian karst lakes and paleolakes

In this study, hydroclimatic variations are best reconstructed using stable isotope ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) analyses of lake sediments, primarily $\delta^{18}\text{O}$ records of lacustrine carbonates (calcite and ostracods). $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ composition of endogenic calcite was analyzed in lake sediments from Lake Velo Blato and Prološko Blato, while $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of ostracod shells were analyzed in Velo Blato. At both study sites, the $<80\text{ }\mu\text{m}$ size fraction used for stable isotope analysis of lacustrine carbonates is predominantly composed of endogenic calcite (Ivkić Filipović et al., 2026a, 2026b). However, during the wetter periods (lower $\delta^{18}\text{O}$ values), there is a significant input of detrital (siliciclastic and carbonate) material from the catchment (e.g., from flysch marls), suggesting a higher possibility of detrital carbonate contamination of the stable isotope signal (Ivkić Filipović et al., 2026a, 2026b). In such cases, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of lacustrine carbonates primarily reflect variations in mineralogical composition (authigenic versus detrital) rather than hydroclimatic changes (Leng et al., 2010). Therefore, in Dalmatian karst lakes, care must be taken when interpreting stable-isotope signals from lake sediments, particularly during wetter periods and if the wider catchment area comprises both carbonate rocks and flysch deposits. The preferred approach is to combine $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analyses of lacustrine carbonates and ostracod shells, as ostracod shells may provide an independent stable isotope record unaffected by detrital contamination (Leng et al., 2010). In contrast, higher $\delta^{18}\text{O}$ values in both lakes likely reflect lower effective rainfall (lower precipitation/evaporation ratio (P/E)) and limited input of detrital carbonates from the catchment (Ivkić Filipović et al., 2026a, 2026b).

In Prološko Blato, the period between 9000 and 8000 cal yr BP lacks $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ records due to low carbonate content (Ivkić Filipović et al., 2026b). However, other proxies, such as high magnetic susceptibility, high content of siliciclastic minerals (quartz, K-feldspar, plagioclase, clay minerals), high content of siliciclastic elements (Al, Fe, Ti, Mg, Zr), abundant charcoal, and absence of ostracods in micropaleontological samples all indicate high erosional input from the catchment, likely under the generally wetter climate conditions (Ivkić Filipović et al., 2025, 2026b). Similar dynamic environmental conditions were inferred at the onset of the lake-sediment record at Lake Velo Blato. Here, the lowest $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of lacustrine carbonates between 8100 and 7500 cal yr BP, together with high detrital input from the catchment, indirectly imply wetter climate conditions, while the lowest $\delta^{18}\text{O}$ values of ostracods support this interpretation (Ilijanić et al., 2022; Ivkić Filipović et al., 2026a). These pronounced wetter conditions during the Early-Middle Holocene correspond to the so-called “pluvial” period recognized in marine and lake sediment records and speleothems from the Adriatic region (Brunović et al., 2020; Combourieu-Nebout et al., 2013; Razum et al., 2021; Schmidt et al., 2000; Smrkulj et al., 2025; Ilijanić et al., 2024, 2025; Surić et al., 2025). Wetter and warmer climate conditions during the Early-Middle Holocene are widely recognized in lake sediments across the Mediterranean

region, as evidenced by low $\delta^{18}\text{O}$ values (Roberts et al., 2008). However, while many lakes in the central Mediterranean show higher lake levels under the generally wetter climate (Roberts et al., 2008), the permanent lake conditions in Prološko Blato were not established until ca. 8000 cal yr BP, interpreted as a consequence of high surface-to-subsurface connectivity in karst poljes (Ivkić Filipović et al., 2026b), where a permanent water body could not be established until the surrounding ponors were blocked, as discussed above.

Throughout the Middle-Late Holocene, both sediment cores show an increasing trend in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, whose covariation is often used as an indicator of hydrological closure (Talbot, 1990), suggesting similar controlling mechanisms, such as evaporation and increased CO_2 exchange with the atmosphere. This increasing trend in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ was interpreted as a decrease in the effective moisture (precipitation/evaporation ratio (P/E)), leading to preferential loss of lighter isotopes ^{16}O and ^{12}C into the atmosphere (Ivkić Filipović et al., 2026a, 2026b). Such an aridification pattern is observed in other Croatian (Razum et al., 2021; Surić et al., 2021, 2025) and Mediterranean records (Roberts et al., 2008; Zanchetta et al., 2012, 2022; Lacey et al., 2015; Leng et al., 2013; Bar-Matthews et al., 2003), suggesting regional climate coherence and shared hydroclimatic patterns.

Both sediment cores show significant environmental changes during the Late Holocene. In Velo Blato, ostracods and other proxies suggest a shift from an open lake to a more stagnant, organic-rich wetland from ca. 2100 cal yr BP, while the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ display a decoupling due to changes in carbon cycling in the lake, i.e., increasing production of organic matter associated with emergent macrophytes and reed vegetation (Ivkić Filipović et al., 2026a). $\delta^{18}\text{O}$ values continue to increase until ca. 840 cal yr BP during the Roman and Medieval Warm Periods, but sustain relatively low values during the Little Ice Age and in the most recent sedimentation period, suggesting wetter climate conditions during that time (Ivkić Filipović et al., 2026a). Anthropogenic influences during the Roman and Medieval Warm Periods are possible (Ivkić Filipović et al., 2026a), particularly since the island of Pag was inhabited during that time, with smaller settlements and livestock husbandry, particularly sheep grazing, and salt production as the most important activities on Pag Island (Rogić, 1971). Therefore, humans likely used the rocky pastures around the island's largest freshwater reservoir for pastoralism and sheep grazing, which may have affected lake water quality. The only evidence of potential anthropogenic influence in this study is localized enrichment of Cd, Cr, Cu, Pb, and Zn, roughly corresponding to the Roman and Medieval Warm Periods (Ilijanić et al., 2022). However, given the generally low enrichment factors, these signals should be regarded as weak or indirect anthropogenic influence rather than contamination. Another plausible mechanism affecting lake levels is hydrological intervention, including spring capture and water diversion via channels. For example, a stable isotope record from

gypsum sediments at Lake Zóñar in southern Iberia (Spain) indicates low lake levels during Roman times, coinciding with abundant archaeological evidence of activities associated with a Roman *villa* (a Roman country house), including channels that diverted water from a nearby spring feeding the lake (Gázquez-Sánchez et al., 2023). Water-balance modeling suggests that combined arid conditions and diversion of inlets feeding the lake most likely affected lake levels during drought periods (Gázquez-Sánchez et al., 2023). However, archaeological evidence of such interventions on Lake Velo Blato is lacking, and small-scale water withdrawal would not be expected to produce such a clear geochemical signal in the VB-2 record. Hence, given the limited historical and archaeological evidence, as well as weak anthropogenic metal enrichment observed in the lake sediment record, warmer and drier climatic conditions during this period currently provide the most plausible explanation for the environmental transition from a brackish lake to a brackish wetland (Ivkić Filipović et al., 2026a). In contrast, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ records from Prološko Blato show a significant shift toward more negative values between 2100 and 500 cal yr BP, in contrast to other Mediterranean lakes and speleothems, which display higher values during this period (Ivkić Filipović et al., 2026b). Thus, such a shift may be associated with the opening of the Prološko Lake sinkhole, which introduced a new hydrological input to the lake system (Ivkić Filipović et al., 2026b). Other processes were also considered, such as changes in precipitation and recharge rates in the Herzegovinian mountains, which would presumably lead to higher lake levels in Prološko Blato (Ivkić Filipović et al., 2026b). Instead, ostracod assemblages and other proxies support the hydrological disturbance and formation of a seasonally flooded karst wetland (Ivkić Filipović et al., 2026b). Thus, even if the collapse sinkhole did not cause the hydrological disturbance, other processes cannot explain the onset of seasonal desiccation. This pronounced offset in the isotopic record effectively “masked” the climate signal, and thus, sub-millennial climate changes during the Late Holocene cannot be inferred from Prološko Blato lake sediments. Instead, this shift supports the notion that geomorphological processes in karst play a major role in interpreting paleoclimate signals ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) from lacustrine carbonates in such settings (Ivkić Filipović et al., 2026b).

The Little Ice Age (LIA) in Lake Velo Blato is marked by a pronounced shift in $\delta^{18}\text{O}$ to lower values, indicating higher input of detrital carbonates from flysch deposits, as well as lake freshening inferred from the noded valves of brackish ostracod *Cyprideis torosa* (Ivkić Filipović et al., 2026a) and changes in dominant mineral phases in lake sediments from high-Mg to low-Mg calcite (Ilijanić et al., 2022), altogether indicating a decrease in salinity. LIA is generally considered one of the coldest periods of the last 8000 years, marked by cold winters and advances of alpine glaciers (Wanner et al., 2022). However, many records in the Adriatic region testify to increased precipitation and terrigenous input from the catchment, including high frequencies of turbidity-tolerant foraminifera, implying enhanced

precipitation and consequently river runoff on the Italian coast (Piva et al., 2008) and increased sea storm surges in the Venice lagoon from historical records (Camuffo et al., 2000). Similar to the pluvial period during the Early-Middle Holocene, lake sediment records along the EAC document increased terrigenous input from the catchment (Ilijanić et al., 2024) and lower $\delta^{18}\text{O}$ values in estuarine environments, indicating relatively higher river-over-marine influence (Smrkulj et al., 2025). These records correlate well with speleothem-based paleotemperature reconstruction in the northern Adriatic (Frisia et al., 2005) and hydroclimatic variations in speleothems from Modrič Cave (Rudzka et al., 2012), corroborating that the LIA in the Adriatic region was probably characterized by colder and wetter, rather than drier, climatic conditions (Ivkić Filipović et al., 2026a).

5. CONCLUSION

The main objective of this thesis was to provide paleoenvironmental and paleoclimate reconstructions for the three karst lakes in Dalmatia, using sedimentological, geochemical, and ostracod proxies in lake sediments. These reconstructions provided insights into the timing of lake formation, hydroclimatic variations, and geomorphological aspects of lake formation in coastal settings and in karst poljes situated more inland in the Dinaric karst. Therefore, the thesis successfully achieved its main objective. Based on the initial hypotheses, the thesis demonstrated and confirmed that:

- 1) The evolution of karst lakes and paleolakes in Dalmatia is indeed controlled, although not solely, by geomorphological processes in karst, including dissolution, fluvial (alluvial) processes, migration (avulsion) of channels, and, most importantly, changes in surface-to-subsurface connectivity in karst poljes. These processes are prerequisites for forming permanent lakes in such settings. Climate changes in combination with geomorphological and sedimentological processes played a crucial role in the evolution of karst lakes. During the Late Pleistocene to Holocene transition, higher detrital input from the catchment generally indicates wetter climate conditions. These conditions favored lake formation and basin deepening, even in coastal settings influenced by Holocene sea-level rise. During the Middle to Late Holocene, stable isotope analyses of lake carbonates and ostracods inferred a progressive aridification trend, aligning with other records from the Mediterranean region and suggesting regional similarities in climate patterns. The Late Holocene is characterized by dynamic environmental conditions, such as the transition from an open lake to a wetland in coastal Lake Velo Blato and the desiccation of lakes in Bribir-Ostrovica Polje and Prološko Blato. Because no clear evidence of anthropogenic influence was found, climate change and sedimentological and geomorphological processes are the most probable factors shaping the evolution of the studied lakes.
- 2) Changes in ostracod assemblages in all three studied lakes reflected changes in hydrology, such as lake level changes in Lake Velo Blato and desiccation of lakes in karst poljes, as well as geochemical (salinity, nutrient status) and sedimentological (detrital versus authigenic sedimentation) changes, particularly in karst poljes. This confirms that ostracods can serve as reliable proxies for environmental change in Dalmatian lakes, even when the population is dominated by a single species, as in Prološko Blato.

The thesis contributed new paleoclimate data from a previously underexplored region of the central Mediterranean, which are readily available for regional comparisons. Moreover, the thesis demonstrated how geomorphological processes in karst affect the evolution of karst lakes, and

that other site-specific processes must be evaluated using geomorphological, geophysical, and sedimentological methods, particularly in complex settings such as karst poljes. By demonstrating that karst poljes indeed contain valuable sedimentary archives in an otherwise barren karst landscape, this thesis presents a key step towards recovering long terrestrial paleoclimate records of glacial-interglacial cycles in the Dinarides.

Finally, the thesis raised new questions and perspectives for future research, including the determination of the timing of sinkhole formation via coring of lake sediments in collapsed structures supported by improvements in chronology and high-resolution analysis, as well as deeper drilling in karst poljes to extend the sedimentary record to Late Pleistocene (or older) deposits. The comparison with other micropaleontological proxies in lake sediments, such as zoological remains, particularly subfossil chironomids, is proposed. Recent sedimentation processes should be evaluated to better understand catchment-lake dynamics and their relationship to seasonal variation in individual proxies and climate. The origin of spherulitic aragonites in freshwater lakes should be determined, and further sampling of living ostracods is recommended in Prološko Blato to confirm the presence of living species *Juxilyocypris kempfi*, which was thought to be extinct. Finally, the use of geochemical proxies for paleotemperature, including GDGT biomarkers and carbonate clumped-isotope ($\Delta 47$) measurements, is suggested for terrestrial, aquatic, and marine records from the central Mediterranean to improve regional paleotemperature reconstructions.

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7. RESEARCH PAPERS

Research paper 1

Ilijanić, N., Miko, S., **Ivkić Filipović, I.**, Hasan, O., Šparica Miko, M., Petrinec, B., Terzić, J. & Marković, T. (2022). A Holocene Sedimentary Record and the Impact of Sea-Level Rise in the Karst Lake Velo Blato and the Wetlands on Pag Island (Croatia). *Water* 14, 342. doi: 10.3390/w14030342.

Article

A Holocene Sedimentary Record and the Impact of Sea-Level Rise in the Karst Lake Velo Blato and the Wetlands on Pag Island (Croatia)

Nikolina Ilijanić ^{1,*}, Slobodan Miko ¹, Ivona Ivkić Filipović ¹, Ozren Hasan ¹, Martina Šparica Miko ¹, Branko Petrincec ², Josip Terzić ¹ and Tamara Marković ¹

¹ Croatian Geological Survey, Sachsova 2, 10000 Zagreb, Croatia; smiko@hgi-cgs.hr (S.M.); iivkic@hgi-cgs.hr (I.I.F.); ohasan@hgi-cgs.hr (O.H.); mtsparica@hgi-cgs.hr (M.Š.M.); jterzic@hgi-cgs.hr (J.T.); tmarkovic@hgi-cgs.hr (T.M.)

² Institute for Medical Research and Occupational Health, Ksaverska cesta 2, 10001 Zagreb, Croatia; petrincec@imi.hr

* Correspondence: nilijanic@hgi-cgs.hr

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Abstract: Lakes in coastal lowland areas represent a critically vulnerable environment as a transitional space between freshwater and seawater environments. The paleoenvironmental reconstruction and anthropogenic impact are assessed through the lake sediment cores from Velo, Malo, and Kolanjsko Blato using multi-proxy analyses (sedimentological, mineralogical, geochemical, ¹³⁷Cs and ostracod analyses, and AMS ¹⁴C radiocarbon dating). The freshwater lake Velo Blato was formed at 8100 cal yr BP due to rising groundwater levels as a consequence of sea-level rise. The brackish conditions in Lake Velo Blato started at 7100 cal yr BP, giving the index point for the sea-level curve of 7-m lower than present. Lead concentrations showed slightly increased values in the last 1800 cal yr BP, while the spike in Malo Blato lake sediments probably derived from bird hunting with lead bullets. Kolanjsko Blato sediment core archives the sediment record of the last 2050 years, which represents a shallow brackish coastal wetland under marine influence. Enrichment factors showed the accumulation of Cu, Hg, P, Pb, S, and Zn in the sediments from Kolanjsko Blato in the last 650 cal yr BP, which coincides with the high organic carbon content, and in sediments from Malo Blato after the lake's formation (from the depth of 20 cm upwards). Anthropogenic Cu introduced into the Kolanjsko Blato sediments is the highest in the surface sample. Surficial sediments from Velo Blato are characterized by the high organic carbon, S, P, and N content, indicating high productivity and eutrophication which led to occasional anoxic conditions on the lake bottom in the last 200 years.

Keywords: coastal lake and wetlands; lake sediments; karst; eastern Adriatic coast; geochemistry; heavy metals; total organic carbon; ostracods

1. Introduction

The low-lying coastal areas in the Mediterranean, such as the eastern Adriatic coast (EAC), are under constant threat of marine influence during Holocene transgression, i.e., relative sea-level (RSL) rise. A fluctuating sea level generates changes in coastal areas due to the increase in salinity. The lake–wetland systems in coastal areas are especially vulnerable in this context. This paper tries to determine whether this is due to human anthropogenic activities (industry, urbanization, tourism, and food production) or naturally occurring environmental changes. The sedimentary lake record presents a valuable archive to identify this impact in the past and to reconstruct the trends for future changes. Lake sediments have been widely used as environmental indicators [1], and they can record

Late Quaternary paleoclimate changes and hydrology, but they also reflect local, catchment-specific processes, evidenced across the Mediterranean lakes [2]. Holocene climate variability is generally weaker in amplitude than the climate fluctuations of the last glacial interval; therefore, high-resolution multi-proxy records are essential [3,4]. In karst areas, most of the Quaternary deposits are not preserved due to the nature of karst and its porous features and high permeability [5]. Compared to rivers and streams, lake wetlands may seem like peaceful unchanging environments, but they undergo physical changes at spatial and temporal scales, especially under marine influence. Changes in vegetation, lake levels, and seawater impacts may greatly influence wetland biota. Coastal wetlands are defined as ecosystems found within an elevation gradient that ranges between sub-tidal depths, at which light penetrates to support photosynthesis of benthic plants, and the landward edge, where the sea passes its hydrologic influence to groundwater and atmospheric processes [6]. Coastal lakes and wetlands are transitional ecosystems between land, freshwater, and seawater. In addition, the Croatian karstic coast is scant in terms of permanent freshwater body occurrences; most of the basins drowned from the period of the Last Glacial Maximum (LGM) lowstand to the Holocene sea-level rise, well-known along the EAC [7]. Therefore, karst, near the sea, has generally evolved in response to Quaternary sea-level changes. The recent EAC has been shaped by the last (Late Pleistocene–Holocene) sea-level rise, when the karstified relief was partially submerged [7].

In general, present-day coastal lakes and wetlands started to evolve in the last 120,000 years [6], when the mean global sea level was comparable to the present one [8]. About 20,000 years ago, during the LGM, the sea level was 120-m below the present mean sea level [8], causing the existence of coastal wetlands along those coasts that were not buried by permanent ice. Rapid and global sea-level rise from the LGM period made a high disturbance for coastal ecosystems. In the Holocene, the sea level rose from about 60 m to 1 m, and the mean sea level reached its present, world-averaged level about 6000 years ago [8,9]. Mediterranean coastal lowlands are affected by the Holocene marine transgression, which led to the flooding of closed basins and embayments [10–17].

The natural coastline of the Eastern Adriatic Sea was affected by changes in sea level during the Late Pleistocene and Holocene. Vast areas were dry land between the islands representing depressions and valleys, i.e., karst poljes, intersected by river flows [10–17]. Isolated karstic basins evolved from freshwater lakes and karst poljes to marine lakes during the last 50,000 years, as indicated by a sedimentary record in Lošinj Bay in the northern Adriatic Sea [15]. The coast retreated from an advancing sea, and the sea drowned the Late-Pleistocene/Early-Holocene landscapes. This is evidenced on the eastern Adriatic coast by submerged freshwater lakes and wetlands in Lake Veliko and Stupa Bay on the Island of Mljet [16,18], in Pirovac Bay [19], as well as a sub-marine archaeological Roman site and salt marsh in the Caska Bay on the Island of Pag [20,21], and prehistoric pile-dwellings in Zambratija Bay [22]. Most of the freshwater lakes on the eastern Adriatic coastal area formed during the Late Pleistocene/Early Holocene, such as Lake Vrana [23–25], a lake in Bokanjačko Blato [26], the Baćina Lakes (Crniševno) [19], and Lake Veliko on the Island of Mljet [16–18,27]. Holocene palaeohydrological changes from shallow to deeper lakes are driven by the sea level rise, while climate variability was only partly recorded, also due to the low resolution. Lake sediments from these lakes provide records of Holocene paleoenvironmental changes containing a combination of natural hydrological to climatic and anthropogenic signals, in relation to sea level rise and local catchment-specific processes. In the central and eastern Mediterranean, a wetter climate prevailed in early to mid-Holocene [28–31], followed by the drier climate conditions during the mid-Holocene, and several arid phases, with considerable site-to-site differences [2,31–33]. In the Adriatic Sea marine sediment core records, the wet early to mid-Holocene was determined [34,35], supported by the lake and marine sediment cores in the eastern Adriatic Sea [10,14,15,18,23,26,27,36,37]. High-resolution paleoclimate reconstruction was possible in lake sediments in the period of the deep-lake phase, between 8300 and 2600 cal yr BP,

in Veliko Jezero on the Island of Mljet with four major and six minor cold and dry events identified [27], which correlates well with Adriatic marine cores [35,38].

Holocene climate conditions were reconstructed, with several wetter and dry periods during mid and early Holocene, using stable isotopes on speleothems from Croatian caves in Dalmatia, the Modrič Cave near the town of Zadar [39], Manita peć in the Velebit Mountains [40], Strašna peć on the Island of Dugi Otok [41], and two caves on the Island of Mljet [42]. All these mentioned lake, marine, and speleothem records from coastal Croatia are compared with the isotopic signal from speleothem data from continental Croatia, namely, from the Nova Grgosova Cave [43].

Holocene sea-level rise data points were determined on specific localities on the Eastern Adriatic Sea: in Lošinj Bay [14,15], in Novigrad and the Karin Sea [44,45], in Veliko Jezero and Stupa Bay on the Island of Mljet [16,27], in Caska Bay on the Island of Pag [20], in western Istria [46], in the Mirna and Neretva valleys [47], and on submerged speleothem records along the eastern Adriatic coast [48,49]. The salt pans and fish tanks were also used as sea-level markers on the eastern Adriatic coast [50–52], as well as archaeological and biological markers [53–55].

The coastal marine and estuarine environments along the eastern Adriatic coast were investigated using the marine and lake sediment cores at specific locations [14,56–66]. The studies of Dolenec et al. [67] and De Lazzari et al. [68] provided geochemical data for surface sediments along the southern part of the eastern Adriatic coast (EAC). The studies of trace elements in sediments of the central-southern Adriatic Sea indicate that contamination is only limited to specific areas [69]. Based on the analysis of a core from the MAD, trace element concentrations are consistent with the average composition of fine-grained middle Adriatic sediments, and major variations depend on changes in the silicate/carbonate ratios and the type and abundance of silicate supply [70]. The depth profiles of short marine sediment cores, collected at locations on a transect along the western rim of the EAC, showed that there is no contamination with priority contaminants in aquatic systems (As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn). At the same time, Mo, Mn, Al, and Ca were identified as geogenic elements in those sediments, and the elemental composition was used to trace sediment sources [19]. Coastal lakes and wetlands host large and dynamic reservoirs of organic carbon. Higher values of TOC are evident in isolated karst basins during the freshwater phase, compared to recent marine and lake sediments [14,15,23,26,27].

In karstic areas, surface and underground water circulation are vital to the sedimentation processes, chemistry, and biology of coastal lakes and wetlands [6]. There is vital feedback between fresh and saline groundwater flows, sediment dynamics and organic matter mineralization, and the constantly changing geomorphology of coastal lakes and wetlands. Physical factors, such as water level, salinity range, and rising sea level, determine the type of coastal lake and wetland at a particular site. All the coastal lakes respond to sediment sources. Available material deposited in the basin influences the sedimentary environment. Sediment accumulation through deposition is a critical process because it maintains the relationship between a lake and wetland surface and sea-level change.

The evolution of coastal lakes and wetlands, Velo, Malo, and Kolanjsko Blato of the Pag Island on the central part of the eastern Adriatic coast (Figure 1) is examined using lake sediment cores. Paleoenvironmental reconstruction relied on the sedimentary records using grain-size, mineralogical and elemental composition, organic carbon and nitrogen content, and natural and anthropogenic radionuclides, coupled with micropaleontological ostracod analyses. The overall objective of this study is to identify paleolimnological and paleo-hydrological processes controlling the Holocene evolution of karst lakes in the coastal karstic region of Croatia using multiproxy methods. The Island of Pag, hosting the studied lake and wetlands, is a geologically highly complex low-lying karst coastal environment under the marine influence. As such, the karst lakes are well suited to be used to monitor environmental changes based on the interplay of sea-level rise and hydrological conditions due to changes in groundwater level and precipitation. Variations

in lake levels during the Holocene were determined, which significantly influenced lake–wetland geochemical processes and vegetation habitats. Although the sea water intrusion is not the prime focus of the present paper, the process is considered most relevant, for the formation of these water bodies and the sediments play a crucial role as archives of the paleo-hydrological conditions. Records of multiple variables archived in sediment successions were used to evaluate environmental changes across time scales beyond the reach of monitoring data.

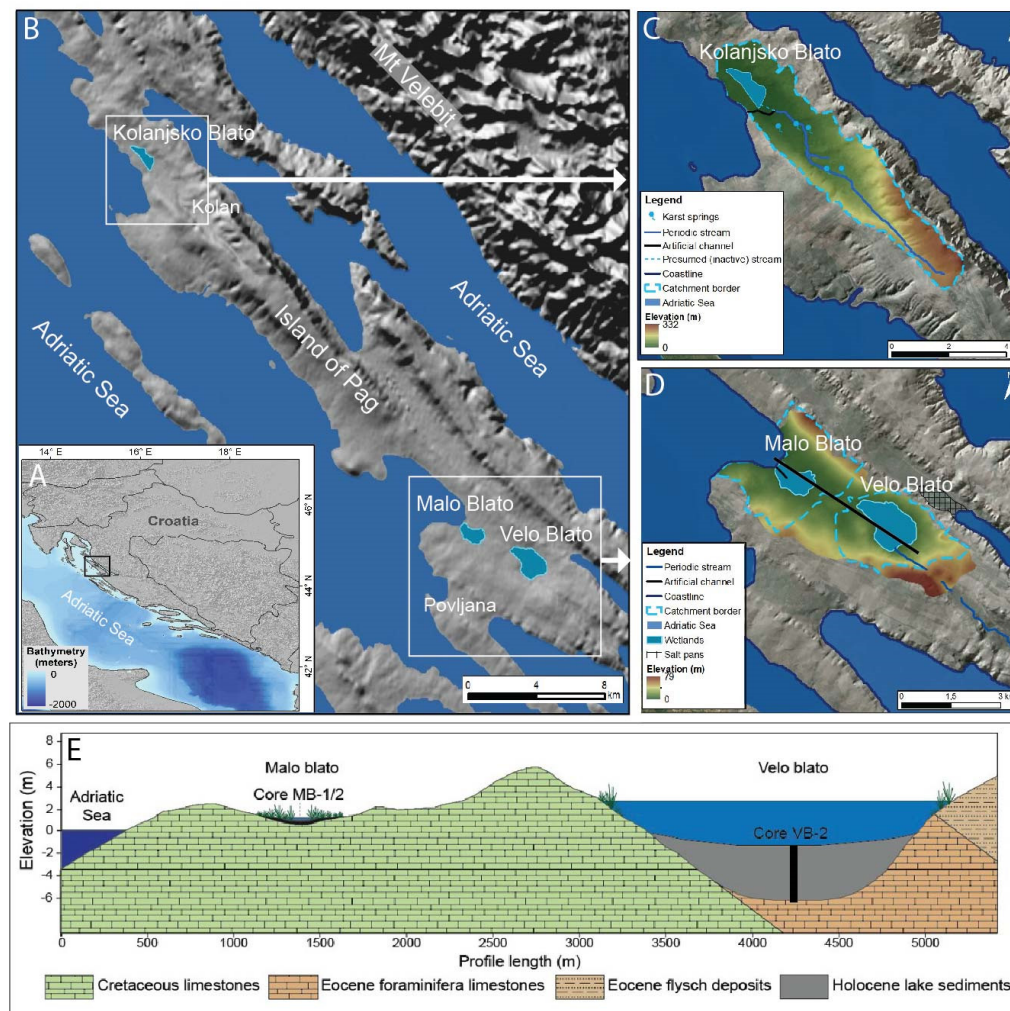


Figure 1. (A) The Island of Pag in Croatia, in the central part of the eastern Adriatic coast (black rectangle) (B) The study locations of Kolanjsko, Malo and Velo Blato on the Island of Pag; shallow coastal wetland Kolanjsko Blato (C) and lake Velo Blato and wetland Malo Blato (D) detailed maps with catchments area. The black line in figure D presents a profile through Velo and Malo Blato (E) to emphasize geomorphological and geological settings. Note that boundaries between geological units are schematic.

2. Materials and Methods

2.1. Study Site

Velo, Malo, and Kolanjsko Blato are coastal shallow lakes and wetlands in the central and southwestern part of the Island of Pag. The Island of Pag lies on the eastern Adriatic coast in Croatia, a typical Dalmatian-type coast with chains of islands and channels parallel to the coastline [71]. It is part of the Northern Dalmatian Archipelago, elongated in a NW–SE direction (Dinaric strike) in a length of approximately 60 km, and only 2 to 10 km

wide. It is one of the largest islands on the Croatian coast (284.2 km²), and the most indented, with a 302.5-km long shoreline [72]. The Island of Pag is characterized by low altitudes (the highest peak is 349 m asl.), with the most settlements located at an altitude of up to 50 m, except for a few settlements located at altitudes up to 100 m (Kolan and settlements on the Lun peninsula). Geologically, it belongs to the External Dinarides, which are a part of the Adriatic carbonate platform (AdCP) [73].

On the island of Pag, Upper Cretaceous rudist limestones predominate, followed by Upper Cretaceous limestones and dolomites and Paleogene clastic rocks (Eocene foraminiferal limestones and flysch) (Figure 2) [74–77]. On the Island of Pag there are occurrences of Eocene bauxite deposits. Miocene lacustrine deposits on Pag, presented by marls, clays, and sandstones with coal, are restricted to two NW–SE elongated basins, developed in two isolated syncline cores, Kolanjsko polje and the Crnika area [78,79], with most of the Miocene deposits hidden below the Pleistocene and Holocene sand and debris. The lacustrine sediments transgressively onlap the Cretaceous basement and attain a maximal thickness of 140 m in Kolanjsko polje [77]. Brown coal with black clay and lignite appears within lacustrine deposits in Kolanjsko Polje, and it was commercially exploited in the 19th and the first half of the 20th century. Quaternary sediments (alluvial/colluvial sands and clays) fill the larger dolines (karst valleys), such as Kolanjsko, Novaljsko, Paško, Dinjiško, Povljansko, and Vlašičko polje. Paško and Dinjiško polje are used as salt pans for salt production.



Figure 2. Geological map of the Island of Pag, with study locations Velo, Malo, and Kolanjsko Blato (modified after [74–77]).

Generally, relief is in accordance with the geological structure, which means the anticlines correspond to the highest parts of the island and the synclines correspond to shallow depressions. Valleys and poljes filled with Paleogene clastic rocks (Eocene marls, sandstones, and foraminiferal limestones), covered by Quaternary deposits (clay, sand) are favorable for water accumulation [80,81]. The anticlines, composed of Upper Cretaceous rudist limestones and dolomites, and Paleogene foraminiferal limestones, can direct groundwater flow locally, depending on the ratio of dolomitic layers in their cores. Infiltrated water naturally outflows on a large number of small coastal springs and vruljas, but in geologically and morphologically favorable zones, such as poljes, small local karst aquifers can be formed. Due to the relatively low altitude of that part of the terrain, a lake was formed on Velo Blato. That lake is in direct connection with a karst aquifer, and is slightly brackish; the chloride ion content is partially derived from the underground transition or mixing zone, and partially originates from the small seawater spray particles brought by strong NE wind bora. Although geological and morphological relations (high indentation and lack of favorably situated groundwater barriers) do not allow the formation of larger karst aquifers, the Island of Pag has several small aquifers, and some of them were used for public water supply. They are mutually not connected, and extracted quantities are limited. In the north-western shores of Lake Velo Blato, the pumping station was built for the public water supply in 1971. The groundwater and the slightly brackish surface lake water of Velo Blato was used mainly. In recent years, it has not been used frequently for water supply because of the limited water quality due to salinization problems [81,82]. The hydrogeological study confirmed that salinity increases with depth, with significantly higher values at approximately 15 m bsl [82]. The groundwater and surface water characteristics also vary according to the season, especially in chloride content and electrical conductivity, as well as in oxygen concentrations (Table 1). The data shown are derived from the water pumping station of Velo Blato between 2016 and 2018 (4 measurements annually), compared to the surface waters from Velo, Malo, and Kolanjsko Blato, which were measured within this study.

Table 1. Groundwater characteristics and geochemistry from the water pumping station of Velo Blato (VB), measured between 2016 and 2018, and presented as winter (November–May) and summer (July–October) periods; and surface water samples from Velo (VB), Malo (MB), and Kolanjsko (KB) Blato, measured in this study.

Water Sample	VB Water Pumping Station (Winter)	VB Water Pumping Station (Summer)	VB-1 (NW Part)	VB-2 (E Part)	MB-1	KB-1 (W Part)	KB-2 (Central Part)	KB-3 (E Part)
T (°C)	14.2	21.1	10.1	11.2	9	7.9	8.9	9.3
pH	7.4	7.7	8.32	8.5	7.8	8.11	8.18	8.26
O ₂ (mg/L)	4.3	6.6	11.6	13.4	11	10.8	11.6	11.9
EC (mS/cm)	1.75	2.27	2.08	2.09	3.8	4.88	9.8	9.55
Cl ⁻ (mg/L)	404.7	617.2	996.6	1000.1	1898.1	2700.8	6257.9	6042.3
NO ₂ ⁻ (mg/L)	0.31	<0.009	<0.01	0.31	<0.01	<0.01	<0.01	<0.01
NO ₃ ⁻ (mg/L)	0.45	0.45	0.37	0.39	0.7	<0.1	<0.1	<0.1
SO ₄ ²⁻ (mg/L)	85.4	91.8	92.2	90.7	176.4	216.6	584.8	569.7
NH ₄ ⁺ (mg/L)	0.1	0.4	0.06	0.04	0.01	0.04	<0.01	<0.01
Ca ²⁺ (mg/L)	n.a.*	n.a.*	82.5	82.1	108.1	114	145.1	138.1
Mg ²⁺ (mg/L)	n.a.*	n.a.*	30.6	30.8	53.9	77.2	166.8	161.7
Na ⁺ (mg/L)	n.a.*	n.a.*	575.1	575.9	1118.6	1618.4	3604.7	3554.3
K ⁺ (mg/L)	n.a.*	n.a.*	9.1	9.2	17.0	23.9	57.9	56.2
HCO ₃ ⁻ (mg/L)	n.a.*	n.a.*	250	250	280	360	380	370
TN (mg/L)	0.002	0.0024	n.a.*	n.a.*	n.a.*	n.a.*	n.a.*	n.a.*
TP (mg/L)	0.0058	0.0082	n.a.*	n.a.*	n.a.*	n.a.*	n.a.*	n.a.*

T—temperature; EC—electrical conductivity; * n.a.—not analyzed.

Coastal lake Velo Blato and wetland Malo Blato are located near Poveljana, and they are approximately 1.5 km apart, with an up to 5-m high ridge between them. The total catchment area is 23 km². Velo Blato is the largest freshwater lake on the Island of Pag and represents an open-water surface area (surface 2 km²). Nearby, Malo Blato (surface 0.9 km²) comprises a larger wetland area that is rarely filled with water; only a smaller central part represents the permanent water body of Malo Blato. Malo Blato directly connects to the sea through the 450-m long artificial drainage canal, probably built before the 19th century. Velo Blato is located further away from the sea, without a direct connection to the sea. The large part of the lake is covered with wetland flora, especially reedbeds (reeds) and sedges, mainly in the north-western parts. Flora extends towards the central part of the lake in parallel lines perpendicular to the direction of the lake. The lake is a cryptodepression, with an average water depth between 0.5 and 2.36 m [83]. It has no inflow or outflow rivers, only periodic streams on the south-eastern shores of the lake that occur during wet seasons. The lake level in Velo Blato strongly depends on the precipitation and groundwater level [75,76]. It was noted that lake levels varied between 0.5 and 2.36 m asl. during the five years of monitoring within the hydrogeological research of its sanitary protection zones [82]. The seasonal variations in lake levels in Malo, Velo, and Kolanjsko Blato are visible in the false-color composite Sentinel-2 satellite images [84]. False-color composite is commonly used to study vegetation and its density (red color) and can be easily distinguished from the water and sea, which appear black or blue (Figure 3). Malo Blato is dominantly under the influence of daily tides, and the seasonal wet and dry periods have less impact on water level at Malo Blato than at Kolanjsko and Velo Blato, which have higher water levels in the wet period (Figure 3).

Kolanjsko Blato is located further away from Velo and Malo Blato, in the north-western direction, near Kolan. It comprises a larger water surface area during wet periods of the year in winter months, while, during summer months, the lake level decreases and three irregular shaped water bodies appear, separated from one another only by wetland vegetation (Figure 3). The catchment area is 23 km². It is separated from the sea through the carbonate ridge to the SE–S direction, 300- to 500-m wide. Geomorphological characteristics of the terrain indicate the surficial connection to the sea through the narrow artificial canal in the area of Rogoza, in the SW edge of the Kolanjsko Blato, through which the sea enters the Kolanjsko Blato at high tides; at low tides and at high water levels, the freshwater is drained into the sea. At the geomorphologically lowest part of the lagoon, salinity is occasionally higher. All together, they form a Kolanjsko Blato–Blato Rogoza lake–wetland ecosystem.

The climate of the Island of Pag belongs to a warm humid climate with hot summers— a Cfa type, according to Köppen’s classification [85]. The average annual air temperature is 15.5 °C, and the average annual precipitation is 978 mm, with maximum precipitation between March and June (from 1981 to 2000, meteorological station Pag [86]). The whole island is exposed to the blows of the north-eastern wind bora; therefore, the vegetation is low and degraded, especially in very windy areas. The average number of days with strong or stormy winds was 23.5, while the mean number was 3.5 days, most of which occurred during winter (from December to March). During a period of strong bora winds, the sea salt is spread through the air throughout the island.

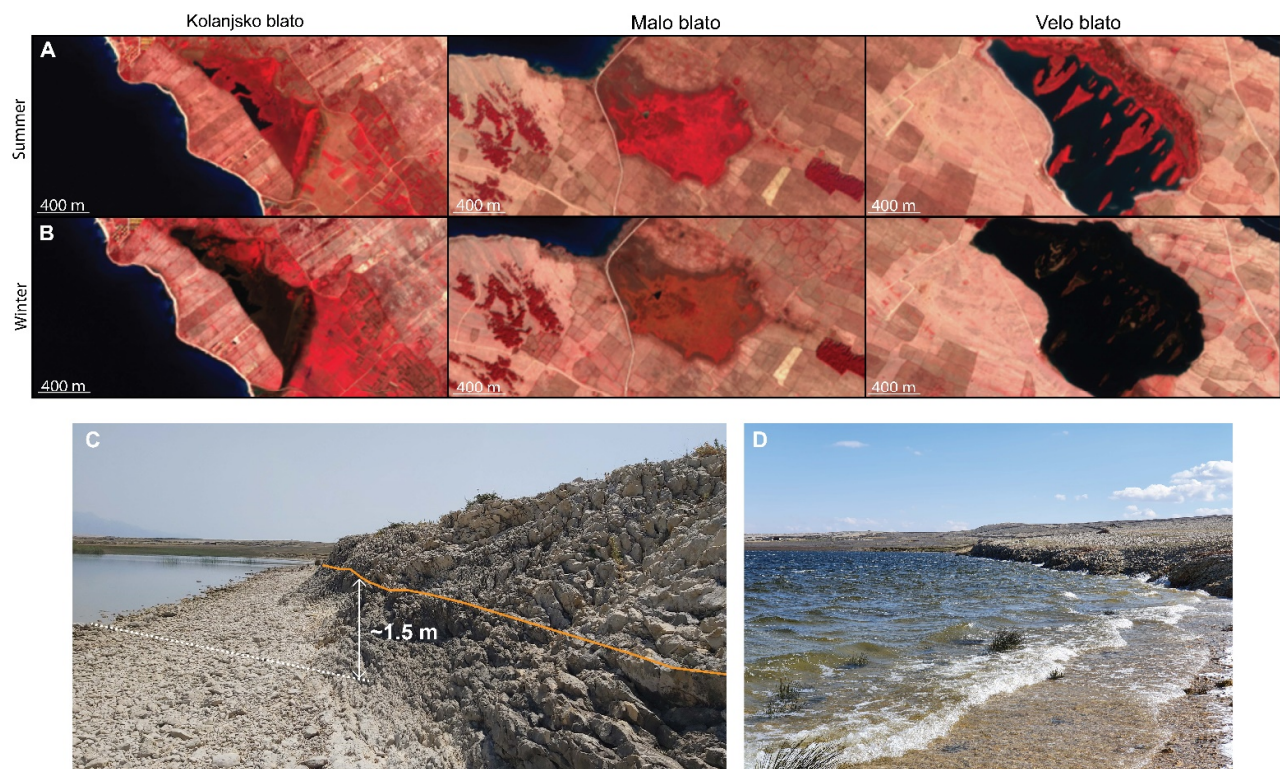


Figure 3. Satellite images (false-color composite Sentinel-2) of Kolanjsko, Malo, and Velo Blato during the dry (A) and wet (B) seasons in 2021 [84]; photos of the Lake Velo Blato surface level during the dry (June 2021; (C)) and wet (March 2021; (D)) periods—the lake level was up to 1.5-m lower during dry periods.

Velo, Malo, and Kolanjsko Blato represent freshwater-to-brackish wetlands, with characteristic wetland flora, fauna, and habitats. In vegetation, annual halophytes (*Salicornia* in Velo and Malo Blato, *Cakiletea maritima* p. in Kolanjsko Blato) predominate. *Salicornia* is a salt-tolerant halophyte flowering plant that usually grows in salt marshes. Other species in the area of Malo Blato include *Cladium mariscus*, which was rare in the past, but its number has increased during the past 80 years [86]. It usually grows on peat at the margins of the lakes and ponds. Habitats that prevail in Velo and Malo Blato are Mediterranean sitine (*Juncetalia maritimi*), Mediterranean and thermoatlantic vegetation of halophilous shrubs (*Sarcocornetea fruticosi*), Isoeto-Nanojuncetea wetland habitats, eastern sub-Mediterranean dry grasslands, and natural eutrophic waters with Hydrocharition or Magnopotamion vegetation. The habitats of Kolanjsko Blato belong to coastal lagoons, eastern sub-Mediterranean dry grasslands, Mediterranean occasional pools, Mediterranean sitine, sub-Mediterranean wet grasslands, Molinio–Horedion. In Velo and Malo Blato appear wetland birds, spindles, and butterflies. Various birds, such as herons, gleaming ibis, and especially turkeys, the great reed warbler and the silkworm, various species of woodpeckers, and many others inhabit Kolanjsko Blato. The endangered sea sandpiper, a nesting bird of Pag salt pans, appears here, in addition to spindles, land and pond turtles, red snakes, meadow clefts, and butterflies. In the past, there has been evidence of the presence of eels in Lake Velo Blato [83]. Grazing sheep maintain the surrounding dry pastures. Both Velo and Malo Blato, as well as Kolanjsko Blato, are protected areas as Ornithological Reserves since 1988, and are managed by the Public Institution Natura Jadera, Zadar County. These reserves are part of ecological networks HR4000004 and HR2000911.

2.2. Sampling and Side-Scan Sonar Survey

A long sediment core in Velo Blato (VB-2, 0–568 cm) was extracted from the central part ($44^{\circ}21.292' \text{ N}$, $15^{\circ}9.308' \text{ E}$) at the water depth of 2.7 m (Figure 4) using the Uwitec piston corer, which consists of rope-operated piston corer mounted on a tripod tower on an aluminum platform and pontoon floaters. The coring is performed by a hammer from the platform, using 3-m long plastic liners, 60 mm in diameter, in a stainless steel liner, and it is possible to retrieve contiguous 3-m sections of the sediment core. Due to the limited access and unapproachable terrain of the water bodies of Kolanjsko and Malo Blato, the sediment sampling was made possible only by rubber boats (in the case of Kolanjsko Blato) or by foot (in the case of Malo Blato) (both in March 2020). As a result, the sediment cores recovered from these lakes are only 107-cm long from Kolanjsko Blato (KB-1; $44^{\circ}31.442' \text{ N}$, $14^{\circ}54.662' \text{ E}$) and 35-cm long from Malo Blato (MB-1/2; $44^{\circ}22.017' \text{ N}$, $15^{\circ}7.114' \text{ E}$) (Figure 5). The sampling campaign was performed in April 2020. The cores were transported into the laboratory of the Croatian Geological Survey for core description and sub-sampling. The cores were split lengthwise and photographed. Archive halves were stored in the cooling chamber. In addition, several short sediment cores (<50 cm) and grab samples were collected in Velo Blato using a gravity corer and a Van Veen grab sampler, respectively (Uwitec, Mondsee, Austria). On the southern shores of Lake Velo Blato, the samples of flysch marls were taken for mineralogical analysis.

During fieldwork in March 2020, the surface water was sampled in Velo Blato—2 locations, Kolanjsko Blato—3 locations, and Malo Blato—1 location. Prior to sampling, the field parameters of electrical conductivity (EC), temperature (T), pH, and dissolved oxygen (DO) were measured using a portable multiparameter probe (WTW). Basic anions and cations were determined using the ion chromatograph Dionex ICS 6000 in the Hydrochemical Laboratory of the Croatian Geological Survey. The results are compared to groundwater from water pumping station Velo Blato and presented in Table 1.

Side-scan sonar (SSS) was used to better understand the morphology and bathymetry of the lakebed. The survey was conducted in Lake Velo Blato (Figure 4). A side-scan sonar Humminbird 999 HD SI was used, which was mounted on a small rubber boat. This side-scan sonar device operates at frequencies of 80 or 200 kHz with an external Humminbird AS + GPS HS antenna and heading sensor used for positioning.

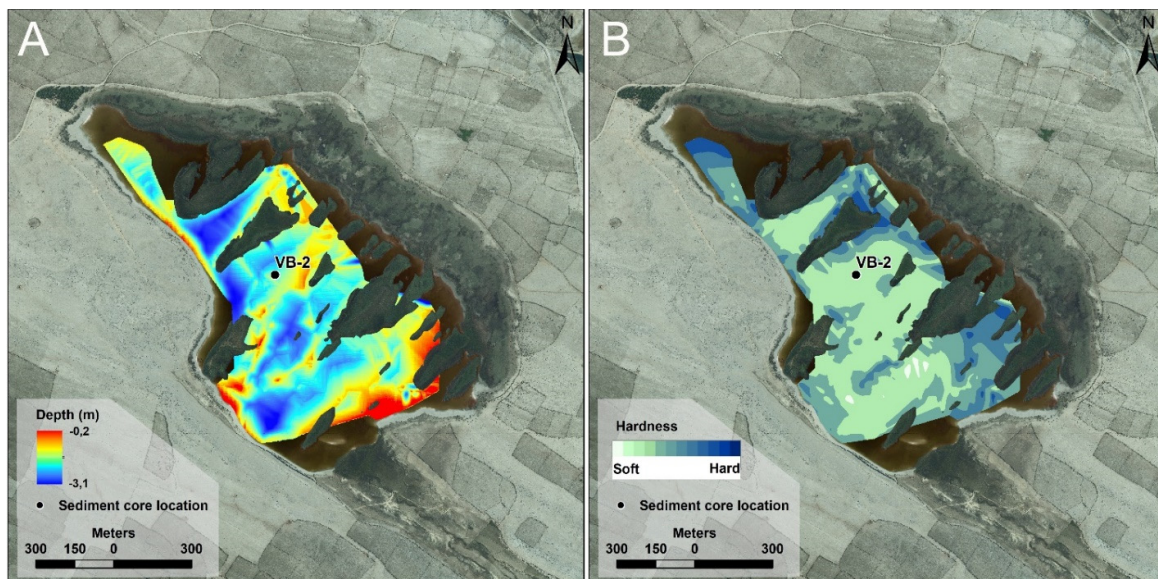


Figure 4. Lake Velo Blato images obtained using side-scan sonar: (A) lake bathymetry map; (B) backscatter images (sediment “hardness”) map. Sediment core location VB-2 is marked on both maps.



Figure 5. Sampling locations in Kolanjsko (A) and Malo Blato (B).

2.3. Sedimentological and Mineralogical Analysis

The sediment cores from Velo and Kolanjsko Blato were imaged, and spectral color measurements were performed, using an X-Rite spectrophotometer (DTP22). Magnetic susceptibility was measured (MS, SI units $\times 10^{-5}$) using a Bartington MS2E surface sensor with a 1-cm resolution. In addition, wet/dry bulk density and water percentage were measured in 70 samples throughout the sediment core from Velo Blato. Smear slides were prepared using Norland 61 optical adhesive and a UV lamp on glass slides. Grain-size analysis was performed using a Shimadzu SALD-2300 laser diffractometer, between 0.17- μm and 2-mm particle size. Samples (0.2 g) were pre-treated with 30% H_2O_2 on a hot plate at 80 °C to remove the organic matter. Next, 2 mL ($\text{Na}_4\text{P}_2\text{O}_7$) was added as a dispersant; then, the samples were sonicated before being analyzed. The obtained result for every sample is the average of three measurements. The data were processed using the software GRADISTAT v8 [87]. In total, thirty-seven samples were measured for grain-size from a sediment core from Velo Blato, and ten samples were measured from both Malo and Kolanjsko Blato. Mineralogy was determined on selected samples by a PANalytical X'Pert Powder X-ray diffractometer (Cu $\text{K}\alpha$, 45 kV, 40 mA, Ni filter). The back-loading technique was used for specimen preparation of the powdered samples. The angular range of measurements was 4° to 66°2 θ . Identification was performed using HighScore X'Pert Plus software by ICDD database (PDF-4/Minerals) and XRD patterns [88]. The bulk mineralogical composition was determined for thirty-eight samples from Velo, Malo, and Kolanjsko Blato. The clay mineral analysis on oriented samples was performed on two samples from the sediment core from Velo Blato (289–296 cm, 445–446 cm) and flysch marls from the southern lake shores of Velo Blato. The clay fraction was prepared after calcite removal on glass slides, and the clay minerals were identified after air drying, ethylene glycol saturation, and heating to 400 and 550 °C [88].

2.4. Geochemical Analysis

Geochemical analyses were performed as quantitative elemental assays of forty-five major and trace elements, in addition to Hg, on 52 samples covering all sedimentary facies, by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma-Emission Spectrometry (ICP-MS and ICP-ES), at the commercial laboratory Bureau Veritas in Vancouver, Canada. Samples (1 g) were dissolved in multi-acid (HCl - HNO_3 - HClO_4 - HF) at 200 °C. Mercury (Hg) was dissolved using aqua regia digestion. Reference standard materials were STD DS11, STD OREAS262, STD BVGEO01, STD OREAS25A-4A, and STD OREAS45H.

The Enrichment Factors (EF) of selected elements were used to estimate the status of environmental contamination and the degree of anthropogenic heavy metal pollution. Element concentrations are normalized against an immobile conservative element to eliminate grain-size effects and dilution by mineral phases such as quartz and carbonates. Al is the most frequently used geochemical normalizer in coastal and marine sediments, based on the assumption that Al is present in terrigenous (detrital) aluminosilicates [89–91]. Background reference values were taken from deeper layers [92]. Trace metals that derive entirely from naturally occurring rocks and weathering processes display values between 0.5–1.5, whereas trace metals from dominantly anthropogenic sources show values greater than 1.5 [93]. The EF values were calculated using Formula (1) given in Zhang et al. [93]:

$$Ef = (\text{Metal}/\text{Al})_{\text{sample}}/(\text{Metal}/\text{Al})_{\text{background}} \quad (1)$$

The sediment core from Velo Blato was sub-sampled every 5 cm in the upper part of the core (0–200 cm) and every 10 to 15 cm in the lower part of the core (200–550 cm) for Total Carbon (TC) and Total Nitrogen (TN), and Total Organic (TOC) and Total Inorganic (TIC) Carbon. In total, seventy-one samples from the Velo Blato sediment core, and ten samples from both Malo and Kolanjsko Blato, were analyzed. They were measured with a CN elemental analyzer, Thermo Fisher Flash2000. Total carbon (TC) and nitrogen (TN) were measured directly, while total organic carbon (TOC) was measured after the removal of carbonates using 4M HCl and heating for 2 h. Total inorganic carbon (TIC) was calculated as the difference between TC and TOC. The C/N ratio was calculated by dividing the TOC and TN.

2.5. Ostracod Analysis

For micropaleontological analyses, forty-three samples were taken from the Velo Blato sediment core (VB-2), and ten samples from both Malo (MB-1/2) and Kolanjsko (KB-1/1) Blato. The sampling resolution was, in general, 1 cm, but it sometimes needed to be 2 or 4 cm (for the topmost sample) due to high organic matter contents in the sediments. The samples were first freeze-dried, after which they weighed at ~5 g (Malo and Velo Blato) and ~3 g (Kolanjsko Blato). The freeze-drying method was shown to be very successful in preparing micropaleontological samples from lake sediments. Thus, no additional chemical treatment was used during the preparation. The samples were wet-sieved with distilled water to 400 and 125 µm, and finally, they were oven-dried at 40 °C. Samples from all sediment cores (Malo, Velo, and Kolanjsko Blato) were examined qualitatively to determine the general species variability and general fossil content in the recent sediments from all wetlands. Preliminary qualitative analyses of the samples from the VB-2 sediment core from Velo Blato showed greater potential for the quantitative ostracod analysis. Samples from Velo Blato are very rich in ostracods, and they contained some smaller species which were not present in the 400-µm fraction (e.g., *Limnocythere inopinata* and *Cypria ophthalmica*). Thus, it was decided to re-sift previous and additional samples to 0.2 and 0.125 µm, and only the larger size fraction was quantitatively analyzed. The dry-sieved sediment was weighed, and samples were analyzed using the AmScope 3.5×–90× trinocular zoom stereomicroscope. Due to the high abundances of the species, ostracod shells were manually picked only from the 0.2-mm fraction using a fine brush and deionized water. Abundances were normalized to 1 g of dry sieved sediment. Species identification was based on Fuhrman [94] and Meisch [95].

2.6. Radioactivity Measurements

The gamma-spectrometry was performed on short sediment cores from Velo and Kolanjsko Blato. Cores were sliced in 1-cm intervals, dried in a freeze-dryer, and ground to ensure homogeneity. Samples were packed in 100-cm³ volume geometry, sealed, and left for four weeks to establish radiochemical equilibrium before the activities of radionuclides (²¹⁴Bi, ¹³⁷Cs, ⁴⁰K, ²¹⁰Pb and ²²⁶Ra) were determined. The sample masses varied from 9.5 to 26.6 g. The radioactivity measurements were performed on 20 samples (10 per sediment core from Velo and Kolanjsko Blato) at the Institute for Medical Research and Occupational Health in Zagreb, using ORTEC p-type coaxial high purity germanium (HPGe) detectors. The data acquisition was performed using a computerized system (GammaVision software). Samples were counted for a minimum of 80,000 s. Activity concentrations of ¹³⁷Cs were used to determine the sedimentation rate on the analyzed sediment cores. The calibration of the measurement setup was carried out using standards prepared by the Czech Metrology Institute, whereas quality assurance was performed through regular participation in interlaboratory comparisons organized by the International Atomic Energy Agency (IAEA), World Health Organization (WHO), and European Union Joint Research Centre (JRC).

2.7. Radiocarbon Dating

Throughout the Velo Blato sediment core, a total of seven samples were selected for accelerator mass spectrometry (AMS ¹⁴C) measurements, of which five were shells (freshwater/terrestrial). Two samples were plant materials from the same depths as shells (at 105–106 cm and 308–309 cm) to determine the reservoir hardwater effect due to the carbonate watershed. In Kolanjsko Blato, three samples of shells (marine) were used to obtain the radiocarbon age. The radiocarbon dating was carried out at the Beta Analytics Laboratory, Miami, USA. The Conventional Radiocarbon Age (BP), Percent Modern Carbon (pMC), and stable isotopes (δ¹³C and δ¹⁸O) were provided. The age is reported as radiocarbon years before present (BP; “present” = AD 1950). Radiocarbon dates were calibrated using the INTCAL20 database [96] for freshwater samples from Velo Blato, and MARINE20 [97] for marine samples from Kolanjsko Blato. The 95.4% distribution (2σ probability interval) was taken into account to build the age–depth model using CLAM 2.2 software.

3. Results

3.1. Sedimentological and Mineralogical Description of Sediment Cores

Along the sediment core from Velo Blato (0–557 cm, +11 cm in core catcher), changes in the color of the sediment are visible from dark grey, almost black in the upper 21 cm, to the bright lake carbonate sediment with occasional layers of darker sediment. Darker layers have an evident decrease in the brightness color value L* (Figure 6). Shells and their fragments appear along the entire length of the sediment core, and certain intervals contain significantly accumulated shells, predominantly the shells of freshwater snail *Bithynia tentaculata*, especially between 130 and 300 cm (intervals: 137–140, 159–160, 219–221, 276–278, and 282–288 cm). In the lower parts of the core, they appear less frequently. From 300 to 557 cm, the sediment core is a brighter grey, less yellow and more bluish in color, with occasional dark intervals, especially from 439 to 450 cm and from 530 to 557 cm. The base of the drilled core (from 554 cm to 568 cm) is composed of limestone fragments as part of the weathered geological bedrock, i.e., flysch deposits. The lower parts of the core (from 530 to 550 cm), contain calcite predominantly, while between 504 and 445 cm, calcite and quartz are present in equal amounts; dolomite is also present, along with feldspar, muscovite/illite, kaolinite, pyrite, and aragonite. Clay minerals analysis showed the presence of the smectite, illite, and kaolinite, which presents the same clay mineral assemblage as the flysch marls from the southern shores of Velo Blato. From 388 to 102 cm, calcite with a significant proportion of magnesium is present, and can be defined as Mg-calcite. In the

interval from 255 to 102 cm, magnesium calcite appears in the samples, along with quartz, aragonite, muscovite/illite, and halite. Low-Mg calcite is dominant in samples from 74 to 40 cm, with the appearance of quartz and aragonite as accessory phases. Equal amounts of calcite and quartz are present in samples from 25 to 0 cm, with muscovite/illite, aragonite, and pyrite. Halite is present in the samples as a result of sample drying. Aragonite is of biogenic origin, the result of the shell fragments grinding. Smear slide analysis of several surface sediment samples (VB-2 0–1, 10–11 cm) showed calcite and quartz grains in the lake sediment of Velo Blato, and a significant amount of algal organic matter was observed. Throughout the core, sponge spicules, diatoms, and ferrous sulfide mineral pyrite in the form of framboidal aggregates, composed of crystalline forms of hexahedra, occasionally appeared. The upper parts of the core have relatively lower dry densities and higher water contents, compared to the rest of the core (Figure 6). Magnetic susceptibility (MS) values are relatively low throughout the Velo Blato sediment core, especially in the upper parts of the core (from 60 cm and upward), where its values are negative on average (-0.52×10^{-5} SI) (Figure 6). The highest magnetic susceptibility values are between 438 and 450 cm, with the highest values of 4.7×10^{-5} SI. After this interval, the lower parts of the core show slightly higher values of magnetic susceptibility than the rest of the core (average 1.26×10^{-5} SI).

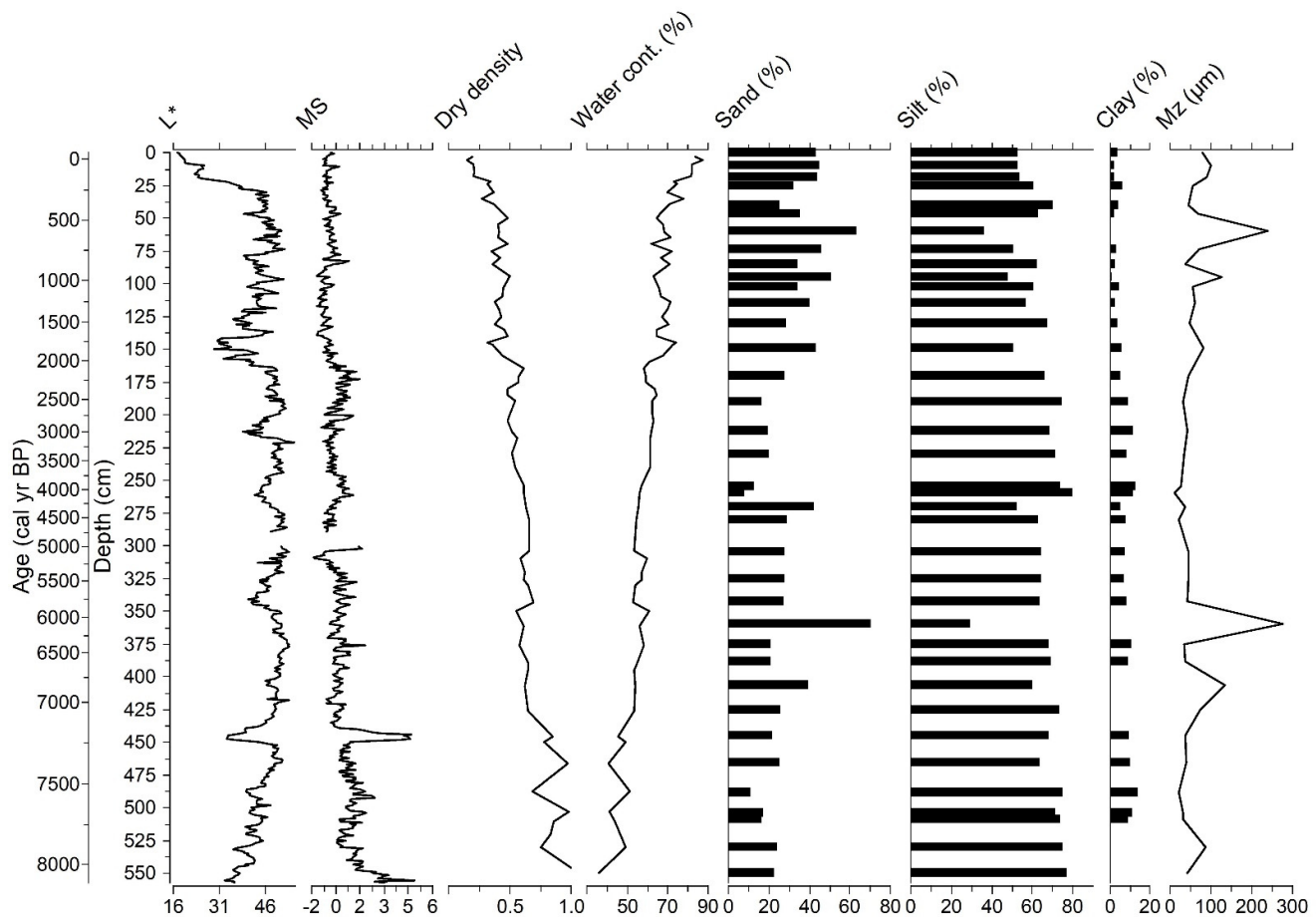


Figure 6. Color brightness (L^*), magnetic susceptibility (MS; 10^{-5} SI), dry density (g/cm^3), water content, and grain-size down-core variation in the sediment core VB-2 from Lake Velo Blato.

The sediments from the Kolanjsko Blato sediment core (KB-1/1), along its entire length of 107 cm, consist of a relatively homogeneous dark grey to black sediment, with occasional appearances of shell fragments. In the lower part of the core, at 95 cm until 107

cm, the sediment is full of fragments of shells (snails and marine shells). From 60 cm towards the deeper parts, the sediment becomes light grey in color. In the upper part of the core (from 60 cm upwards), the sediment contains plant remains and significant amounts of organic matter, which almost presents peat sediment. Within the sediment, larger pieces of coal were observed (>0.5 cm), which are probably derived from the Kolanjsko Polje from Miocene deposits that contain coal and lignite, which was exploited in the last century, having been brought to the Kolanjsko Blato by surface streams. Therefore, although ideal for radiocarbon dating, this material is not used. In general, XRD analyses of sediment samples from Kolanjsko Blato have high background values and low diffraction maximum (peaks). Such diffractograms indicate significant amounts of organic matter in the samples. In the lower parts of the core (105–60 cm), sediment samples contain calcite, quartz, aragonite, pyrite, halite, muscovite/illite, and in the lowest sample (105–106 cm), also kaolinite and clay minerals (Sm/Verm/Chl). From 50 to 0 cm, calcite, Mg-calcite, aragonite, quartz, pyrite, halite, and muscovite/illite are present in the samples. In the uppermost sample (0–2 cm), Mg-calcite was not observed.

Samples from the sediment core from Malo Blato contain, in the lower parts of the core (34–24 cm), predominantly quartz and calcite, muscovite/illite, kaolinite, pyrite, aragonite, and clay minerals (Sm/Verm/Chl) appear as minor mineral phases. From 20 to 0 cm, calcite and quartz are present in equal amounts in the samples, while aragonite and halite are minor minerals. As well as in sediments from Velo Blato, halite is present in the samples from Kolanjsko and Malo Blato as a result of sample drying, while aragonite derives from the grinding of the shell fragments.

3.2. Sediment Chronology

The chronology of the sediment core from Velo Blato is constrained by five radiocarbon dates obtained from freshwater shells (Table 2). To determine the reservoir effect, two additional samples from the same depths, at 105–106 cm and 308–309 cm, were measured for radiocarbon dating using plants. The reservoir effect in the interval of 105–106 cm is 80 years, while at a depth of 308–309 cm, it is 190 years, which are determined using shells and plants combined from the same intervals, but it should be emphasized that the reservoir effect could be higher because the plants can also uptake the old carbon from the water. The deepest analyzed sample in Velo Blato (552–554 cm) showed the age of the sediments deposited in Lake Velo Blato, and it is dated to the last 8300 years. In Kolanjsko Blato, the sample at the very bottom of the drilled core (106–107 cm) showed the age between 1100 and 2491 cal year BP. Two additional marine shell samples were used to constrain the depth–age model for the Kolanjsko Blato sediment core (Figure 7). The determined reservoir ages were calculated into the model for the depth–age model in Velo Blato (Figure 7).

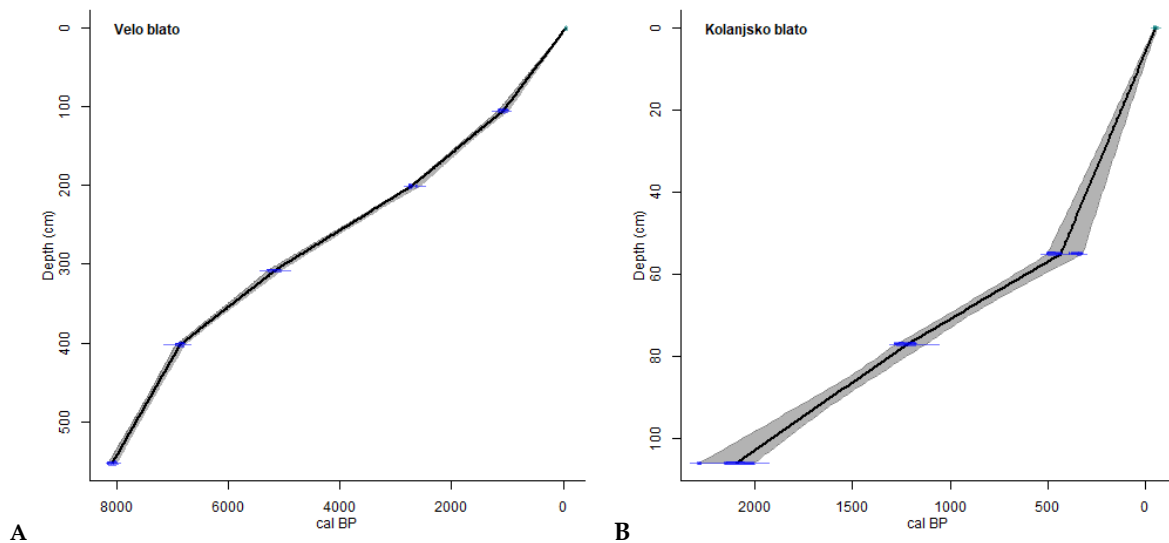


Figure 7. Depth–age models of sediment cores from (A) Lake Velo Blato (VB-2) and (B) Kolanjsko Blato (KB-1/1).

The sedimentation rate (SR) in Velo Blato is relatively high (1.24 mm/year) at the base of the core (554–402 cm), followed by slower SR in the middle part of the core (402–201 cm), where it varies between 0.4 and 0.6 mm/year. Again, the upper part of the core shows higher SR (0.9 mm/year). The sedimentation rate in Kolanjsko Blato is higher (1.1 mm/year) in the upper part of the core (0–55 cm), compared to the lower values (0.3 mm/year) in the lower part of the core (55–106 cm).

Table 2. Radiocarbon dates obtained in the Velo (VB-2) and Kolanjsko Blato (KB-1/1) sediment cores.

Lab ID	Sample (cm)	Material	$\delta^{13}\text{C}$ (‰)	$\delta^{18}\text{O}$ (‰)	pMC	Conventional ^{14}C Age	Calendar Age (2 σ Calibration)
Beta-591017	KB-1/1 55–56	Shell (marine)	−5.7	+1.5	95.26 ± 0.36	390 ± 30 BP	560-Post BP cal BP
Beta-591018	KB-1/1 77–78	Shell (marine)	−5.3	+0.3	85.27 ± 0.32	1280 ± 30 BP	1468–316 cal BP
Beta-591019	KB-1/1 106–107	Shell (marine)	−9.7	−0.2	76.80 ± 0.29	2120 ± 30 BP	2491–1110 cal BP
Beta-591020	VB-2 105–106	Shell (fresh-water)	−3.1	−0.2	85.7 ± 0.32	1240 ± 30 BP	1192–1070 cal BP
Beta-591021	VB-2 105–106	Plant	−25.8		86.55 ± 0.32	1160 ± 30 BP	1130–972 cal BP
Beta-591022	VB-2 201–202	Shell (fresh-water)	+0.1	−1.5	71.54 ± 0.27	2690 ± 30 BP	2851–2752 cal BP
Beta-591023	VB-2 308–309	Shell (fresh-water)	−1.2	−2.2	55.71 ± 0.21	4700 ± 30 BP	5423–5321 cal BP
Beta-591024	VB-2 308–309	Plant	−25.8		57.04 ± 0.21	4510 ± 30 BP	5202–5048 cal BP
Beta-591025	VB-2 402–403	Shell (fresh-water)	+2.9	−2.0	46.10 ± 0.17	6220 ± 30 BP	7134–7003 cal BP
Beta-591026	VB-2 552–554	Shell (fresh-water)	−5.8	−1.9	39.56 ± 0.15	7450 ± 30 BP	8346–8187 cal BP

3.3. Grain-Size Analysis

Sediments from Velo Blato are predominantly silt-sized (63.2%), with a significant proportion of sand (30.9%), while the percentage of clay is ~5% (Figure 6). In the sand fraction, very fine sand prevails on average (17.3%) in relation to fine sand (7.5%), medium sand (4.9%), and coarse sand (1.2%). The most common silt fraction is very coarse silt

(19.2%), followed by coarse silt (14.4%) and medium silt (13.3%). Fine silt and very fine silt are present in proportions less than 10%, except in the samples at 406–407 and 425–426 cm, which have higher proportions of medium silt (35.9 and 37.1%) and fine silt (17.2 and 16.0%) but do not contain a very fine silt fraction. These samples (406–407 and 425–426 cm) do not contain a clay fraction and are classified as coarse silts [98], as are the samples at 60–61 cm and 360–361 cm (very fine and fine sands), and the lower core samples at 530–531 and 550–551 cm (very coarse and coarse silts). In the sediment core, a higher proportion of sand (39.6%) is observed in the upper parts of the core (170–0 cm) than in the lower parts of the core (550–190 cm; 25.0%). At the same time, the silt and clay fractions are higher in the lower parts of the core (550–190 cm; 67.5% and 7.5%, respectively) compared to the upper part of the core (170–0 cm; 57.0% and 3.4%). The average clay content in the upper parts of the core (0–170 cm) is 3.4%, and in the lower parts (190–550 cm), 7.4%. More than 10% of the clay fraction have samples in the lower parts of the core, at 212–213 cm (12.0%) and 255–256 cm (13.1%), 375–376 cm (10.7%), and the interval between 465 and 504 cm (10.2–13.8%). The mean particle size (M_z) in the analyzed sediment samples is 33.5 μm , while in the sand samples, it is much higher than the average values (70.7–147.1) (Figure 6). Additionally, in these samples, the median particle size (M_d) is much higher (63.5–289.5 μm) than the average values of the sediment core (40.7 μm). Bimodal and trimodal distributions of particle-size curves predominate in most samples, unimodal distribution is present in two samples (40–41 cm and 74–75 cm), while polymodal distribution is present in samples 25–26, 212–213 and 375–376 cm. All analyzed samples are very poorly to poorly sorted. According to asymmetry (skewness), the samples are mostly very positive and positive skewed (very fine, fine skewed), are partially symmetrical, and several samples show very negative and negative skew (very coarse, coarse skewed). According to the sharpness (kurtosis), the samples in the upper parts of the sediment core mostly have medium-pointed curves (mesokurtic), with occasional leptokurtic curves, while in the lower parts, the curves are platykurtic.

Sediment samples from Kolanjsko Blato consist of a significant amount of sand (44.0%) and silt (49.5%), while a clay fraction is present in only 6.5%. The sample at 30–31 cm is the only sample that contains a fraction of coarse sand (14.2%) and the highest amount of medium sand (38.4%), compared to the rest of the sediment samples, and does not contain clay fractions. In the sand fraction in the analyzed samples, very fine sand (21.6%) predominates, while in the silt fraction, very coarse silt predominates (17.1%). The individual particle-size curves of the analyzed sediment samples from Kolanjsko Blato show a mostly trimodal distribution, while the 0–1-, 10–11- and 50–51-cm samples have a bimodal distribution. Most of the samples are classified as very coarse and coarse silts, while the sample at 30–31 cm is classified as fine sand [98]. The samples are very poorly and poorly sorted, very positively and positively skewed, and primarily have medium-sharpened curves (mesokurtic), while the rest are platykurtic and/or leptokurtic. The average particle size (M_z) in the analyzed sediment samples is 32.1 μm , except in the sample of 30–31 cm, which is significantly higher (161.7 μm). Moreover, the median particle size (M_d) is larger (268.9 μm) than the other samples (45.4 μm).

Sediment samples from Malo Blato consist mainly of a fraction of sand (55.8%) and silt (42.2%), with a clay fraction <2%. It is characteristic of the sample at 16–17 cm, which is predominantly sandy (95.6%) with a very low silt content (4.4%) and no clay present. Clay is also absent in other samples throughout the sediment core, and it is the highest in the lower sample, the interval at 30–31 cm (8.4%). In the sand fraction, the very fine sand (18.9%) is the most common, except in the sample at 16–17 cm, where coarse sand predominates (58.6%). The very coarse silt (17.0%) is the dominant silt fraction in all the samples. The particle-size distribution curve is mostly unimodal, and in some samples bimodal (30–31 cm), trimodal (4–5, 12–13 and 24–25 cm), and polymodal (34–35 cm). Most of the samples are classified as very coarse silts or very fine and fine sands [98]. The samples are generally poorly sorted, while in the lower parts of the core, the samples are very poorly sorted, and the sample at 16–17 cm is moderately well sorted. The kurtosis of the

curves also varies from very platykurtic (34–35 cm), platykurtic (12–13 and 24–25 cm), mesokurtic (0–1, 4–5, 30–31 cm), leptokurtic (8–9, 10–11, 20–21 cm), to very leptokurtic (16–17 cm), and are generally very fine and fine skewed. The mean particle size (Mz) in the analyzed sediment samples is 120.6 μm , with the sample at 16–17 cm exceeding this value, with a Mz of 551.2 μm . In addition, this sample's median particle size (Md) is 604.0 μm , while the median of all samples is 147.4 μm .

3.4. Major and Trace Element Abundances

Elemental concentrations in the analyzed samples from the Velo Blato sediment core are presented by depth and age (Figure 8), and by descriptive statistics (Table 3). Concentrations of main lithogenic elements Al, Ti, Fe, K, and Na have similar vertical distributions, i.e., they are elevated in the samples in the lower parts of the core (550–445 cm), are relatively lower in the middle part of the core (425–47 cm), and increase in the upper part of the core (47–0 cm). The Al, Ti, Na, K, and Fe contents are the highest in the sample at 445–446 cm, in which the Ca content is much lower than the rest of the core. In addition to this interval, the Ca content is evenly distributed throughout the sediment core; the highest values appear in the interval of 95–47 cm, but from 47 cm of the core, it significantly decreases upward. The Mg content shows a different distribution than Ca and is different from Al and other siliciclastic elements. It is low in the base of the core, where it shows elevated concentrations in the interval between 509 and 445 cm, where dolomite appears in the sediments. The Sr concentration is lower from the base of the core to 425 cm, when it starts to have an increased trend upward, and the highest values are in the same interval where the Ca content is the highest. Sr and Ca have similar vertical trends and represent carbonate components, showing an elevation in the base of the core and a decrease in the upper part of the core from 47 cm upward. P and N content also show the same increase in the sediment core, from 47 to 0 cm. Other trace elements (As, Ba, Cd, Co, Cr, Cu, La, Ni, Pb, Rb, V, Zn, and Zr) show the same trend as the main lithogenic elements and are connected with the siliciclastic component. They have elevated concentrations in the lower and the upper part of the sediment core. Mn has elevated concentrations in the upper part of the core (47–20 cm), while the top of the sediment core decreases. At the same time, in the topmost samples, the content of Mo increases. The Hg concentrations are elevated in the lower part of the core, in the sample at 488–489 cm, and in the interval from 445 to 325 cm. Then, the proportion decreases and is very low, i.e., below the limit of detection in the interval of 130 to 60 cm, and then increases towards the top of the core, and is high in the surface sample (1–2 cm).

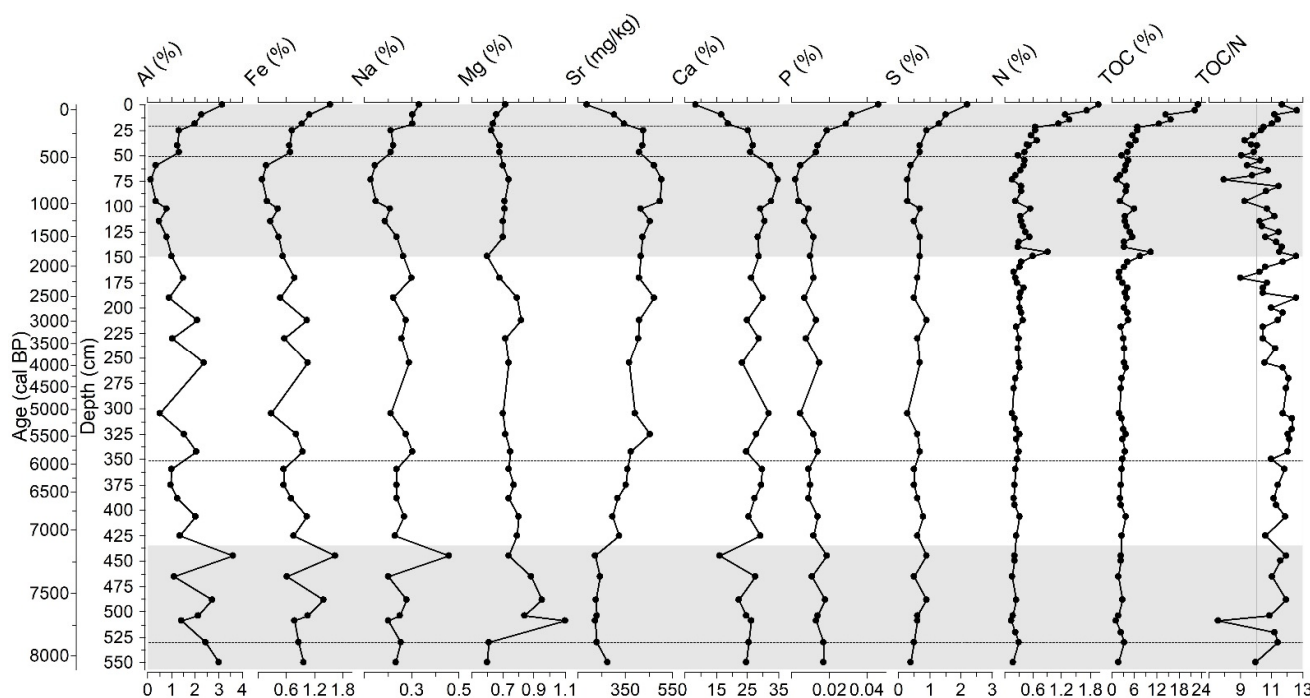


Figure 8. Selected major and trace element concentrations, and N, TOC, and TOC/N values in the sediment core VB-2 from Lake Velo Blato. The grey-shaded and white horizontal bars indicate the changes in sedimentary deposition zones explained in the discussion.

In the sediments from Kolanjsko Blato, the composition of the main elements, Al, Ti, and K, is elevated in the lower part of the core (from 105 to 60 cm) and decreases towards the upper parts of the core (Figure 9; Table 3). The share of Fe has a similar distribution, but it is quite low in the lowest sample (105–106 cm). The content of Na differs from the above elements—it is lowest in the lower part of the core, increases towards the upper parts of the core, and is highest in the sample at 1–2 cm. Mg and Sr concentrations have a similar trend to Na, which increases from the lower parts of the core upwards. On the other hand, the distribution of Ca with depth is similar to the distribution of lithogenic elements Al and Ti, i.e., it decreases from the base of the core upwards, and is lowest in the upper parts of the core. The shares of P and S increase from the bottom up, i.e., inversely from Al and Ti, and similarly to Na and Mg. The concentrations of trace elements Ba, Cr, La, Ni, Rb, V, and Zr in Kolanjsko Blato have a similar distribution as the main lithogenic elements: higher in the base of the core and decreasing upwards. The elements As, Cd, Co, Cu, Pb, Sr, and Zn deviate from this trend. The proportion of As is higher in the lower parts of the core (105–60 cm) and lower in the upper parts of the core (40–0 cm). The Cd and Co contents are only higher in the samples at 90–91, 70–71, and 60–61 cm. The Pb concentrations are low in the lower parts of the core (105–106 cm, 90–91 cm), increases from 70 cm, and are relatively constant upwards, showing a slight increase in the surface sample (1–2 cm). The Zn content is also low in the lower part of the core and increases upwards, with a decrease in the sample at 10–11 cm. The concentrations of Cu are higher only in the surface sample (1–2 cm), as well as those of Mo. In the lower parts of the core, the Hg content is elevated in the sample at 90–91 cm, while it is low in the samples at 105–106 and 70–71 cm. The concentrations increase from the sample at 60–61 and are constant in the core's upper parts (50–10 cm), slightly increasing in the surface sample (1–2 cm).

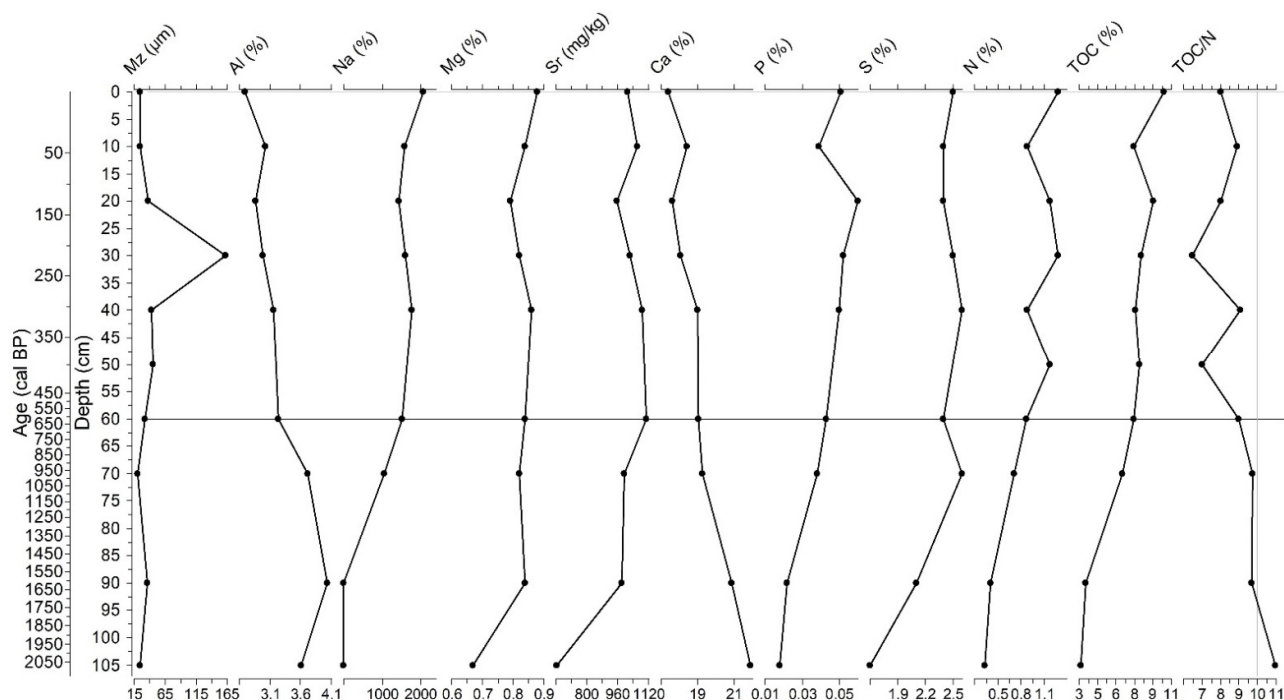


Figure 9. Selected major and trace element concentrations, mean grain size (Mz), and N, TOC, and CN values in the sediment core KB-1/1 from Kolanjsko Blato, with a marked black horizontal line indicating sediment deposition changes.

The sediments of Malo Blato have a uniform composition of the main lithogenic elements Al, Ti, K and Fe, which show elevated concentrations in the lower part of the core from 34 to 24 cm, and lower concentrations in the upper part of the core from 20 to 0 cm. Descriptive statistics of elemental concentrations are presented in Table 3. The share of Na has a similar trend, with elevated concentrations in the samples at 8–9 and 0–1 cm, compared to the listed lithogenic elements. The Mg content differs from this trend and shows an increase in concentrations from the lower to the upper parts of the core. The Ca and Sr concentrations are opposite to the concentrations of the lithogenic elements; they are lower in the base of the core (34–24 cm) and higher in the upper parts of the core (20–0 cm). P and S contents show higher concentrations in the lower and upper parts of the core, and are lowest in the middle part of the core (20–12 cm). The concentrations of trace elements in Ba, Co, Cr, Cu, La, Ni, Rb, V, Zn, and Zr show a similar content as the main lithogenic elements, with elevated concentrations in the lower part of the core (34–24 cm) and lower concentrations in the upper part of the core (20–0 cm). Additionally, the Cu content increases slightly in the surface sample (0–1 cm). The share of Cd is higher in the lower parts of the core, especially in sample 24–25 cm, then lower from 20 to 8 cm, and then increasing in the uppermost samples. The Pb concentrations are higher than the rest of the core in the sample at 16–17 cm. The Mo content shows lower values in the middle part of the core (24–12 cm). The Mn content is reversed; the highest concentrations are in the middle part of the core (20–16 cm) and decrease to the surface samples. The Hg concentrations are higher in the lower parts of the core and they decrease in the middle and increase again to the surface samples, except in the 8–9-cm sample, where it has low concentrations.

3.5. Total Organic Carbon and Nitrogen Concentrations

Concentrations of the total nitrogen (TN) and total organic carbon (TOC) in the sediments of Velo Blato (VB-2) are lower in sediment core between 550 and 150 cm, after

which they increase slightly and are the highest from 19 to 0 cm (Figure 8). Nitrogen concentrations in the upper 19 cm of the sediment core are much higher (1–2%) than the rest of the core (0.14–0.68%). In this interval, significantly high concentrations of organic carbon (TOC) are observed (12.58–23.03%). The TOC content is also high in other sediment samples throughout the sediment core from Velo Blato, varying between 1.06 and 7.54%. The inorganic carbon (TIC) content is lowest in the upper 19 cm of the core, where the TOC content is the highest. The TIC values are also low in the 445–446-cm sample, in which the insoluble residue is high. The ratio of organic carbon to nitrogen (TOC/N) varies between 7.60 and 12.63, and in most of the samples, it is higher than 10.

Nitrogen and total organic carbon increase from the lower parts of the core upwards in the sediments from Kolanjsko Blato (Figure 9). Nitrogen reaches values higher than 0.8 in the upper part of the core from 60 cm upwards. The TOC concentrations are high in all samples throughout the sediment core KB-1/1 (>3%) and show an upward trend from the deeper to the surface samples. The lower TOC values are in the lower part of the sediment core, at 105–90 cm (3.14–3.50%), compared to the higher concentrations from 70 to 0 cm, where it varies from 6.49 to 9.91%. The inorganic carbon (TIC) content is relatively constant, with the lowest values in the uppermost samples.

Malo Blato is characterized by low nitrogen values (<1%), while TOC concentrations are relatively high (2.83–9.72%) in all samples from the sediment core MB-1/2. The TOC content is the highest in the lower parts of the core, from 34–24 cm (8.00–9.72%), which are, at the same time, the samples with TOC/N ratios higher than 10, i.e., between 16.45–17.91. Lower values of TOC than the rest of the sediment core have samples from 20 cm upwards with an increasing trend; although these concentrations are not low at all, the values are higher than 2.6%. The uppermost samples of the sediment core have values between 3.94 and 5.22% (8–0 cm). The values of inorganic carbon (TIC) are lowest in the lower part of the core (34–24 cm), and increase towards the upper part of the core (20–0 cm), and have a trend opposite to the insoluble residue.

Table 3. Descriptive statistics of selected major and trace elements from sediments of Velo, Malo, and Kolanjsko Blato (minimum, maximum, mean, median, and standard deviation—SD).

Element	Velo Blato Sediment Core (VB-2)					Malo Blato Sediment Core (MB-1/2)					Kolanjsko Blato Sed. Core (KB-1/1)				
	Min	Max	Mean	Med.	SD	Min	Max	Mean	Med.	SD	Min	Max	Mean	Med.	SD
Al (%)	0.14	3.63	1.53	1.33	0.86	0.57	4.66	1.75	0.86	1.57	2.64	3.99	3.21	3.11	0.42
Ba (mg/kg)	44	165	79	74	25	37	160	73	47	47	75	114	91	89	11
Ca (%)	8.42	34.75	26.17	26.77	5.14	6.77	27.22	20.40	24.64	7.91	17.38	21.85	19.05	18.97	1.39
Cd (mg/kg)	0.1	0.7	0.3	0.2	0.2	0.4	0.9	0.6	0.6	0.2	0.4	0.7	0.5	0.5	0.1
Co (mg/kg)	0.6	7.9	3.7	3.1	1.9	0.7	8.4	3.0	1.3	3.0	8.1	11.9	9.2	8.7	1.2
Cr (mg/kg)	5	80	32	28	16	12	74	30	16	25	43	66	52	51	7
Cu (mg/kg)	1.5	17.6	7.1	6.3	3.6	4.7	12.8	7.4	5.8	2.8	13.5	429.2	104.4	94.2	121.1
Fe (%)	0.09	1.64	0.75	0.72	0.37	0.22	2.43	0.77	0.28	0.84	1.94	2.51	2.20	2.16	0.15
Hg (mg/kg)	0.01	0.06	0.02	0.02	0.02	0.04	0.07	0.06	0.06	0.01	0.06	0.10	0.09	0.09	0.01
K (%)	0.04	0.92	0.39	0.35	0.20	0.16	1.09	0.43	0.23	0.35	0.48	0.75	0.57	0.57	0.08
La (mg/kg)	1.8	21.8	8.7	7.3	4.6	4.4	25.8	10.9	6.4	8.0	13.3	24.4	18.0	17.7	3.6
Mg (%)	0.60	1.10	0.74	0.72	0.10	0.57	0.72	0.65	0.65	0.05	0.67	0.88	0.82	0.84	0.06
Mn (mg/kg)	121	325	236	242	49	63	129	89	87	20	481	748	652	660	68
Mo (mg/kg)	0.10	1.00	0.44	0.40	0.17	0.30	1.90	0.68	0.55	0.46	1.40	3.40	2.09	2	0.52
Na (%)	0.128	0.457	0.247	0.238	0.059	0.491	0.814	0.608	0.555	0.114	0.639	2.073	1.371	1.519	0.461
Ni (mg/kg)	1.3	42.9	18.6	17.0	9.8	3.4	40.2	14.2	6.7	13.8	31.5	43.8	38.2	39.4	3.7
P (%)	0.002	0.046	0.014	0.012	0.008	0.014	0.037	0.022	0.021	0.007	0.018	0.060	0.041	0.043	0.013
Pb (mg/kg)	1.0	15.4	5.7	5.1	3.3	9.7	313.0	42.3	10.9	90.3	12.6	30.2	25.1	27.5	6.3
Rb (mg/kg)	2.00	58.90	24.83	22.10	13.86	8	69.80	25.73	12.20	23.52	30.80	55.30	39.56	36.90	7.83
S (%)	0.3	2.2	0.7	0.6	0.4	0.4	2.2	0.9	0.5	0.7	1.6	2.6	2.3	2.4	0.3
Sr (mg/kg)	188	504	360	373	89	127	389	305	365	106	643	1107	985	1012	130
Ti (%)	0.008	0.208	0.081	0.072	0.044	0.034	0.243	0.094	0.052	0.078	0.114	0.182	0.140	0.136	0.022
V (mg/kg)	3	55	27	24	14	8	71	25	11	24	28	58	39	35	10
Zn (mg/kg)	5	61	25	22	12	18	60	29	20	15	52	63	60	61	3
Zr (mg/kg)	1.8	42.7	18.0	16.3	9.8	6.7	56.7	21.2	10.8	19.0	30.7	48.5	37.4	36.9	6.1

3.6. Ostracod Assemblage

The Velo Blato sediment core samples are very rich in ostracods, mollusks, characean stems, and gyrogonites, except for the uppermost (0–20 cm) organic-rich sediment. Several intervals throughout the core are made almost exclusively from gastropods *Bithynia tentaculata* and ostracod shells, which are visible to the naked eye. The most abundant species throughout the core are *Cyprideis torosa* (Jones), *Candona angulata* (Müller), and *Candona* sp., *Limnocythere inopinata* (Baird), *Darwinula stevensoni* (Brady and Robertson), *Cypridopsis vidua* (Müller), and *Cypria ophtalmica* (Jurine), with *C. torosa* being extremely abundant among them. Other notable species, but less abundant, are *Paralimnocythere psammophila* (Flössner), *Pseudocandona marchica* (Hartwig), *Herpetocypris* sp., *Ilyocypris* sp., *Metacypris cordata* (Brady and Robertson), *Cypris bispinosa* (Lucas), and *Hungarocypris madaraszii* (Örley). Selected ostracod species are presented in Figure 10.

The most dominant species in the lower part of the core (550–435 cm) are *C. vidua* and *P. psammophila*, while *L. inopinata* and *D. stevensoni* are subordinated (Figure 10). *Ilyocypris* sp. and *C. bispinosa* are also present. From 550 to 531 cm, ostracod valves are mostly broken and dominated by juveniles (e.g., *Candona* sp., and *C. vidua*) and fragmented gastropods. Between 531 and 435 cm, valves are well preserved, more adults appear, mollusks such as *B. tentaculata*, *Planorbis* sp., and *Pisidium* sp., and large diatoms (*Campylodiscus* sp.) are present.

The upper part of the core (435–20 cm) shows a higher species richness and the clear dominance of *C. torosa*, *C. angulata*, and *Candona* sp., but also *L. inopinata*, *D. stevensoni*, and *C. ophtalmica* (Figure 10). In several depth intervals (23–24, 48–49, 74–75, and 131–132 cm), the hyperproduction of *C. torosa* (>1500 valves per 1 g dry sieved sediment) was recorded. From 531 to 20 cm, ostracod valves are numerous, and often come as well-preserved carapaces. Good preservation can also be seen in numerous mollusks, especially *B. tentaculata*. Species richness suddenly decreased in the topmost (20–0 cm) darker, organic-rich samples, and only a few valves of *C. torosa* and *C. ophtalmica* dominated. Valves of *C. torosa* are smoothed (forma *torosa*) from their first appearance (435 cm) until 51 cm, when they are dominantly in noded form (forma *littoralis*) to the top of the sediment core.

Samples retrieved from the sediment core from Malo Blato are rich in ostracods in the upper part (20–0 cm), while in the lower part (35–20 cm), ostracods almost vanish. In the lower zone, organic detritus and quartz grains are observed, as well as very fragmented mollusk shells, except for the juvenile gastropods and *Pisidium* sp. Large diatoms were also recognized (*Campylodiscus* sp.). In contrast, the upper zone is calcareous, rich in ostracods, mollusks, and *Chara* remains. The sample at 12–13 cm contains a fragment of an echinoid spine. The most abundant ostracod species are *Cyprideis torosa* (Jones), *Heterocypris salina* (Brady), *Candona angulata* (Müller), *Candona* sp., and *Herpetocypris* sp. Other noted species are *L. inopinata*, *D. stevensoni*, *P. marchica*, and *H. madaraszii*.

Common ostracod species in the sediment core from Kolanjsko Blato are *C. torosa*, *C. angulata*, *Candona* sp., and *H. salina*, which were identified in all samples. There are no significant changes in macro- and micro-faunal composition with depth. Brackish foraminifera (*Ammonia* sp.) and bivalves (*Cerastoderma* sp.) were present throughout the sediment core.

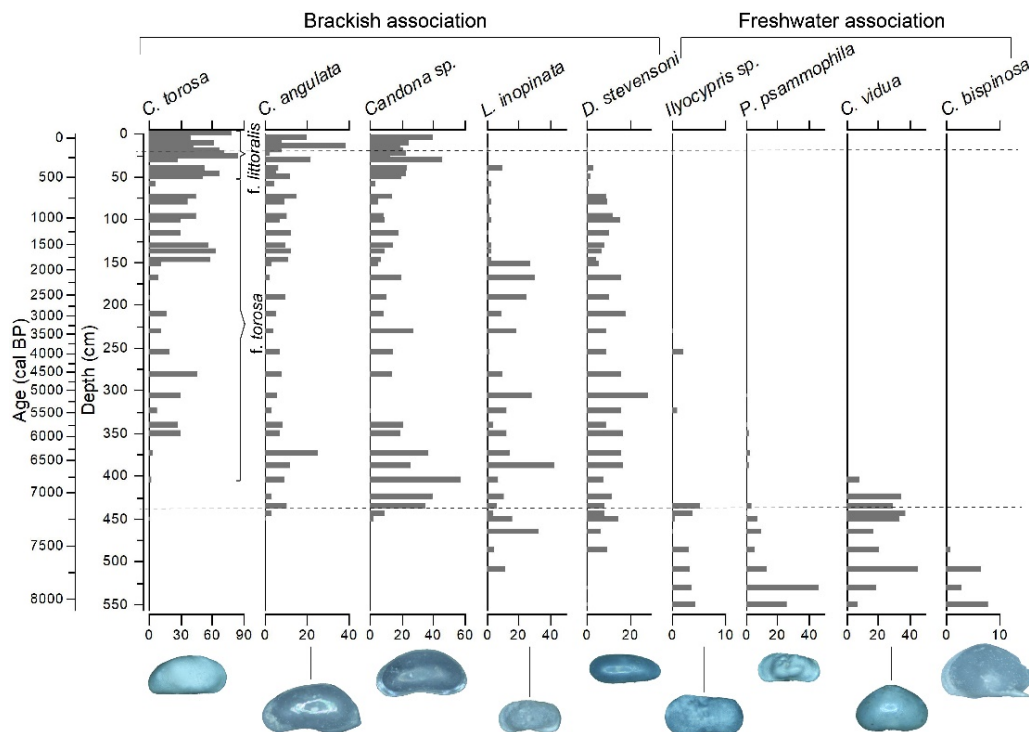


Figure 10. Relative distribution (%) of selected ostracod species in the sediment core from Velo Blato, with their photographs. Three general zones are marked by horizontal dashed lines.

3.7. Radionuclides Activities and Sedimentation Rates

The measurement of anthropogenic radionuclide ^{137}Cs from sediment core profiles can be used as a chronological marker since the radioactive emissions are well known: the development of the nuclear power industry and weapons testing during 1950s and 1960s, and the fallout from the Chernobyl accident [99]. The first significant appearance of ^{137}Cs peak in both sediment cores appeared at a depth of 10 cm (Figure 11), indicating the 1960s, when the emissions of anthropogenic radionuclides occurred due to nuclear weapons testing [99]. The recent peak (4–5 cm) is due to the Chernobyl accident, which produced a radioactive discharge in 1986. Furthermore, residues were observed at a depth of 22 cm in Velo Blato sediments (2.50 Bq/kg) and 16–17 cm in Kolanjsko Blato sediments (38.33 Bq/kg). Down-core mobilization of ^{137}Cs is evident because the oldest measured subsamples from Velo and Kolanjsko Blato (40–41 cm) contain trace amounts of this anthropogenic radionuclide. Concentrations of ^{137}Cs activity in Kolanjsko Blato sediments generally show higher values (12.1 to 48.2 Bq/kg) than Velo Blato sediments (1.5 to 3.9 Bq/kg).

Similar lower ^{137}Cs activity concentrations were found in Neretva Channel (3.7 to 13.7 Bq/kg) [100]. Lake sediments from Lake Vrana near Biograd contain ^{137}Cs concentrations that vary between 0.3 and 68 Bq/kg [101]. In the sediment profiles from Lake Kozjak and Lake Prošće, the ^{137}Cs activity maximum of 125 Bq/kg at depth 1–2 cm in Lake Prošće, and 131 Bq/kg at depth 4–5 cm in Lake Kozjak, are attributed to the Chernobyl accident in 1986 [102]. Velo Blato sediments have ^{137}Cs activity concentrations similar to the activity values in the sediments from the middle part of the Adriatic Sea (1.3 to 6.0 Bq/kg) [103] and near the Palagruža Island, and the middle and south Adriatic pits (0.22 to 10.42 Bq/kg) [104].

The estimated sedimentation rates in Velo and Kolanjsko Blato are 2.9 mm/yr. Compared to other values from the Adriatic Sea, the stated sedimentation rates are approximately the same; the sedimentation rates determined in the outer part of the Adriatic Sea are 5 mm/yr [103] and 3.1 mm/yr [104] in the Jabuka pit, while in the area of Palagruža and

the south Adriatic pit it is 1.8 mm/yr [104]. In the Krka River Estuary and Lake Prokljan, rates vary between 1 and 4 mm/yr [105]. In the sediments from Lake Vrana near Biograd, sedimentation rates are 6.4 mm/yr in the NW part of the lake and 4.2 mm/yr in the SE part of the lake [101]. In front of the Neretva River mouth, the sedimentation rate is 6 mm/yr and 4 mm/yr in the Neretva channel area [100].

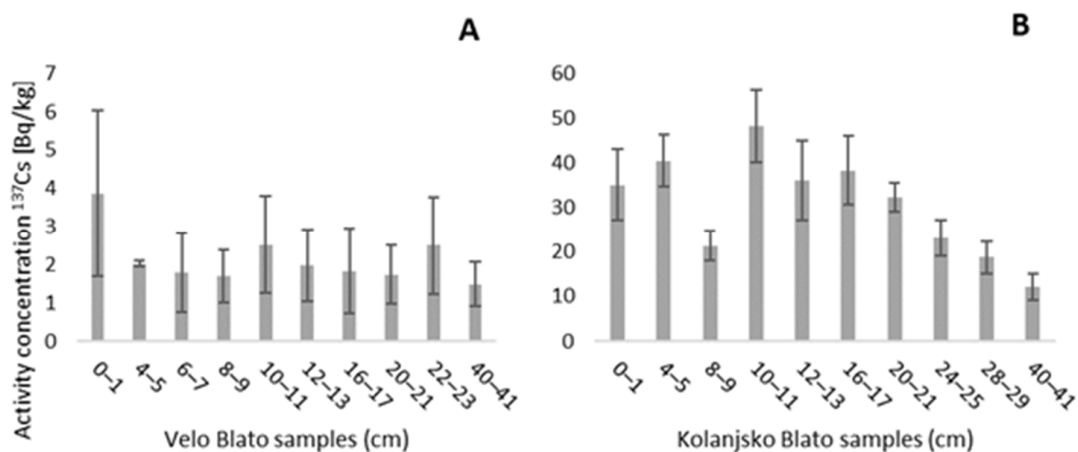


Figure 11. Activity concentrations of cesium radionuclide (^{137}Cs) in sediment core samples from Velo (A) and Kolanjsko Blato (B).

4. Discussion

4.1. Paleoenvironmental Reconstructions of Lake Velo Blato and Wetlands Malo and Kolanjsko Blato

The sediment core from Velo Blato (VB-2) comprises lake sediments in the length of 554 cm. The base of the core, from 554 to 568 cm, is made of limestone fragments that present weathered carbonate bedrock on which lake sediments were deposited. This implies the lake formation at the depth of the transition from bedrock into lake sediments, which yields the time of 8100 cal yr BP. The relative sea level (RSL) 10,000 years ago was approximately 40-m lower than today [106]. The coastline was further away from Velo and Malo Blato; therefore, the seawater had no influence on their ecosystem, nor on the Kolanjsko Blato. The paleoshoreline of the eastern Adriatic coast in the area of Pag Island at approximately 9000 years BP was more distant (seaward) from the present shoreline, and the vast area was dry land (Figure 12). At the time of the Early Holocene lowstand on the eastern Adriatic coast, Velo and Malo Blato exist as lakes, but as geomorphological depressions, karst poljes (Figure 12A). During the Early Holocene, the sea level rose rapidly, and at about 8000 years BP, it was approximately 10-m lower than today [9,106,107]. The rising sea level enabled the formation of a freshwater lake in Velo Blato at 8100 cal yr BP (Figure 12B).

Coastal areas of Pag Island on the EAC are shaped under the influence of the Late Pleistocene–Holocene sea-level rise [108]. The formation of the present-day coastline is the result of post-Last Glacial Maximum (LGM) sea-level rise [8,109,110]. The EAC coastal zone shows typical morphologic features associated with the chemical dissolution of carbonates, water rich in carbonate ions (hard water), and the intrusion of seawater through the karstified underground, inherited from the karstification processes.

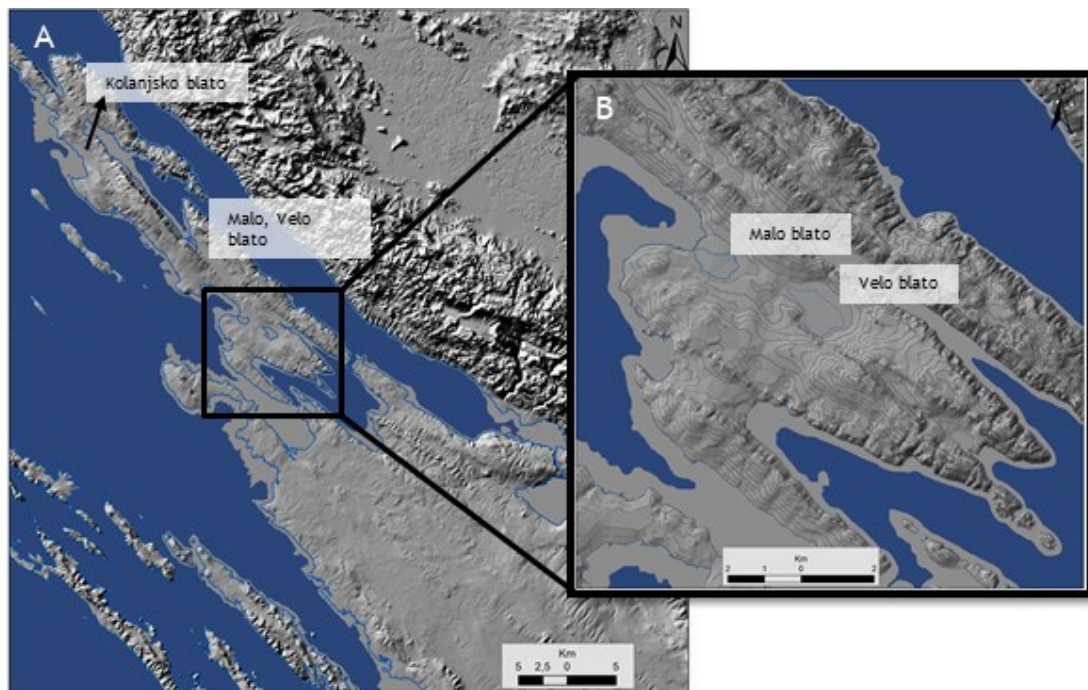


Figure 12. (A) Paleoshoreline of the eastern Adriatic coast at approximately 9000 years BP (20 - lower than today); (B) detailed locations of Malo and Velo Blato karst poljes—basins.

The lake sedimentation in Velo Blato began 8100 years ago (from 554 cm upwards). Generally, lake sediments in Velo Blato are characterized by lake carbonate sedimentation due to the saturation of lake water with carbonate ions resulting from the karst environment and calcareous bedrock, in which the precipitation of endogenic calcite from the lake-water column predominates. Photosynthetic processes enhance calcite precipitation on the lake bottom caused by aquatic plants (algae and macrophytes), due to the water's carbon dioxide consumption and increased pH [111]. The more productive the lake, the more endogenic calcite is precipitated, while in contrast, the decomposition of organic matter leads to the formation of CO_2 , the pH decreases, and calcite dissolves [1]. The solubility of calcite decreases with increasing temperature; therefore, increased water temperature promotes calcite precipitation. In the lower part of the core (554–435 cm), which corresponds to the period between 8100 and 7100 cal year BP, lithogenic elements Al, Fe, K, and Na, which are bound to the siliciclastic material, are slightly increased. In this interval, in addition to the carbonate minerals calcite and aragonite, dolomite and related elevated concentrations of magnesium are observed in the samples, except in the base of the core. Dolomite is defined as a detrital mineral, and this indicates erosional processes and the input of the material from the catchment into the lake. At first, in addition to carbonate lake sedimentation, a significant portion of material with elevated content of Al and other siliciclastic elements were deposited, followed by the carbonate lake sedimentation alongside detrital material with dolomite. The interval with the magnetic susceptibility peak corresponds to the peaks of Al and other siliciclastic elements and higher clay mineral contents, while the calcium content is lower. Erosional input from the lake catchment area can also be inferred from the micropaleontological data. Ostracod valves in the lower part of the core (531–550 cm) are represented dominantly by juveniles, while adult valves are often poorly preserved. This is especially the case with some large species, e.g., *H. madaraszii* and *Herpetocypris* sp., as well as with gastropod shells. A large number of juvenile valves or a low adult/juvenile ratio is often used as an indicator of a dynamic environment [112,113], in which juvenile ostracod valves are easily transported away by

waves and streams. In contrast, a higher adult/juvenile ratio indicates a more stable environment, where both juvenile and adult valves can be preserved, and thus represents an autochthonous assemblage. A higher number of adults and juveniles appear after 531 cm and continue throughout the core. The most dominant species from 550 to 425 cm are *C. vidua* and *P. psammophila* (Figure 9), and they occur together with *L. inopinata*, *D. stevensoni*, *Ilyocypris* sp., and *C. bispinosa*. Although most of them can tolerate a small increase in salinity, these species thrive in freshwater environments. The predominance of *C. vidua* (maximum salinity 10 ‰, prefers lakes and ponds, [95]) and *P. psammophila* (so far only recorded from small freshwater lakes and pools [95]) point to the development of a small lake.

In the next phase of the Lake Velo Blato evolution, from 7100 to 1800 cal year BP (435–150 cm), the content of lithogenic elements slightly decreased, and calcium and strontium concentrations increased. Magnesium-calcite was recorded as a mineral phase, alongside quartz, while muscovite/illite appeared as an accessory mineral phase. Unlike endogenic carbonate formation that depends mainly on biological processes, authigenic carbonates, such as Mg-calcite, result from specific abiotic conditions in the lake, and seem to be a common feature in the sediments of lakes with high salinities [111]. The sediment runoff from the catchment decreased, while the deposition of endogenic Mg-calcite characterizes carbonate precipitation. The nitrogen and total organic carbon show relatively low and constant values during this period. The organic carbon to nitrogen (TOC/N) ratio is higher than 10, which indicates a terrestrial source of organic matter [114,115] throughout this period of lake evolution. Slightly lower values of TOC/N occurred between 3900 and 3100 cal year BP, and by the end of this phase, between 2400 and 2000 cal yr BP, the values were the lowest, at 2200 cal year BP (<10). In these periods, lowering the TOC/N ratio indicates algae's significant influence to the dominance of vascular plants and terrestrial origin of organic matter [114]. The significant change in ostracod assemblage occurred from 7100 cal yr BP, and is marked by the appearance of brackish ostracod species, the most prominent being *Cyprideis torosa*, a euryhaline species. This is often used as an indicator of more saline conditions, especially in the marginal marine environments that were influenced by the Holocene sea-level rise, such as coastal lakes, lagoons, marshes, and estuaries [116–118]. The species is known to tolerate a wide range of salinities, from 0.5 to more than 60‰, with a reported optimum of 2–16.5‰ [95]. It is accompanied by *C. angulata*, which prefers slightly brackish conditions, and is often found in coastal lakes with *C. torosa* [95]. At approximately 6000 cal year BP (355 cm), a significant increase in the relative abundance of *C. torosa* occurred, and it became the dominant species in the ostracod community, which coincides with the increase of Sr content. At the same time, freshwater species *C. vidua*, *P. psammophila*, *Ilyocypris* sp., and *C. bispinosa* decrease, while *D. stevensoni* and *L. inopinata* are still well distributed. *C. angulata* and *Candona* sp. occur earlier than *C. torosa*, between 450 and 350 cm. However, the presence of oligohaline species, which have a much smaller range of salinities (e.g., from 0 to 25‰ for *L. inopinata*, and from 0.5 to 15‰ for *C. angulata* [119]) suggest moderate saline conditions in the lake [118]. This is supported by the presence of freshwater mollusks *B. tentaculata*, *Planorbis* sp., and *Pisidium* sp.

Freshwater bodies are influenced by dynamic groundwater, especially in coastal karst terrains, where seawater is connected. Seawater intrusions into the coastal Dinaric karst aquifers are investigated on the islands on the Dalmatian coast [120,121]. The groundwater table declines towards the sea, and freshwater overlies saltwater, penetrating the aquifer at a certain depth, in a wedge-like form. On smaller islands, an aquifer is partially formed as a lens of fresh and brackish water above seawater, according to the Ghyben–Herzberg principle of gravitational equilibrium [122,123]. This says that the depth below sea level at which the freshwater–saltwater interface (the halocline) occurs is related to the elevation of the water table above sea level and the density of the fresh (1.0 g/cm³) and salt (1.025 g/cm³) waters, respectively [5]. Since the Ghyben–Herzberg law de-

scribes the sharp interface contact of two fluids (freshwater and seawater), in natural conditions—due to the groundwater dynamics, chemical mixing, and tide effects—that contact is not sharp, and the model can be taken only as a rough estimation. A relatively wide transition (or mixing) zone is formed between freshwater and seawater, making part of the aquifer brackish [121]. Although the Island of Pag is one of the largest Adriatic karst islands, most aquifers are separated and relatively small due to their high indentation. The sea-level rise during the Holocene in the Adriatic Sea changed the aquifer boundary conditions, which controlled the fresh and saline groundwater flows. The scheme of the seawater intrusion into freshwater in control of the sea-level rise is presented in the example of Velo and Malo Blato in the last 10,000 years (Figure 13A–C). Three phases of lake development in Velo Blato are presented in the sketch (the first two were already mentioned): (A) Early Holocene, at ~10,000 years ago, when the sea level was much lower than today (~40 m) and seawater had no impact on the waters of Velo and Malo Blato, and they existed as geomorphological depressions or karst poljes, under the strong influence of erosional processes and with no sediment preserved (all the material was washed away from the polje); (B) Early–Middle Holocene transition, at 8100 years ago (the sea level was ~10 m lower than today), when the rising sea level caused the formation of the freshwater lake in Velo Blato and lake carbonate sedimentation began on karstic weathered bedrock; and (C) Middle Holocene, at 7100 years ago, when the further sea-level rise influenced the movement of the salt- and freshwater boundary towards the underground of Velo Blato and resulted in the influence of brackish water on the sediments of Velo Blato from that period onward, especially from 6000 cal yr BP, as well as lake-level deepening in Velo Blato. The saltwater intrusion and saline groundwater influence on lake sediments in Velo Blato are evident by the geochemical and ostracod proxies. According to the geomorphological characteristics of Velo Blato, the lowest relief around the lake is a 5-m high ridge towards Malo Blato. This is also the height over which the lake level did not exceed. The known water depth of the core VB-2 in Velo Blato (2.75 m), and a sediment length of 4.25 m under the sea-water influence, lead to the conclusion that the maximum possible depth of the lake in Velo Blato could be approximately 12 m.

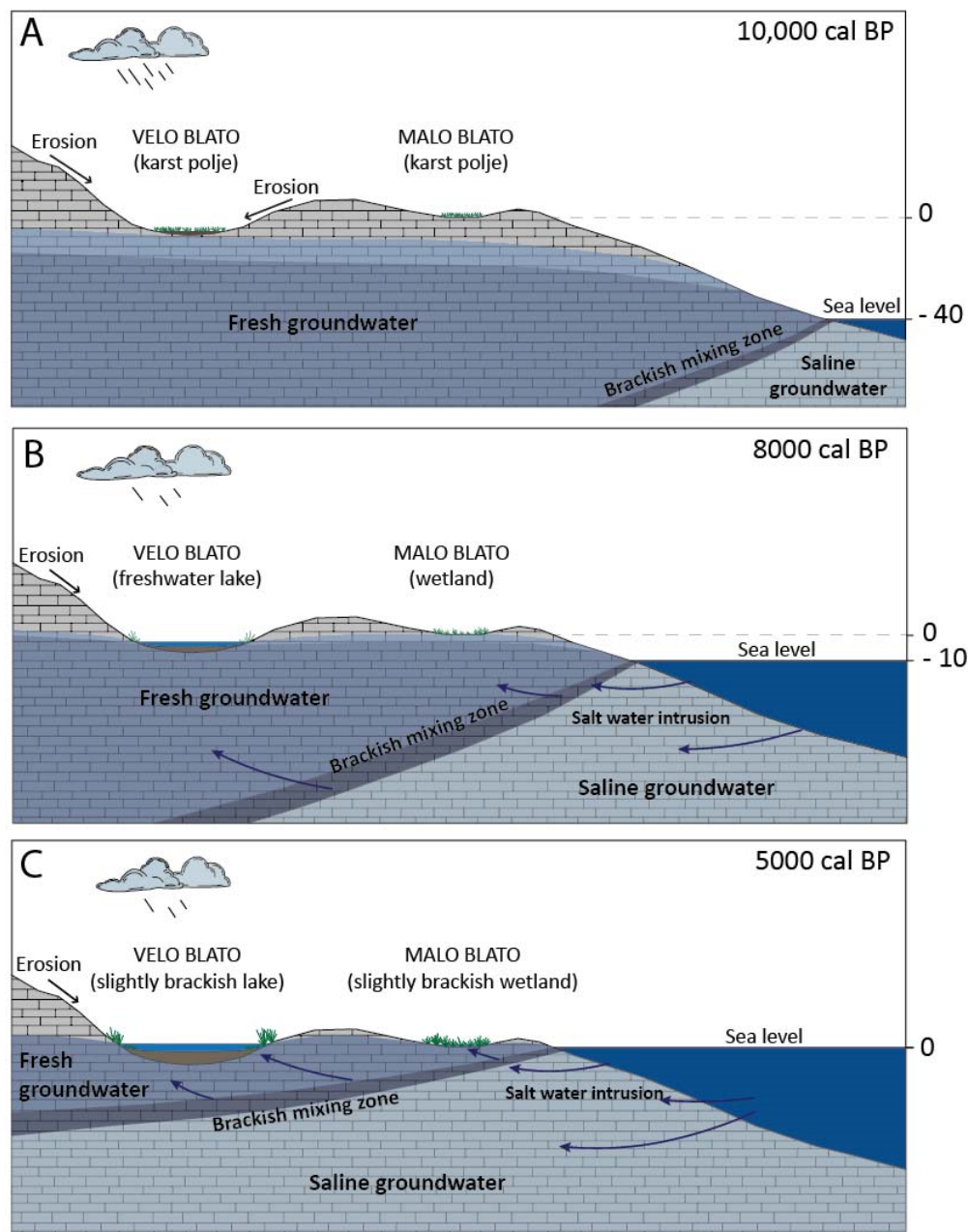


Figure 13. Schematic presentation of seawater intrusion into freshwater coastal lakes and wetlands, caused by the sea-level rise, on the example of Velo and Malo Blato in the last 10,000 years. (A) Velo and Malo Blato as karst poljes during the Early Holocene lowstand. (B) Sea-level rise in the Adriatic Sea resulted in rising the groundwater level and the formation of a freshwater lake in Velo Blato at approximately 8100 cal year BP, and the formation of a wetland in Malo Blato. (C) Saltwater intrusion and saline groundwater influence on lake sediments in Velo Blato in Middle Holocene at 5000 cal year BP (started from 7100 cal year BP), resulting in brackish environments in Lake Velo and wetland Malo Blato.

The reconstruction of sea-level influence during the Holocene in lake sediments in Velo Blato enabled the sea-level curve reconstruction in the Adriatic Sea. The time of marine influence on the lake sedimentation is determined when the sea level rose enough to infiltrate into the lake sediments in Velo Blato. At approximately 7100 cal year BP, the brackish ostracods are present, and the geochemical signal indicates marine influence; therefore, that is the apparent age when the sea level was ~7-m lower than today (Figure

14). The data points from Velo Blato are compared with other studies on the eastern Adriatic coast [14–17,48,49], and it fits well into the relative sea-level curve in the Adriatic Sea [107] and global eustatic sea level curve [106].

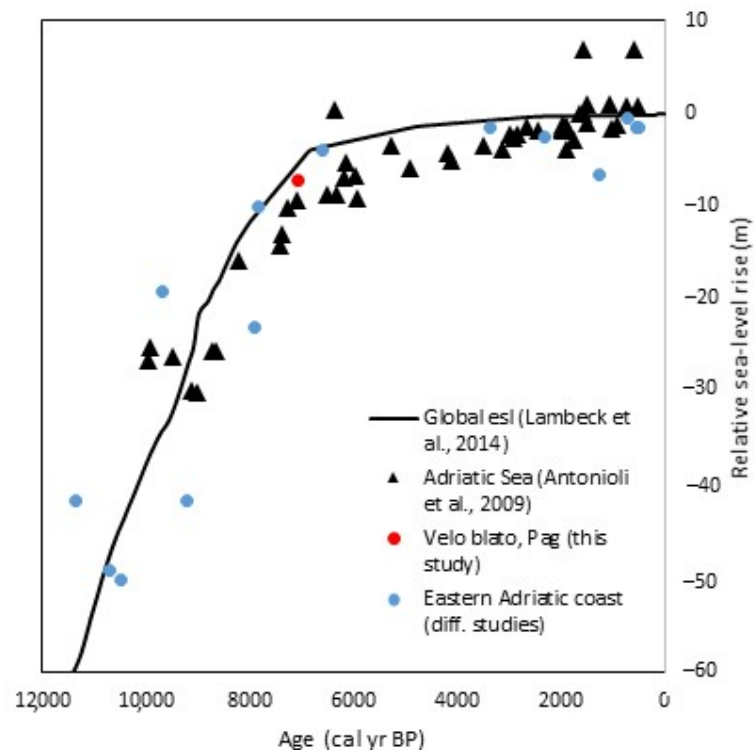


Figure 14. Relative sea-level rise during the Holocene in the Adriatic Sea [107] in relation to the global eustatic sea-level (esl) curve [106], and index points from this study (red dot) and other studies on the EAC [14–17,48,49].

In the Late Holocene, at 1800 cal year BP (150 cm), the next phase is determined, marked by the increase of TOC and N content in lake sediments from Velo Blato, especially at 1750 cal year BP at the beginning of this period. Between 1800 and 600 cal year BP (150 and 50 cm), there is an evident decreasing trend in lithogenic elements (Al, Fe) and somewhat lower values of TOC/N compared to the rest of the core. At the same time, an increasing trend is evident in carbonate elements (Ca, Sr) and TIC. This is accompanied by metal accumulation, especially lead, copper, and zinc (Figure 15). Additionally, the increased number of brackish ostracod species *C. torosa* and *C. angulata* indicate higher salinity. This period is, therefore, characterized by higher water salinity and carbonate precipitation. This indicates a warmer interval, which is approximately equivalent to the Roman (0–800 AD) and Medieval Climate Anomaly periods (800–1400 AD) [124], with a global increase in temperature [125]. During this period, accelerated sea-level rise is identified in the central and northern part of the eastern Adriatic Sea, based on the algal rim morphology and the tidal notches positions [53,54]. From approximately 750 cal year BP (74 cm) upward, calcite occurred as the dominant mineral phase, in contrast to Mg-calcite deposited until that period. Together with the Sr decrease, this indicates the decrease in salinity. Nutrient elements P and S have elevated concentrations in the last 600 years (sediments from 50 cm upwards). This period, from 600 to 200 cal year BP, coincides with the cold and humid period of the Little Ice Age (LIA; 1300–1800 AD; [124]). This is supported by the increased siliciclastic input of lithogenic elements (Al, Fe), introduced into the lake by increased precipitation and sediment runoff. This is followed by the changes in the valve morphology of *C. torosa* from smooth (forma *torosa*) to noded (forma *littoralis*), which

points to the changes in salinity, i.e., *f. torosa* is indicative of more saline conditions, while *f. littoralis* prefers reduced salinity [95]. The LIA period is identified in the eastern Adriatic as a relatively stable sea level period [53,54]. Increased precipitation and sediment input correlate well with this more humid phase in the central Mediterranean, evidenced in Lake Butrint, Albania [12], and Lake Dojran [126,127].

Recent times, i.e., the last 200 cal yr BP (after 1800 AD; interval 21–0 cm), are characterized by significantly higher P, S, N, and TOC values. The concentrations of carbonate elements (Ca and Sr) and TIC decreased. At the same time, the proportions of organic carbon (TOC) were the highest (12–23%). An increased accumulation of organic matter led to anoxic conditions: a high production of CO₂ due to the breakdown of organic matter in sediments and a decrease of water pH, which dissolved calcite reaching the lake bottom. These processes are responsible for the seemingly lower concentrations of calcite and carbonate elements (Ca, Sr) and the elevated concentrations of lithogenic elements. In reductive conditions, the formation of framboidal pyrites, which occurred in significant amounts in this interval, is characteristic of being rich in organic matter. High TOC indicates an increased primary production and development of aquatic plants (algae and phytoplankton) and macrophytes and eutrophication in the lake. Changes in nutrient status influenced the ostracod relative and absolute abundances. Samples were rich in organic detritus, plant remains, and seeds, but poor in calcareous microfossil remains, and only a few ostracod valves of *C. torosa* and *C. ophtalmica* were found in the topmost sample. High TOC and nutrient elements versus a low Ca content point to the anoxic conditions in recent sediments of Velo Blato, which would promote the dissolution of calcified ostracod valves [118,128]. During the fieldwork in spring and summer, a load of macrophyte algae was detected on the lake bottom, and recent ostracod valves were detected on calcified Chara stems. Therefore, low ostracod content in the uppermost part of the sediment core from Velo Blato could be related to the periodically anoxic conditions in that part of the lake. The exclusive presence of *C. torosa* and *C. ophtalmica* in the topmost sample (0–4 cm) of organic-rich sediment is due to their known H₂S and hypoxia tolerance [118,128,129].

The paleoenvironmental reconstruction of Kolanjsko Blato is based on a recovered lake sediment core in the length of 107 cm, which holds the record of the last 2050 years. Kolanjsko Blato is a brackish wetland, due to its proximity to the sea through the karstified carbonate ridge and a seasonal surface connection in the SE edge through the Rogoza canal. The influence of the seawater on the wetland is evident in the measured high surface water salinities (EC = 4.88 to 9.8 mS/cm, Cl⁻ content = 2700 to 6257 mg/L, as well as other geochemical parameters), which are the highest in the central and eastern part of the Kolanjsko Blato (Table 1). These values are higher than measured values in both Velo and Malo Blato (Table 1). Consequently, genuine brackish water associations appear in lake sediments *C. torosa*, *C. angulata*, and *H. salina*, accompanied by the brackish foraminifera *Ammonia* sp., and marine bivalve *Cerastoderma* sp. Since no significant changes in ostracod communities were detected by qualitative analysis, Kolanjsko Blato existed as a relatively shallow brackish coastal wetland during the last 2050 years. A relatively high content of sand (avg. 44%) in silty sediments (avg. 50%) indicate a somewhat dynamic depositional environment. The geochemical composition of lake sediments shows depositional changes from 650 cal yr BP (60 cm). A slightly higher content of siliciclastic elements in the lower part of the core indicates higher detrital input and sediment runoff between 2050 and 650 cal BP. In the last 650 years, the content of TOC and nutrients (N, P, S), and heavy metals (Cu, Hg, Pb, and Zn) increased due to the enhanced organic matter accumulation. The TOC concentrations are generally high in the Kolanjsko Blato sediment core (>3%) and increase up to 9% from the 650 cal yr BP, while the TOC/N values turn lower than 10. Thus, the source of the organic matter was dominantly algal (autochthonous) and the result of the primary lake production [114]. The lower Ca content, at the same time, was the result of the calcite dissolution in the water column before it reached the lake bottom due to the increased CO₂ and decreased pH of the water, which led to apparent anoxic conditions. TOC concentrations in Kolanjsko Blato lake sediments are quite high

(3.1–9.9%; avg. 7.05%), compared to Velo Blato lake sediments (1.06–10.5%; avg. 3.6%), except for the upper 20 cm, where it is higher than 12% (12.6–23%), and the upper part of the sediment core from Malo Blato (2.97–5.22%; avg. 3.48%). Such high TOC values (~3–10%; avg. 6.15%) were recorded only in the laminated lake sediments of Lake Veliko on the Island of Mljet [16,27]. In other lake carbonate sediments, such as Lake Vrana near Biograd [23], Bokanjačko Blato [26], and Lake Crniševu in the Baćina Lakes [19], the TOC concentrations are lower than <2%. Sediments from Kolanjsko Blato are enriched in ^{137}Cs compared to the sediments from Velo Blato, which could be related to the higher organic carbon content in the Kolanjsko Blato sediments, as organic matter is essential for ^{137}Cs radionuclide accumulation [130,131]. Similarly, the accumulation of artificial ^{137}Cs is determined in the Neretva River mouth in sediments with higher organic matter content [100].

The Malo Blato wetland is characterized by the unique geomorphological setting, in which the permanent lake makes only the small central part of the area, connected to the sea with an almost 0.5-km long artificial canal. Therefore, the water salinity is reduced compared to the sea, with a surface water electrical conductivity value of 3.8 mS/cm, and a Cl⁻ content of 1898 mg/L (Table 1), which are still higher than in Velo Blato, but lower than in Kolanjsko Blato. The broader area of the Malo Blato wetland is covered with dense vegetation characteristic of swamp and peat. This corresponds to dark, almost-black organic soils surrounding this small lake in Malo Blato. The lower part of the sediment core from lake Malo Blato (34–24 cm) is composed of these soils, high in TOC (~8%) and lithogenic elements (Al, Fe). The lake formation is observed from 20 cm upwards, indicated by grey lake sediments, with higher contents of Ca and calcite, and being rich in ostracods and gastropods. The lake formation is connected with the sea level rise during the Holocene and the influence of the seawater on the lake sedimentation, as previously described in Figure 13. Ostracod assemblage in the upper part of Malo Blato sediment core showed the dominance of *C. torosa*, accompanied by *H. salina* and *C. angulata*. *Heterocypris salina* prefers small and slightly salty coastal water bodies [95]. The presence of freshwater species *L. inopinata*, *D. stevensoni*, and *P. marchica* is also observed. Additionally, the TOC/N values are lower than 10, indicating organic matter's algal origin [114]. Nutritive elements P, N, and TOC increase upwards to the surface samples, and indicate more eutrophic conditions in lake Malo Blato in the recent period.

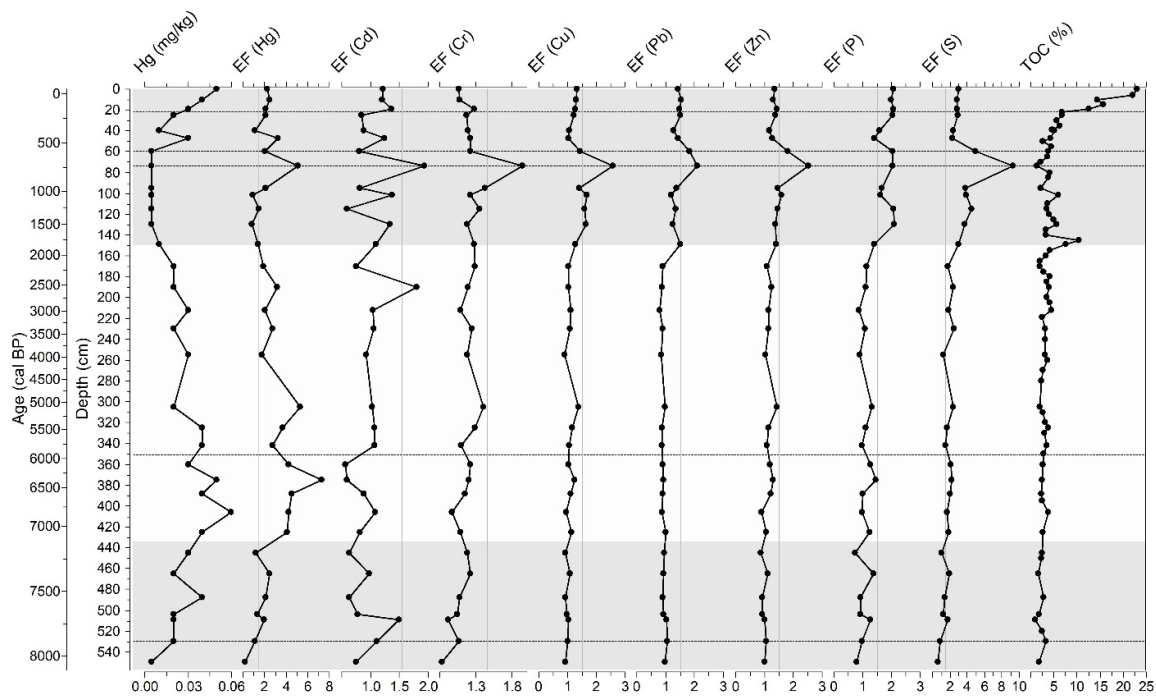


Figure 15. Enrichment factors (EFs) for Hg, Cd, Cr, Cu, Pb, Zn, P, and S, as well as concentrations of Hg and TOC in the sediment core from Velo Blato.

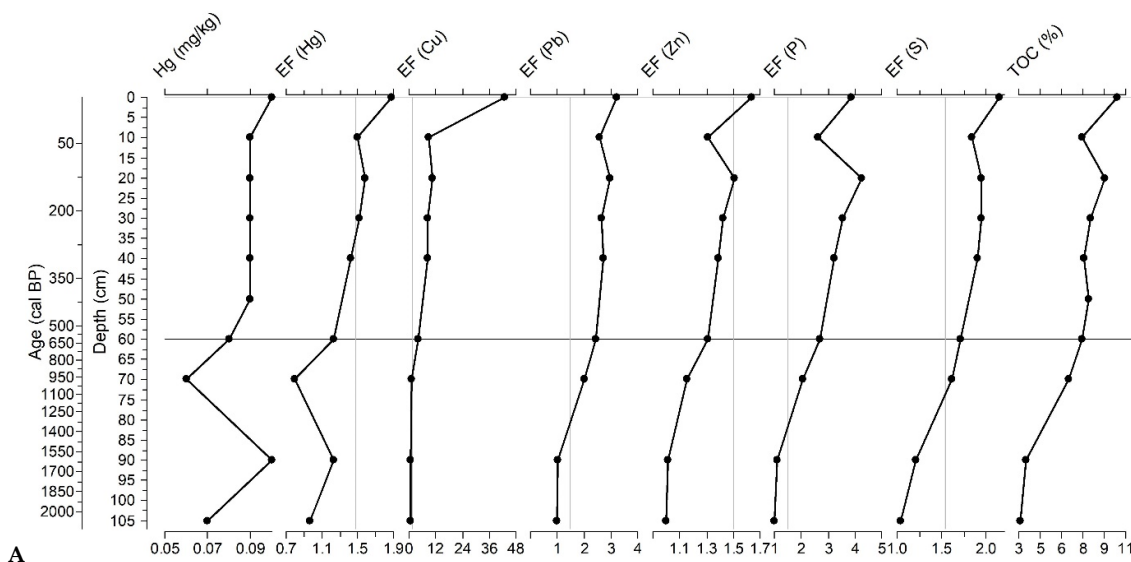
4.2. Evaluation of Metal Enrichment

Potentially toxic elements, i.e., metals (Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, and Zn) analyzed in sediment cores from Velo, Malo, and Kolanjsko Blato show similar concentrations to marine and lake sediments along the eastern Adriatic coast [14,15,19,26,103]. Slightly elevated concentrations of Cr and Ni in the sediments reflect source material in Croatian karst (terra rossa and flysch) and its geological origin [132]. The Enrichment Factor (EF) represents a useful tool for estimating the degree of anthropogenic heavy metal pollution and the status of environmental contamination. This is confirmed by the EF values for metals, with EF medians between 0.5 and 1.4, since the reference threshold for natural/anthropogenic origin of the metals is 1.5 [93]. Elements Cd, Cr, Cu, P, Pb, and Zn are considered here with their EFs presented in the chronological framework for sediment cores from Velo and Kolanjsko Blato, while an in-depth framework is presented for sediments from Malo Blato. Deviations in terms of elevated concentrations from the geogenic origin and natural variations in the concentration of elements originating from lithological units, and their weathering products in the catchment areas of the studied lakes, are found only in few samples for elements Cd, Cr, Cu, Pb, and Cu, and for P and S as nutrients. The EF of Cd is elevated in two intervals (190–191 and 75–76 cm), while the EFs for Hg, Cr, Cu, Pb, and Zn are elevated in the interval between 130 and 60 cm. The P and S EFs increase from the depth of 149 cm upwards. The distributions of metals appear consistent, and variations are the effect of dilution caused by enrichments of carbonate. High organic matter contents and TOC values in the upper part of the lake sediments, from 150 cm upward, coincide with the Pb, S, and P accumulation. This interval corresponds to the period between 1800 and 600 cal year BP (150–60 cm), known as the Roman and Medieval Climate Anomaly periods. The Roman period lead enrichment is recorded in Lake Vrana sediments on the Island of Cres [103].

The Cu, Pb, P, and Zn concentrations are elevated, and the EFs are greater than 1.5 in the upper parts (60–0 cm) of the sediment core from Kolanjsko Blato, which corresponds to the period of the last 650 cal yr BP. The surface sample is significantly enriched with Cu. They can be attributed to the anthropogenic activities in the vast catchment near the

Kolan settlement (Figure 16). High total organic content in the sediment core from Kolanjsko Blato, especially in the upper 60 cm where it is >6%, contributes to these sediments' metal accumulation. In Malo Blato sediments, the enrichment of Cu, P, Pb, and Zn is evident in the upper 20 cm of the sediment core, with the lake formation in Malo Blato. This interval is also rich in TOC content (~3–5%), and the enrichment could be attributed to the organic matter accumulation in the lake sediments. Higher values of Pb than the rest of the sediments from the core show the sample at 16–17 cm, which is also a very coarse sample in terms of grain size. We propose that this is a consequence of bird hunting while using a shotgun and lead bullets, which are commonly used in such wetland habitats in the northern Adriatic coast [91,133], and has been recorded along the EAC in sediments from marine ponds on the Island of Cres [14]. Malo Blato was proclaimed an ornithological reserve in 1988; therefore, hunting was probably carried out in the wetland area until that period, which resulted in the accumulation of lead recorded at a depth of 16 cm. Trace elements in lake sediments from the Lake Kutu and the wetland area of the Neretva River delta indicate a non-contaminated deltaic lake environment [57,134]. The metal enrichments of Pb, Cu, Zn, and Sn in sediments is identified in one location of the Neretva River delta, which is connected with expanded agricultural activities [65].

The Hg concentrations in sediments from Velo Blato are mostly low and vary between 0.01 and 0.06 mg/kg, except in high carbonate sediments, where it is even below the detection limit (<0.01 mg/kg). Higher values (0.04–0.06 mg/kg) appear in the lower and upper parts of the sediment core. The same is for sediments from Malo Blato, where the higher values are 0.06–0.07 mg/kg. In Kolanjsko Blato, the Hg concentrations are slightly higher (0.09–0.1 mg/kg) throughout the sediment core. These values correspond to natural background Hg values of karst soils in the Dinaric-coastal region (median value 0.08 mg/kg) as possible natural sources from catchments karst soils [132]. The similar Hg concentrations are recorded in sediment samples from Lake Prokljan as part of Krka River Estuary [66] and in Lake Veliko on Mljet Island [61], while the increased values from industrial sources are recorded in marine sediments from Šibenik Bay [66] and Kaštela Bay [135]. Additionally, the Hg total concentrations in Velo, Malo, and Kolanjsko Blato are slightly higher than the Hg content in marine sediments from Palagruža, middle, and south Adriatic depressions [19].



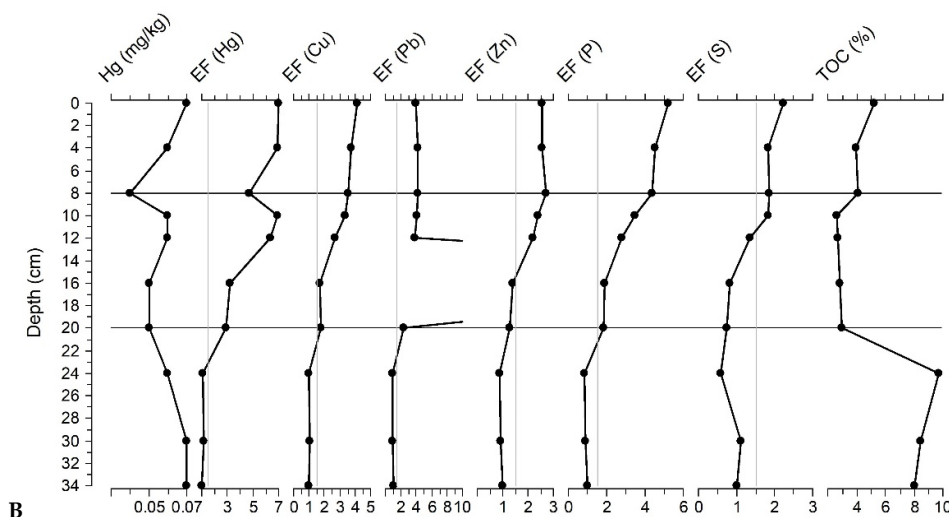


Figure 16. Enrichment factors (EFs) for Hg, Cu, Pb, Zn, P, and S, as well as concentrations of Hg and TOC in the sediment core from Kolanjsko Blato in depth and age (A) and Malo Blato in depth (B). Note the reduced maximum value for EF (Pb) to 10 in the Malo Blato sediment core, to emphasize the slight upward-increasing trend, because the value in the interval 16–18 cm is significantly higher (~70).

5. Conclusions

Lake sediments in Velo Blato on the Island of Pag archived valuable information about lake formation and the development of the area, which is perceived in comparison to the lake sediment deposition in the wetlands of Malo and Kolanjsko Blato. Significant changes in Lake Velo Blato occurred in relation to sea-level changes during the Holocene. In the Early Holocene, Velo and Malo Blato existed as karst poljes without sedimentation, followed by the freshwater lake formation 8100 years ago, due to the rising sea and groundwater levels. The brackish environment in Lake Velo Blato was established from 7100 cal year BP. Further marine transgression caused a more saline environment and the lake-level deepening in Velo Blato during the mid-Holocene. The sediment characteristics clearly indicate warmer periods of the Roman period (0–800 AD) and Medieval Climate Anomaly (800–1400 AD). A decrease in salinity from 600 to 200 cal year BP coincides with the cold and humid period of the Little Ice Age (1400–1800 AD). Increased precipitation and sediment runoff correlate well with this more humid phase in the central Mediterranean. Higher primary production and eutrophication have been evident in the last 200 years. Kolanjsko Blato archives the last 2050 cal yr BP, when it existed as a relatively shallow brackish coastal wetland. In the last 650 years, the organic carbon is accompanied by the heavy metals (Cu, Hg, Pb, and Zn) and ^{137}Cs radionuclide accumulation. A short sediment core from Malo Blato contains the record of lake formation in Malo Blato wetland, which underwent the transition from karst polje and terrestrial soil to the slightly brackish wetland probably during the Early Holocene (not dated).

The studied shallow lake and wetlands have a complex paleo-geographic history related to mid-Holocene sea-level rise, from a polje in a typical karst environment, through freshwater and brackish sedimentation, and more recently eutrophication, to changes in drainage and groundwater abstraction. The study highlights the influence of Holocene sea-level rise on lowland areas in the eastern Adriatic coast and its importance on freshwater lake formation. Lake and wetlands gradually became brackish environments due to the marine intrusion into the groundwater. In addition, analyses allow the sea-level curve reconstruction on the eastern Adriatic coast, which is identified in Lake Velo Blato as 7-m bsl at 7100 cal year BP.

The environmental changes documented in the studied lakes have broader implications elsewhere along the eastern Adriatic coast, as well as in other coastal karst environments, both for the formation of existing lakes as well as paleolakes in karst basins, of which many have been flooded by late-glacial raising sea levels.

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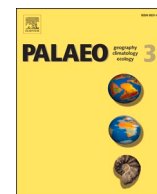
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Research paper 2

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Holocene paleoclimate reconstruction on the eastern Adriatic based on ostracods and stable isotopes from a coastal Lake Velo Blato (Croatia)

Ivona Ivkić Filipović^{a,b}, Nikolina Ilijanić^{a,*}, Ivan Razum^c, Melanie J. Leng^{d,e}, Jack H. Lacey^d, Slobodan Miko^a, Tamara Marković^a, Martina Šparica Miko^a

^a Croatian Geological Survey, Sachsova 2, 10000 Zagreb, Croatia

^b Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, 10000 Zagreb, Croatia

^c Croatian Natural History Museum, Demetrova 1, 10000 Zagreb, Croatia

^d British Geological Survey, Nottingham NG12 5GG, United Kingdom

^e School of Biosciences, University of Nottingham, Sutton Bonington, Loughborough LE12 5RD, United Kingdom

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ABSTRACT

Coastal systems, such as those of the Eastern Adriatic Coast, are complex archives where marine and terrestrial influences can hinder paleoclimate reconstruction. Here, we present a new lake sediment record from coastal karst Lake Velo Blato and use stable isotopes and compositional analysis of ostracod assemblages to reconstruct Holocene paleoclimate and paleoenvironmental changes. Ostracod assemblages revealed three ecological groups: brackish (*Cyprideis torosa*), freshwater (*Cypridopsis vidua*), and wetland (*Limnocythere inopinata*, *Darwinula stevensoni*), indicating that salinity is the main ecological driver, while processes related to lake succession are secondary. Stable isotope composition of calcite suggests the wettest climate conditions between 8100 and 7500 cal yr BP, coinciding with the development of a freshwater lake. Marine influence is evidenced between 7500 and 6300 cal yr BP, marked by a transition from freshwater (*Candona neglecta*, *Cypridopsis vidua*, *Paralimnocythere psammophila*) to brackish (*Cyprideis torosa*, *Candona angulata*, *Heterocypris salina*) ostracod assemblages, which persisted throughout the Middle to Late Holocene. However, shifts in carbon isotopes around 2100 cal yr BP indicate a significant environmental change, coinciding with a transition from a brackish lake to a shallow wetland. Climatically, warm and dry conditions prevailed during the Roman and Medieval Warm Periods, while wetter conditions have dominated since the Little Ice Age. This study provides a high-resolution record of Holocene paleoclimate and paleoenvironmental change, offering a valuable contribution to understanding coastal systems of the Eastern Adriatic region.

1. Introduction

Coastal systems are dynamic and sensitive environments that offer insights into climatic and non-climatic forcings, making them valuable archives of past environmental changes. Positioned at the interface between terrestrial and marine environments, these systems can preserve signals of regional climate variability and local processes such as sea-level changes, marine incursions, catchment hydrology, and anthropogenic pressures (e.g., Morellón et al., 2016; Marco-Barba et al., 2013; Sabatier et al., 2012; Holmes et al., 2007; Shtienberg et al., 2022; Kaniewski et al., 2024). However, deciphering these various processes in the sediment records can be challenging, especially in coastal regions, such as the Mediterranean, which has been shaped by Holocene climate

variability, sea-level rise, and its long history of human occupation. Because of the Mediterranean's unique position between mid-latitude and tropical climates and semi-enclosed nature, the Mediterranean basin is highly sensitive to global-scale climate patterns (Lionello, 2012). Climate projections for this area suggest warmer and drier conditions for the 21st century (Giorgi and Lionello, 2008), which could lead to greater pressures on ecosystems, water resources, and societies. Thus, the Mediterranean represents one of the crucial regions for paleoclimate and paleoenvironmental studies.

Holocene paleoclimate records from lake sediments in the Mediterranean region are numerous (e.g., Leng et al., 1999, 2010; Lacey et al., 2015; Frogley et al., 2001; Zanchetta et al., 2012, 2022; Francke et al., 2013; Marchegiano et al., 2018) and generally characterized by a humid

* Corresponding author.

E-mail address: nilijanic@hgi-cgs.hr (N. Ilijanić).

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Early Holocene and progressive aridification during the Middle-Late Holocene (Roberts et al., 2008). However, spatiotemporal incoherencies in Holocene hydroclimate are well-established between and within Mediterranean sub-regions, highlighting the importance of investigating variability at both local and regional scales (Finné et al., 2019). In the central Mediterranean, a good coverage of paleoclimate data from lake sediments exists in Italy and Southeast Europe (see Finné et al., 2019). Lake sediment archives from the Eastern Adriatic region are limited, although several paleoenvironmental studies have emerged along the Eastern Adriatic Coast (EAC) in the past decade (e.g., Ilijanić et al., 2018, 2024, 2025; Brunović et al., 2020, 2024; Hajek-Tadesse et al., 2018; Razum et al., 2021; Smrkulj et al., 2025). However, paleoclimate studies are notably scarce, particularly those utilizing stable isotope data, which hinders the ability to reconstruct past climate variability with greater precision. The primary causes of these limitations are: 1) the majority of lakes along the EAC are influenced by Holocene sea-level rise, complicating the interpretation of stable isotope records from lake sediments (e.g., endogenic calcite), and 2) the majority of lakes are formed on a karstic bedrock and potentially influenced

by clastic carbonate contamination, affecting the integrity of the stable isotope data (Leng et al., 2010). Nevertheless, these problems can be overcome with careful site selection and examination of paleoenvironmental proxies.

Here we present the results of a multiproxy study in the shallow karstic Lake Velo Blato on the Island of Pag, which expands upon the sedimentary and geochemical analysis and reconstruction of sea-level rise (Ilijanić et al., 2022). Lake Velo Blato represents a unique paleoenvironmental archive due to its coastal setting, karst geomorphology, and endorheic nature, making it sensitive to hydroclimate changes and variable marine influences. Moreover, the lake's catchment is characterized by a barren karst landscape with poor vegetation cover, resulting in isolation from allochthonous organic matter influx. Thus, the organic matter within the lake sediments from Velo Blato reflects predominantly within-lake processes. This study provides a detailed paleoclimate and paleoenvironmental record along the EAC spanning the Holocene based on stable isotope analysis of lake sediments and ostracod shells, coupled with the assessment of modern lake water chemistry. In addition, ostracod assemblages were analysed using multivariate statistics based

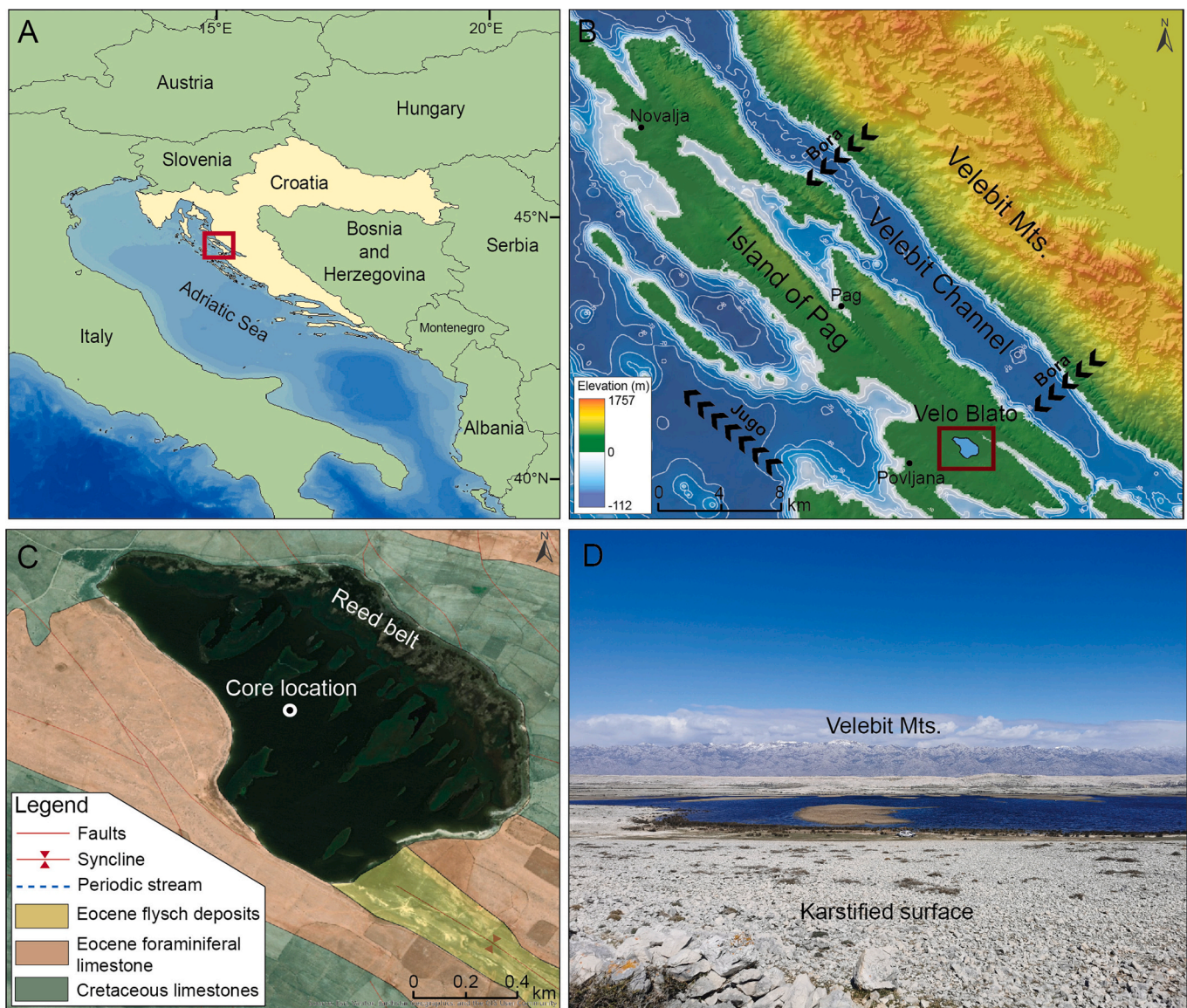


Fig. 1. Geographical location of the study area (A), elevation map of the Island of Pag with location of the lake Velo Blato (red square) (B), satellite image overlaid with a geological map (C), and field photograph of the southern lake shore with a view on the Velebit Mts. (D). Black arrows on B mark the direction of the Bora and Jugo winds. Satellite image source: World Imagery by ESRI, Maxar, Earthstar Geographics, and the GIS User Community (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

on compositional data analysis, thus improving the paleoenvironmental interpretation by accounting for the compositional nature of raw percentage data. This multiproxy research offers new insights into the sensitivity of endorheic coastal lakes to regional hydroclimate changes.

2. Study area

Lake Velo Blato (44.354°N, 15.157°E) is a shallow (< 3 m) coastal karst lake situated in the southern part of Pag Island on the Eastern Adriatic Coast (Croatia) (Figs. 1A, B). It is the largest freshwater reservoir on the island, a cryptodepression, with a surface area of 2 km². The lake lies on Cretaceous rudist limestones, Eocene foraminifera limestones, and Eocene flysch deposits (marls, sandstones) (Sokač et al., 1974, 1976) (Fig. 1C). It has no continuous surface inflow or outflow, except for smaller karst springs around the lake and a seasonal stream in the southeastern part that flows during heavy rainfall. Thus, the water balance in Velo Blato is controlled mainly by precipitation, evaporation, and groundwater. Although often characterized as a freshwater reservoir, it is slightly brackish within the oligohaline range (Ilijanić et al., 2022). This is due to the input from sea salt aerosols during strong NE Bora winds blowing from the Velebit Mts. (Fig. 1B) and salt washout into the groundwater (Magdalenic, 1984), as well as by mixing with sea water in the underlying karst aquifer (Ilijanić et al., 2022). Due to the island's limited freshwater resources, a pumping station was built in 1970 on the northwest shores of Lake Velo Blato, capturing both groundwater and surface water from the lake. The station was used occasionally during the most extreme (dry) conditions, but it was eventually abandoned due to increased salinity (Ljubešić and Munda, 2015). Wind-carried sea spray inhibits vegetation growth and soil formation on the surface, resulting in a barren karst landscape with poor vegetation cover (lithosols) typical for the entire island (Magdalenic, 1984) (Fig. 1D). The lake is a protected ornithological reserve with typical Mediterranean wetland flora and fauna (Mitić et al., 2009). Common reeds are especially well developed in the NE part of the lake, while rocky pastures dominate in the S-SW part (Fig. 1C, D).

The Island of Pag has a typical Mediterranean climate (humid subtropical climate (Cfa) according to the Köppen Climate Classification), characterized by maritime influence, with strong, cold, and dry NE Bora winds blowing from the Velebit Mountains, and warm and wet Jugo winds blowing from the southeast (Zaninović et al., 2008; Signell et al., 2010). Both winds blow throughout the year but are more frequent and stronger in the cold season (Zaninović et al., 2008). The mean annual precipitation is 879 mm, and the mean annual temperature is 15 °C (State Meteorological Service (DHMZ) data from Zadar station for 1971–2000, Zaninović et al., 2008). The wettest month is November, while the driest month is July. The island is characterized by enhanced evaporation (1800 mm/yr for the period 1955–1980, data from salt pans published by Magdalenic, 1984) due to strong Bora winds, high summer temperatures, and a high number of sunny days.

3. Materials and methods

3.1. Core recovery, sampling, and chronology

A 568 cm (557 ± 11 cm in core catcher) long sediment core VB-2 was drilled in the central part of Lake Velo Blato (44°21.292'N, 15°9.308'E) at a water depth of 2.7 m, using a Uwitec piston corer mounted on a floating platform. The sediment core was transported to the laboratory of the Croatian Geological Survey and processed by splitting lengthwise into a working and an archive half. The working half was further investigated by visual core description and sub-sampled at 1 cm resolution for geochemical and ostracod analysis.

The chronology of sediment core VB-2 was initially published by Ilijanić et al. (2022), using classical age-depth modelling in the R package Clam 2.2 (Blaauw, 2010; R Development Core Team, 2013). Here, the chronology is refined using the Bayesian age-depth modelling

package Bacon (Blaauw and Christen, 2011) and the IntCal20 calibration curve (Reimer et al., 2020).

3.2. Water sampling and analysis

Water sampling and field measurements of physico-chemical parameters such as temperature (T), dissolved oxygen (DO), electrical conductivity (EC), and pH were carried out on July 21, 2022, and February 15, 2023, to assess the current stable isotope hydrology and seasonal variations in water chemistry. In the field, these parameters were measured using a multiparameter WTW probe. For water isotope ($\delta^{18}\text{O}$, $\delta^2\text{H}$) and chemical analyses (anions, cations), water samples were collected from the lake surface, stored in tightly sealed high-density polyethylene (HDPE) containers, and transported to the laboratory in a cooled box. Water isotope analyses were performed using a Picarro L2130-I analyser (Picarro, Santa Clara, CA, USA), with calibration using the Secondary Water Isotopes Standard Kit (USGS 46a, USGS 47, and USGS 48) which are periodically compared against the International Atomic Energy Agency (IAEA) standards: Vienna Standard Mean Ocean Water 2 (VSMOW2) and Standard Light Antarctic Precipitation 2 (SLAP2). The results are reported as per mille (‰) deviations relative to the VSMOW2. Chemical analyses were conducted on an Ion Chromatograph Dionex ICS 6000 (Thermo Fisher Scientific, Waltham, MA, USA). Alkalinity was determined by titration with 1.6 N H₂SO₄, using phenolphthalein and bromocresol green–methyl red as indicators, and then converted to equivalent HCO₃[−] concentrations. Calcite saturation index (SI_{calcite}) was calculated using the PHREEQC (version 3) program (Parkhurst and Appelo, 2013). Chemical and isotope analyses of water were conducted at the Croatian Geological Survey. To characterize modern water isotope hydrology of the study area, the measured $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of lake waters were plotted against the local meteoric water line (LMWL) constructed using monthly precipitation data from the Zadar station (IAEA WISER, 2026; Vreća et al., 2006).

3.3. Isotope analysis of carbonate

For stable isotope analysis of lake (endogenic) carbonate ($\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$), about 1 g of freeze-dried sample was immersed in 5% sodium hypochlorite for 24 h to remove any reactive organic matter. The samples were then sieved at 80 µm using deionised water, air-dried on filter paper, and powdered. The samples were analysed at the British Geological Survey (BGS). In general, 30 mg of sample material and 15 mg of the laboratory standards MCS ($\delta^{13}\text{C} - 0.7\text{‰}$, $\delta^{18}\text{O} - 9.2\text{‰}$; calcite) and CCS ($\delta^{13}\text{C} - 22.3\text{‰}$, $\delta^{18}\text{O} - 13.3\text{‰}$; reagent grade calcium carbonate), both calibrated to VPDB using a suite of international reference materials, were reacted overnight in a vacuum with anhydrous phosphoric acid at a constant 25 °C to release CO₂ gas, which was subsequently passed through a water trap and collected under liquid nitrogen for isotope analysis. The CO₂ was analysed using a Sercon Geo HS2022 dual inlet isotope ratio mass spectrometer. The mineral-gas fractionation factor used for calcite was 1.01025 (Rossenbaum and Sheppard, 1986). $\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$ are reported as per mille (‰) deviations of the isotopic ratios relative to the Vienna Pee Dee Belemnite (VPDB) international standard. Analytical reproducibility for the standards was less than 0.1‰ for $\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$. Several samples were prepared for SEM analysis of the <80 µm size fraction to characterize the carbonate mineralogy of the bulk sediment used for isotope analysis. Furthermore, rock samples were taken from lake shores and analysed for their oxygen and carbon isotope composition ($\delta^{18}\text{O}_{\text{rock}}$, $\delta^{13}\text{C}_{\text{rock}}$) to estimate any detrital carbonate influence on the endogenic carbonate isotope record.

3.4. Isotope analysis of organics

For stable isotope analysis of organic matter ($\delta^{13}\text{C}_{\text{COM}}$), 1 g of freeze-dried sample was treated with 8 ml of 4 M HCl to remove carbonates.

Samples were reacted for 24 h at room temperature and then rinsed twice with distilled water. Following this, about 0.5 g of insoluble residue was dried and crushed in an agate mortar, stored in plastic bags, and transported to the BGS. Samples were weighed into 8 × 5 mm tin capsules with a target carbon mass of 500 µg (acidified sediment). Carbon isotope analysis was carried out using an Elementar vario ISOTOPE cube elemental analyser (EA) coupled to an isoprime precision isotope ratio mass spectrometer (IRMS). Stable isotope data are reported in delta (δ) notation in per mille (‰) relative to the international reference scale Vienna Pee Dee Belemnite (VPDB). The isotope ratios $^{13}\text{C}/^{12}\text{C}$ of the sample gas were measured relative to a CO_2 reference gas, and there was negligible system blank contribution. Raw gas values were normalized to the international δ scale using a two-point calibration using the laboratory standard BROCC3 (δ ^{13}C = 27.6‰; broccoli) and the organic analytical standard B2162 (δ ^{13}C = 18.7‰; spirulina algae; Elemental Microanalysis Ltd.), which have been calibrated to VPDB using a suite of international reference materials. Average external precision (1σ) for the within-run standards and samples was <0.05‰ for δ ^{13}C . To strengthen the interpretation of organic matter sources in the lake sediments, we incorporated previously published TOC and TOC/N data (Ilijanić et al., 2022).

3.5. Ostracod analysis

3.5.1. Sample processing and counting of ostracods

For ostracod analysis, a total of 48 samples were taken in 1-cm intervals and freeze-dried. About 5 g of freeze-dried sample was disaggregated in distilled water without any chemical pre-treatment. Samples were sieved using 250 and 125 µm mesh sizes, rinsed on filter paper, and oven-dried at 40 °C. Both size fractions were examined qualitatively to assess the abundance of juvenile and adult valves. In general, all ostracod valves were picked and counted from the 250 µm fraction. However, in two exceptionally rich samples where the total number of valves exceeded 1000, only a portion of the sieved sediment was picked. The analysed sieved sediment was weighed in all samples, and the abundances were normalized to 1 g of dry sieved sediment. Species identification was based on Meisch (2000), Fuhrmann (2012), and Mazzini et al. (2014).

3.5.2. Multivariate analysis

Ostracod relative abundances, which are normally used in statistical analyses (e.g., Principal Component Analysis, cluster analysis), are compositional by nature, i.e., the information they carry is stored in ratios between components and assumes interdependence of variables (Aitchison, 1986). Such data form a sample space called a simplex, which is different from the Euclidean space where distances and variance are measured independently. Thus, standard statistical methods based on Euclidean geometry are not suitable for compositional data and can lead to misleading interpretations. Simplex space is defined as:

$$s^D = \left\{ x = [x_1, x_2, \dots, x_D] \mid x_i > 0, i = 1, 2, \dots, D; \sum_{i=1}^D x_i = K \right\}$$

where K is a constant, which is 100 (%) in our case. It is visible from the above definition of the simplex that zeros are not allowed. There are many types of zeros in the compositional data, depending on the nature of the data acquired (Pawlowsky-Glahn et al., 2015). In this case, counting (true) zeros is encountered as defined in van den Boogaart and Tolosana-Delgado (2013). To replace zeros, the geometric Bayesian multiplicative replacement was used (Palarea-Albaladejo and Martín-Fernández, 2015). This method assumes that all zeros are counting zeros, meaning that a species with zero values was present in the environment but was not observed due to low abundance or limited sampling, in contrast to true zeros indicating genuine absence during a certain period. Thus, if a certain ostracod species contains mostly zero values throughout the sediment core, it is better to exclude those species

from further analysis. In this way, statistical analysis is more robust since it is not burdened by a large number of values produced by the zero-replacement method and does not introduce artificial values for periods where zeros likely represent true absences, which would otherwise bias compositional analysis (Pawlowsky-Glahn et al., 2015). Therefore, rare and scattered species were excluded from the statistical analysis.

First, variations in ostracod assemblages were studied using the compositional biplot (Aitchison and Greenacre, 2002) to identify ecological properties of the first two principal components (explaining ca. 65% of variation) based on PCA scores and loadings. Then, components were back-transformed into simplex for downcore interpretation of ecological parameters. In addition, the constrained cluster analysis was performed to identify ostracod biozones. Ostracod percentages were converted to centered-log-ratio (clr) values in the R program (R Development Core Team, 2013) using the zCompositions package (Palarea-Albaladejo and Martín-Fernández, 2015). The clr-transformed data were then used for cluster analysis in the Past program (Hammer et al., 2001), applying the unweighted pair group method with arithmetic mean (UPGMA) with Euclidean distances.

3.5.3. Isotope analysis

The stable isotope analysis of ostracod shells (δ ^{18}O and δ ^{13}C) was conducted on the two most abundant ostracod species. Generally, between 1 and 3 well-preserved adult valves were picked, while juveniles were used when adults were missing or altered. This is justifiable since the O-isotope fractionation is similar for juveniles and adults, as well as for males and females (Decrouy et al., 2011; Decrouy, 2012; von Graffenstein et al., 1999). Valves were cleaned with ethanol and a fine brush, transferred into glass vials, and treated by plasma-ashing to remove any remaining organic matter. Stable isotope analysis was performed on an IsoPrime100 dual inlet mass spectrometer at the British Geological Survey. Between 23 and 222 µg of ostracod samples were loaded into glass Wheaton vials and reacted with anhydrous phosphoric acid at 90 °C. The δ ^{18}O and δ ^{13}C values of ostracods are reported in delta notation in per mille (‰) relative to VPDB and were corrected using a within-run laboratory Carrara marble standard (KCM). The analytical reproducibility for the standard material was ±0.05‰ for both δ ^{18}O and δ ^{13}C . The vital effect corrections were applied following Curry et al. (2016).

4. Results

4.1. Modern water chemistry

Results of physical and chemical measurements of lake water in summer 2022 and winter 2023 are shown in Table 1. All measured parameters display clear seasonal variability of lake water characteristics. Water temperature varied between 5.4 (winter) and 30.8 °C (summer) (13.0 ± 10.5 °C). Electrical conductivity (EC) varied between 2.3 and 3.7 mS/cm (3.0 ± 0.4 mS/cm), confirming that Lake Velo Blato is not a true freshwater lake, but rather a medium brackish lake within the oligohaline range. Seasonal pH values varied between 7.5 and 8.6 (8.4 ± 0.2). Dissolved oxygen (DO) varied between 0.0 and 14.6 mg/l (11.2 ± 3.4 mg/l). Low dissolved oxygen values in samples VB-3-2 bottom (3.3 mg/l) and VB-3-5 bottom (0.0 mg/l) are due to immersion of the electrode into the bottom sediment. However, right above the sediment-water interface, dissolved oxygen levels rose to ca. 8 mg/l and at 1 m depth to 8.8 mg/l. Within-season variations of all parameters are minor and depth-related.

The chemical composition of lake water samples (Table 2) shows that chloride (Cl $^-$) is the dominant anion and sodium (Na $^+$) is the dominant cation in all samples. During the summer, chloride concentrations reach approximately 1670 mg/l and sodium 1070 mg/l (e.g., VB-3-2), while in winter these values drop to about 890 mg/l for Cl $^-$ and 480 mg/l for Na $^+$ (e.g., VB-4-4). Seasonal dilution is evident, with lower concentrations of

Table 1

Physical and chemical parameters of lake water samples collected from approximately the same locations in two different seasons. Samples labelled VB-3 were collected on July 21, 2022, whereas samples labelled as VB-4 were collected on February 15, 2023.

Water samples	Water depth (m)	T (°C)	EC (mS/cm)	pH	DO (mg/l)
VB-3-2 bottom	0.3	30.8	3.6	7.8	3.3*
VB-3-3 surface	2.0	27.4	3.7	8.6	8.9
VB-3-3 1 m depth	2.0	27.4	3.7	8.6	8.9
VB-3-3 bottom	2.0	27.4	2.3	8.5	8.7
VB-3-4 surface	1.0	28.6	3.7	8.5	8.8
VB-3-4 bottom	1.0	28.2	3.7	8.5	7.3
VB-3-5 surface	1.6	27.7	3.7	8.5	8.7
VB-3-5 1 m depth	1.6	27.4	3.7	8.6	8.8
VB-3-5 bottom	1.6	26.4	3.1	7.5	0.0*
VB-4-2	0.3	9.6	2.8	8.6	14.6
VB-4-3 surface	2.8	6.2	2.8	8.5	13.3
VB-4-3 1 m depth	2.8	5.5	2.8	8.5	13.4
VB-4-3 bottom	2.8	5.4	2.8	8.6	13.5
VB-4-4 surface	2.1	6.0	2.8	8.5	13.3
VB-4-4 1 m depth	2.1	5.4	2.8	8.5	13.3
VB-4-4 bottom	2.1	5.4	2.8	8.5	13.3
VB-4-5 surface	2.5	6.3	2.8	8.5	13.0
VB-4-5 1 m depth	2.5	5.6	2.8	8.5	13.0
VB-4-5 bottom	2.5	5.6	2.6	8.1	12.8
VB-4-6 surface	1.7	5.7	2.8	8.5	13.3
VB-4-6 1 m depth	1.7	5.4	2.8	8.5	13.3
VB-4-6 bottom	1.7	5.4	2.8	8.5	12.0
VB-4-7 surface	2.3	6.6	2.8	8.5	13.2
VB-4-7 1 m depth	2.3	5.5	2.8	8.5	13.2
VB-4-7 bottom	2.3	5.4	2.8	8.5	13.3
VB-4-8 surface	2.2	6.8	2.9	8.5	13.1
VB-4-8 1 m depth	2.2	5.9	2.8	8.5	13.3
VB-4-8 bottom	2.2	5.8	2.8	8.5	13.5

* Electrode immersed in the bottom sediment.

marine-derived ions in winter, reflecting increased freshwater input and reduced evaporation. Magnesium (Mg^{2+}), another major cation of marine origin, decreases from ca. 59 mg/l in summer to ca. 40 mg/l in winter, whereas calcium (Ca^{2+}) concentrations remain relatively stable or even slightly increased in winter (from ca. 104 mg/l in summer to ca. 110 mg/l in winter). $SI_{calcite}$ is positive year-round and highest in summer (up to 1.5), indicating a tendency for carbonate precipitation.

The water isotope composition ($\delta^{18}O$ and δ^2H) of Lake Velo Blato demonstrates clear seasonal variability (Fig. 2). Both summer and winter lake water samples are plotted relative to the Local Meteoric Water Line for Zadar (LMWL-Zadar). All lake samples are positioned along a local evaporation line (LEL), with a slope lower than the LMWL. Winter samples, even those collected in February 2023, are notably shifted below the LMWL, while summer samples have substantially higher $\delta^{18}O$, with values up to 10.6‰ higher compared to the mean $\delta^{18}O$ of local

precipitation (−5.3‰).

4.2. Core lithology and chronology

The base of the sediment core VB-2 is composed of limestone fragments representing karstified bedrock, meaning that sediment core VB-2 contains the entire lacustrine sequence of Lake Velo Blato. The core is dominated by sandy silt rich in shells and shell fragments (Fig. 3) of *Bithynia tentaculata* and *Stagnicola* sp. The lower part of the core (557–250 cm) is made of greyish-brown clayey to sandy silt, while the upper part (250–21 cm) is made of yellowish-brown sandy silt. The topmost part of the sediment core (21–0 cm) is made of dark brown organic mud, and a similar organic-rich layer is at 140–150 cm (Fig. 3).

The age-depth model for sediment core VB-2 shows continuous sedimentation for the last 8100 cal yr BP. However, the default accumulation rate prior (20 yr/cm) produced unrealistically steep age-depth gradients and increased age uncertainty at the base of the sediment core (553–402 cm). This was likely due to higher sedimentation rates in this interval. Thus, we adjusted the default settings by introducing the boundary argument at 402 cm and changed the accumulation rate prior to 10 yr/cm (acc.mean = c(20/10)) for the interval between 553 and 402 cm. For the rest of the sediment core, we applied the default settings. This modification improved the model fit and produced a more plausible age-depth model (Fig. 3) while preserving the stratigraphic order and influence of the dated levels. Sedimentation rate (SR) varies between 0.05 and 0.15 cm/yr. SR is highest in the lower part of the core (8100 and 6800 cal yr BP) and then decreases to lower values between 6800 and 3000 cal yr BP. From that point, SR slightly increases (ca. 0.07 cm/yr) between 3000 and 1100 cal yr BP, and is again relatively high (ca. 0.11 cm/yr) in the upper part of the core (last 1000 years) (Fig. 3).

4.3. Ostracod assemblage

The Velo Blato sediment core contains 22 ostracod species belonging to 17 genera, represented by both adults and juveniles (Fig. 4): *Cyprideis torosa* (Jones, 1850), *Candona angulata* G.W.Müller (1900), *Candona neglecta* G.O. Sars (1887), *Pseudocandona marchica* (Hartwig, 1899), *Pseudocandona* sp. (juveniles), *Candonopsis kingsleii* (Brady & Robertson, 1870), *Darwinula stevensoni* (Brady & Robertson, 1870), *Heterocypris salina* (Brady, 1868), *Cypria ophtalmica* (Jurine, 1820), *Metacypris cordata* Brady & Robertson (1870), *Cyclocypris ovum* (Jurine, 1820), *Ilyocypris* cf. *gibba* (Ramdohr, 1808), *Ilyocypris bradyi* Sars (1890), *Ilyocypris* sp. (juveniles), *Ilyocypris* sp., *Cypridopsis vidua* (O. F. Müller, 1776), *Cypris bispinosa* Lucas (1849), *Hungarocypris madaraszii* (Örley, 1886), *Herpetocypris chevreuxi* (Sars, 1896), *Limnocythere inopinata* (Baird, 1843), *Paralimnocythere psammophila* (Flössner, 1965) and *Notodromas monacha* (Müller, 1776). The most abundant species are *C. torosa*, *C. angulata*, *C. neglecta*, *D. stevensoni*, *L. inopinata*, and *C. ophtalmica*,

Table 2

Alkalinity (as HCO_3), anions and cations, calcite saturation index ($SI_{calcite}$), oxygen ($\delta^{18}O$) and hydrogen (δ^2H) isotopes in lake water samples collected in summer (VB-3) and winter (VB-4).

Water samples	HCO_3 (mg/l)	F (mg/l)	Cl (mg/l)	Br (mg/l)	NO_3 (mg/l)	SO_4 (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	$SI_{calcite}$	$\delta^{18}O$ (‰)	δ^2H (‰)
VB-3-2	250	0.5	1672.5	1.1	b.d	391.8	94.0	60.1	1071.7	19.1	0.7	+5.4	+14.5
VB-3-3	280	1.1	1614.6	1.8	b.d	382.8	104.8	58.6	1052.6	18.5	1.5	+4.4	+13.6
VB-3-4	282	1.1	1619.3	1.8	b.d	384.6	105.0	58.6	1053.0	18.6	1.4	+4.5	+14.5
VB-3-5a	280	1.1	1621.9	1.8	b.d	384.0	104.7	58.7	1053.4	18.8	1.4	+4.5	+14.6
VB-3-5b	284	1.1	1621.3	1.8	b.d	383.4	106.4	58.3	1051.6	18.5	0.5	+4.5	+14.6
VB-4-2	130	1.1	878.2	1.9	1.4	141.3	108.3	39.6	479.1	11.0	1.0	−3.3	−25.7
VB-4-3	135	1.1	890.6	1.9	1.6	144.9	109.5	39.4	484.6	11.1	0.9	−3.2	−23.8
VB-4-4	102	1.1	892.6	1.9	1.6	144.8	94.1	39.8	484.7	11.2	0.7	−3.1	−23.3
VB-4-5	138	1.1	891.3	1.9	1.6	144.2	110.2	39.8	483.5	11.4	0.9	−3.1	−23.0
VB-4-6	120	1.1	891.3	1.9	1.6	144.2	110.3	39.8	480.9	11.2	0.8	−3.1	−23.0
VB-4-7	120	1.1	895.8	1.9	1.5	145.4	110.3	40.2	482.7	11.3	0.8	−3.0	−22.5
VB-4-8	102	1.1	887.6	1.9	1.5	142.8	94.9	39.9	480.2	11.2	0.7	−3.1	−23.0

a = surface sample; b = bottom sample; b.d. = below detection limit.

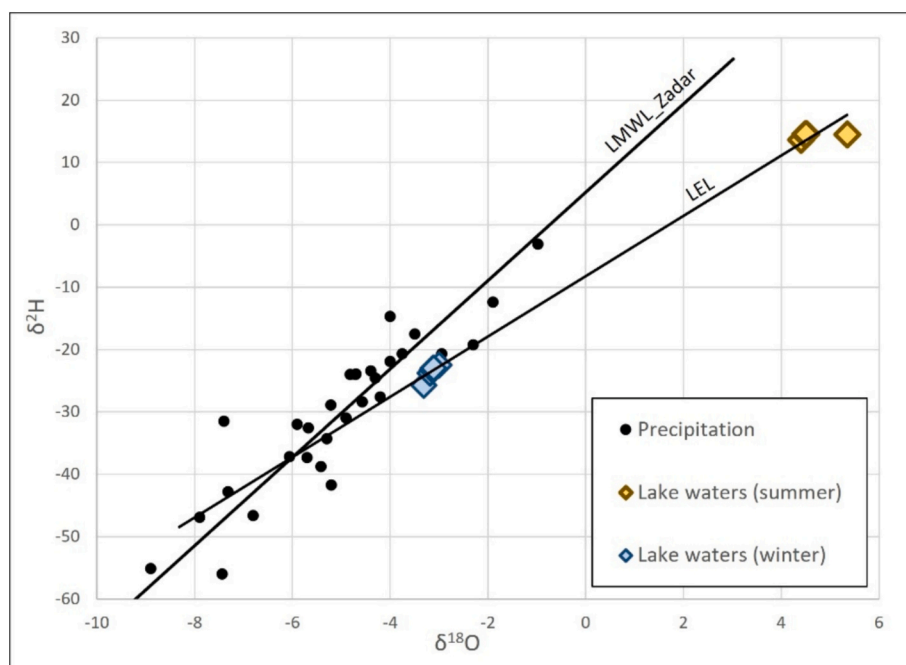


Fig. 2. $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ for the study area. Monthly precipitation data are from IAEA-GNIP data (Zadar station, [Vreća et al., 2006](#)).

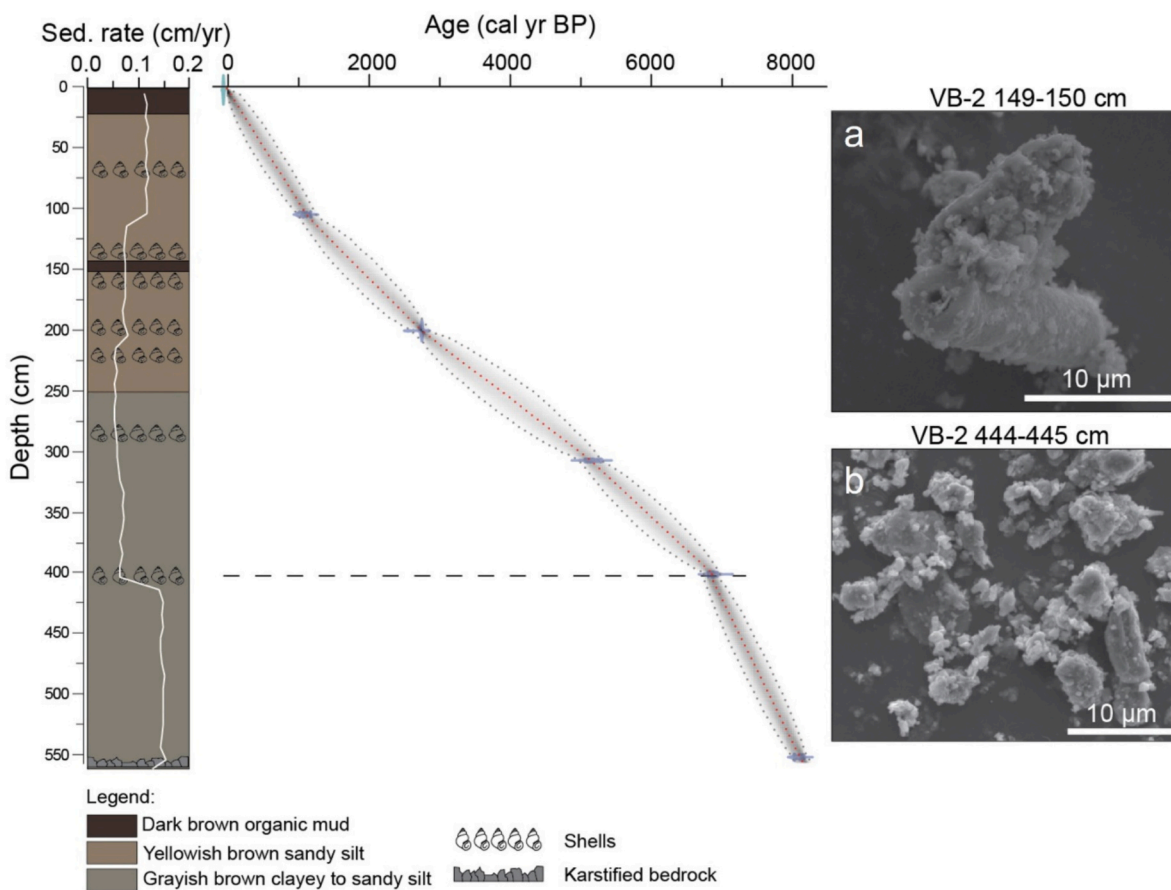


Fig. 3. Core lithology with sedimentation rate, age-depth model, and SEM images on the right showing fine-grained calcite platelets covering (a) tube-like biological fragment (likely a sponge spicule), and (b) dolomite fragments. The dashed line marks the position of the boundary argument in the age-depth model. SEM images provided by BGS © UKRI 2026.

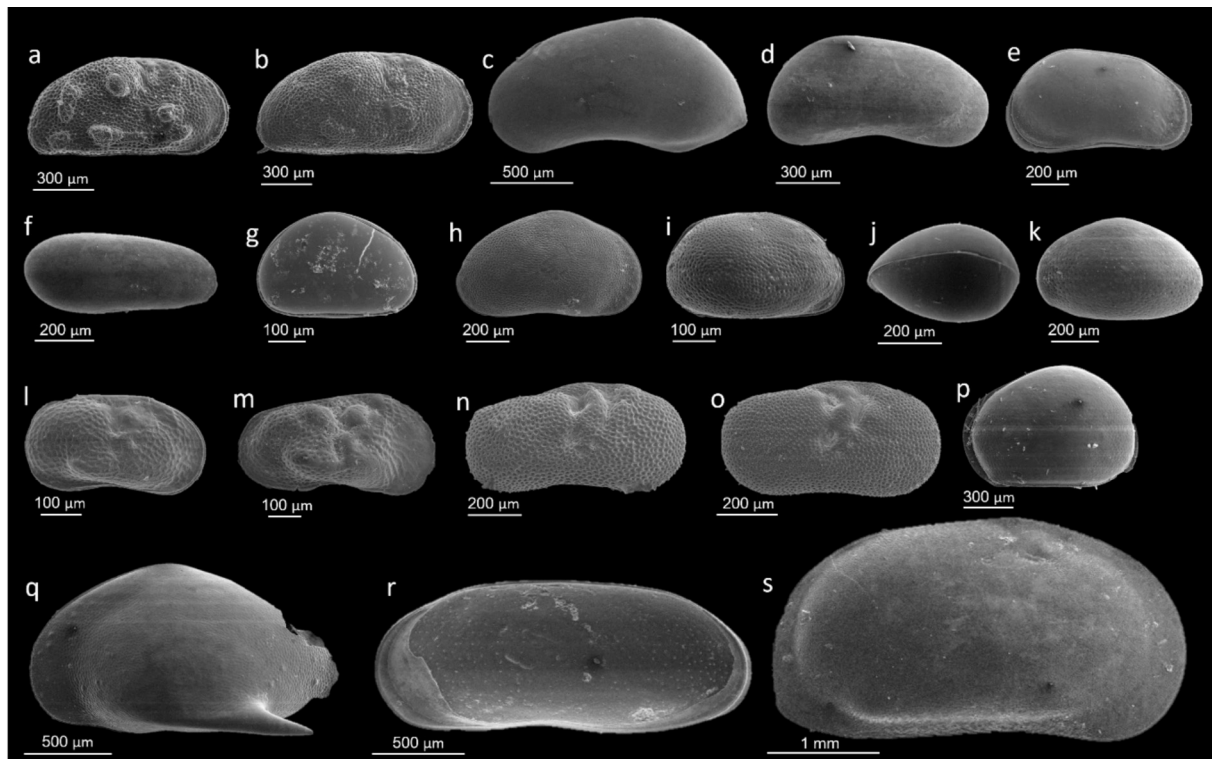


Fig. 4. SEM images of ostracod species. (a) *Cyprideis torosa*, noded male right valve, ext.; (b) *Cyprideis torosa*, unnoded male right valve, ext.; (c) *Candona angulata*, male left valve, ext.; (d) *Candona neglecta*, female right valve, ext.; (e) *Pseudocandona marchica*, female carapace, lateral view; (f) *Darwinula stevensoni*, female right valve, ext.; (g) *Cyprina ophtalmica*, female carapace, lateral view; (h) *Heterocypris salina*, female right valve, ext.; (i) *Metacypris cordata*, female right valve, ext. (j) *Cyclocypris ovum*, carapace, dorsal view; (k) *Cypridopsis vidua*, female left valve, ext.; (l) *Limnocythere inopinata*, female right valve, ext.; (m) *Paralinmocythere psammophila*, female right valve, ext.; (n) *Ilyocypris bradyi*, female right valve, ext.; (o) *Ilyocypris cf. gibba*, female right valve, ext.; (p) *Notodromas monacha*, female carapace, lateral view; (q) *Cypris bispinosa*, female right valve, ext.; (r) *Herpetocypris chevreuxi*, female right valve, int.; (s) *Hungarocypris madaraszsi*, female right valve, ext.

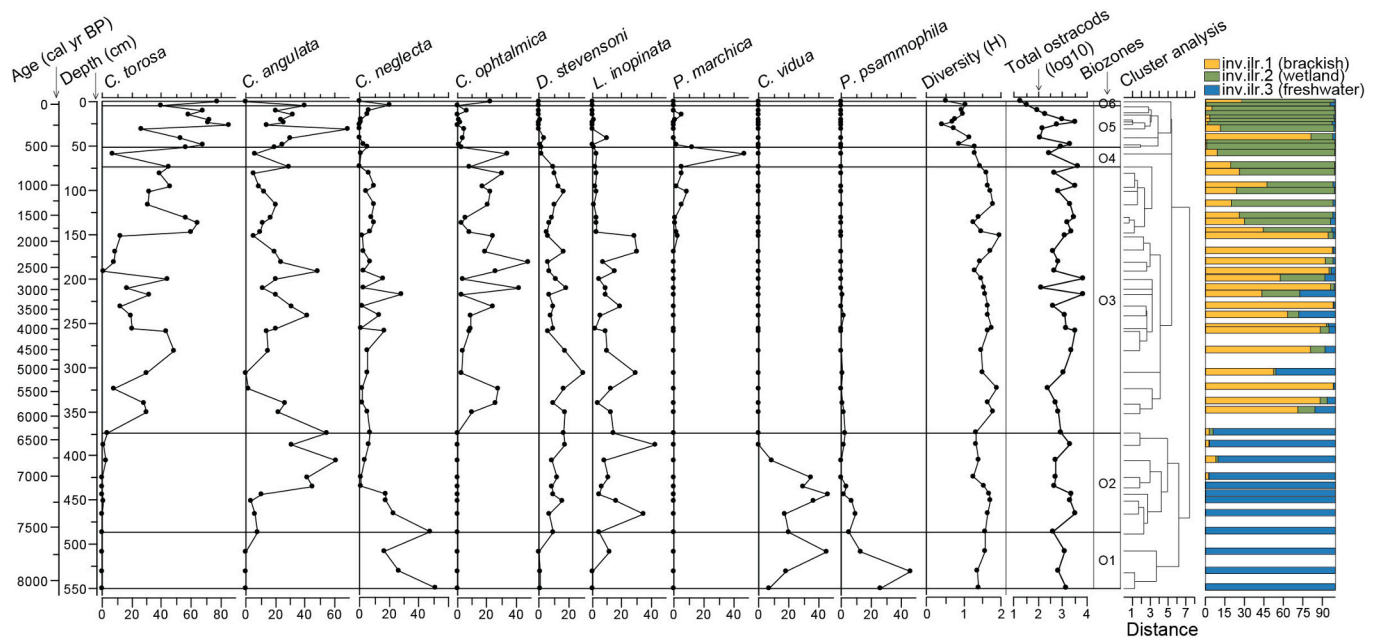


Fig. 5. Relative ostracod abundances of selected species, Shannon diversity index (H) calculated in PAST (Hammer et al., 2001), total ostracod abundances (log10) n° valves/1 g of dry sieved sediment), ostracod biozones obtained from the cluster analysis, dendrogram of the cluster analysis, and stacked chart of the inverse isometric log ratio (inv.ilr.) variables. The species that are shown were used in the statistics.

while *C. vidua*, *P. psammophila*, *P. marchica*, *H. chevreuxi*, and *M. cordata* are subordinated. Other species have <10% relative abundances in the sediment core. *Notodromas monacha* occurs in two samples, and *C. kingsleii* in one sample.

4.4. Multivariate analysis of ostracod assemblages

Based on the cluster analysis performed on the clr-transformed ostracod percentage frequency matrix, six ostracod zones have been identified at a similarity distance of ca. 5 (Fig. 5).

The first ostracod zone, O1 (550–487 cm, 8100–7500 cal yr BP), represents the oldest part of the sediment core. Samples are characterized by fragmented mollusc shells, organic detritus, *Chara* gyrogonites and stems (talli), and crust-like botryoidal carbonates. Ostracods are abundant and dominated by *C. neglecta*, *C. vidua*, and *P. psammophila*, while *L. inopinata* and *D. stvensoni* are subordinated. Less abundant species are *I. cf. gibba*, *Ilyocypris* sp., *Ilyocypris* sp. (juveniles), *C. bispinosa*, *H. madaraszsi*, and *H. chevreuxi*. *C. angulata* appears for the first time at the top of the zone. The average Shannon diversity index (*H*) is 1.5 (at a scale of 0.0 to 2.0). The adult/juvenile ratio is lower at the core bottom and gradually increases upwards. Valves of the larger species *H. madaraszsi* and *H. chevreuxi* are mostly fragmented.

Ostracod zone O2 (487–374 cm, 7500–6300 cal yr BP) is characterized by calcareous sediment with less organic detritus. Gastropod shells and operculums are numerous and less fragmented. Dominant ostracod species are *C. neglecta*, *C. angulata*, *L. inopinata*, and *C. vidua*, while *D. stvensoni* and *P. psammophila* are secondary. Less abundant species are *P. marchica*, *Pseudocandona* sp. (juveniles), *C. ophtalmica*, *I. cf. gibba*, *I. bradyi*, *Ilyocypris* sp. (juveniles), *H. madaraszsi*, and *H. chevreuxi*. *C. torosa* occurs for the first time in sample 451–452 cm. Its proportions gradually increase towards the top of the zone O2 and are accompanied by the less abundant *H. salina*. The average *H* is 1.5.

Ostracod zone O3 (374–74 cm, 6300–770 cal yr BP) is the most numerous and diverse (average *H* = 1.6). The ostracod community is dominated by *C. torosa* and *C. angulata*, accompanied by relatively less abundant *C. neglecta*, *C. ophtalmica*, *D. stvensoni*, and *L. inopinata*. *C. vidua* disappears within this zone, while *P. psammophila* gradually decreases from the bottom of the zone O1 towards the zone O3. *H. salina*

occurs only in three samples at the bottom of the zone and later disappears. Larger ostracod species *H. madaraszsi* and *H. chevreuxi* are more abundant and better preserved. New species, such as *P. marchica*, *C. ovum*, and *M. cordata*, occur towards the top of the zone. Molluscs are mostly represented by *B. tentaculata*, *Stagnicola* sp., *Planorbis* sp., and *Psidium* sp. Large diatoms of *Campylodiscus* sp. were also found.

Ostracod zone O4 (74–51 cm, 770–500 cal yr BP) is characterized by only one sample (59–60 cm) in which previously dominant species *C. torosa* and *C. angulata* suddenly decline, as well as *C. neglecta*, *D. stvensoni*, and *L. inopinata*. Over this time, the abundance of *P. marchica* and *C. ophtalmica* increases. Species diversity is lower than in the previous zone (*H* = 1.3).

Ostracod zone O5 (51–5 cm, 500–30 cal yr BP) is marked by a declining species diversity (lowest *H* = 0.4 at around 250 cal yr BP). Dominant ostracod species are again *C. torosa* and *C. angulata*, while *C. neglecta* and *C. ophtalmica* are subordinated. *D. stvensoni*, *L. inopinata*, and *P. marchica* disappear towards the top. The decline of species diversity coincides with the occurrence of the topmost organic-rich sediment (Fig. 3).

The last zone O6 (5–0 cm, last 30 years) represents the topmost part of the sediment core VB-2, made of dark brown organic mud. Species diversity is very low (*H* = 0.7), ostracods are scarce, and only two species are present, *C. torosa* and *C. ophtalmica*. Valves of *C. torosa* are smoothed throughout the core, except for the last ca. 500 years (51–0 cm) when noded forms also occur.

Analysis of the compositional biplot (Fig. 6) showed that *C. vidua* has a moderately strong positive loading (0.5), while *C. torosa* has a strong negative loading (−0.6) on principal component 1 (PC1). PC1 accounted for ca. 47% of the total variance and is associated with salinity, separating freshwater and brackish assemblages. *D. stvensoni* and *L. inopinata* have moderately strong (≥ 0.5), *C. ophtalmica* weak to moderate (0.3), and *P. marchica* moderate negative (−0.3) loadings on principal component 2 (PC2). PC2 explained ca. 18% of the total variance and reflects a secondary environmental factor probably related to lake shallowing, vegetation expansion, and eutrophication. The inverse transformation of the PC1 and PC2 scores divided the compositions into three ecological groups (inverse isometric log ratio variables, inv.ilr.): freshwater, brackish, and wetland (Fig. 5).

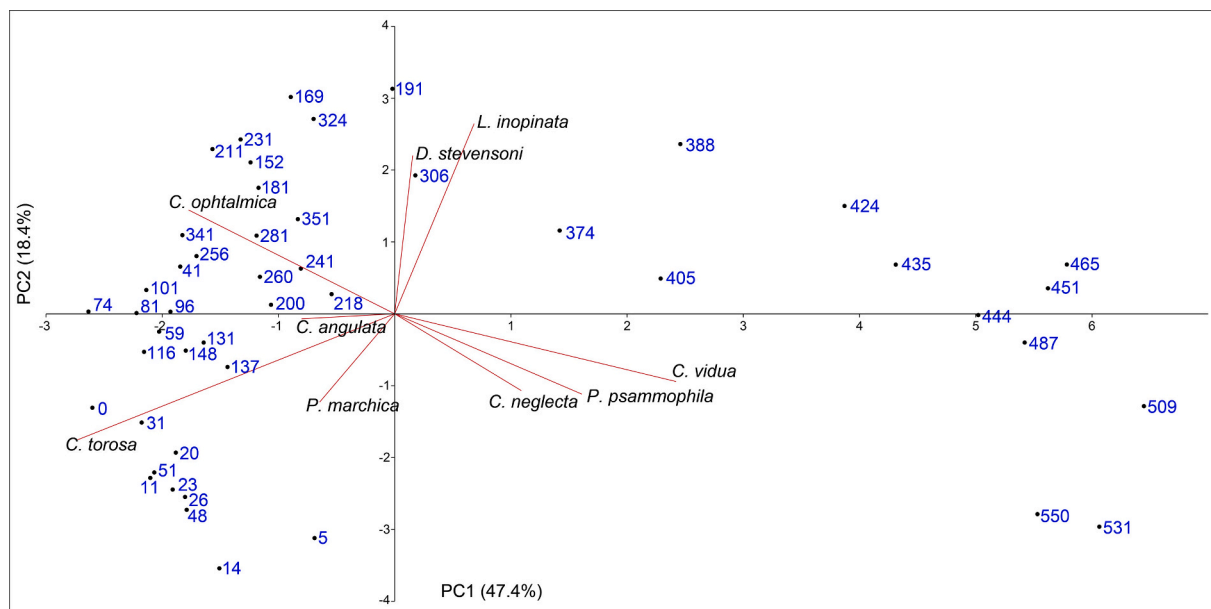


Fig. 6. Compositional biplot showing the distribution of species along the first two principal components (PC1 and PC2). Points represent sediment core samples (blue labels), while red lines indicate species loadings. PC1 reflects the salinity gradient, and PC2 could be reflecting processes associated with lake succession (lower lake levels, expansion of vegetation, eutrophication). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

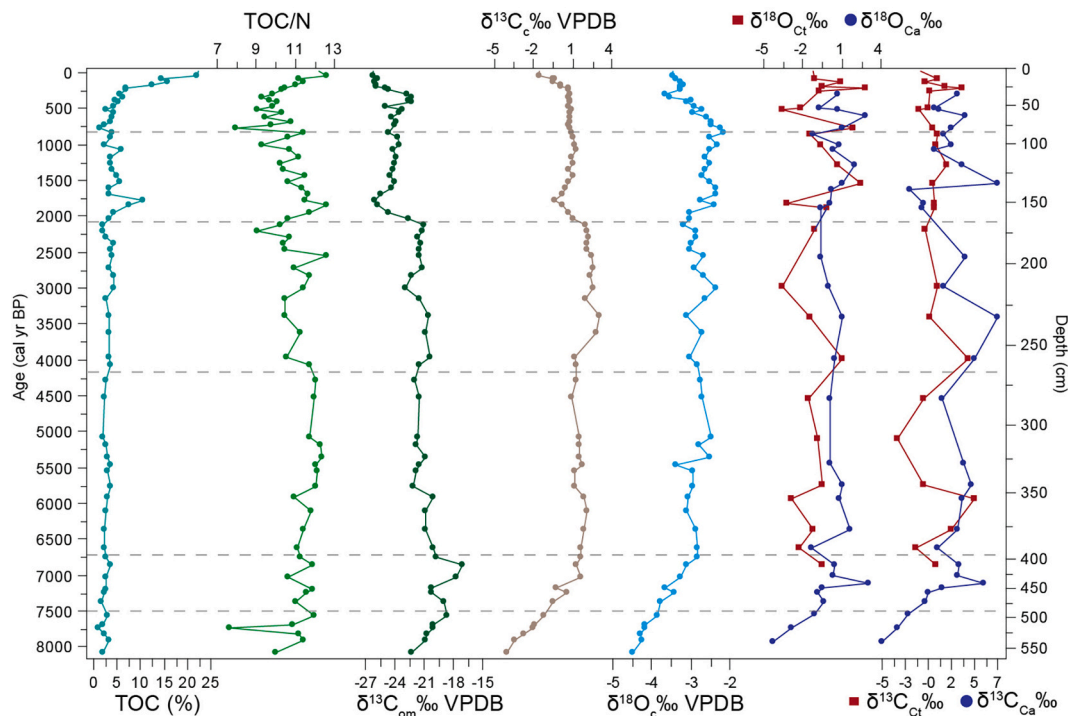


Fig. 7. Proxy data from Lake Velo Blato: total organic carbon (TOC), and total organic carbon/nitrogen ratio (TOC/N) after Ilijanić et al. (2022), carbon isotope composition of organic matter ($\delta^{13}\text{C}_{\text{om}}$), stable isotope composition of lacustrine carbonate ($\delta^{13}\text{C}_{\text{c}}$ and $\delta^{18}\text{O}_{\text{c}}$), stable isotope composition of ostracods *Cyprideis torosa* ($\delta^{18}\text{O}_{\text{Ct}}$, $\delta^{13}\text{C}_{\text{Ct}}$) and *Candona angulata* ($\delta^{18}\text{O}_{\text{Ca}}$, $\delta^{13}\text{C}_{\text{Ca}}$). The TOC/N is given in mass ratios. The dashed lines highlight the major intervals discussed in the text. Stable isotope data provided by BGS © UKRI 2026.

4.5. Stable isotope analysis

Geochemical and isotope data from sediment core VB-2 are shown in Fig. 7. The $\delta^{13}\text{C}_{\text{om}}$ varies between -26.2‰ and -17.1‰ (av. $-22.5 \pm 2.2\text{‰}$), shows an increasing trend in the lower part of the core up to -17.1‰ , after which it decreases to -21.3‰ and remains fairly constant between 6700 and 2100 cal yr BP. This is followed by generally decreased values, especially between 2100 and 1500 cal yr BP, and in the uppermost part of the sediment core, which corresponds to higher TOC values (Fig. 7).

The $\delta^{18}\text{O}_{\text{c}}$ ranges from -4.5 to -2.2‰ (av. $-3.0 \pm 0.5\text{‰}$), and displays a generally increasing trend until 840 cal yr BP, and then decreases towards the top, with a prominent peak around 350 cal yr BP. The $\delta^{13}\text{C}_{\text{c}}$ averages $+0.7 \pm 1.4\text{‰}$, ranging from -4.1 to $+3.0\text{‰}$, and displays a trend similar to the $\delta^{18}\text{O}_{\text{c}}$, with a strong positive correlation ($r = 0.7$, $p < 0.05$). This trend changes around 2100 cal yr BP, when $\delta^{13}\text{C}_{\text{c}}$ starts to decrease and correlates with lower $\delta^{13}\text{C}_{\text{om}}$, while $\delta^{18}\text{O}_{\text{c}}$ increases further. Correlation between $\delta^{13}\text{C}_{\text{c}}$ and $\delta^{13}\text{C}_{\text{om}}$ is weak positive ($r = 0.3$, $p < 0.05$).

The $\delta^{18}\text{O}_{\text{Ca}}$ ranges from -4.3 to $+3.0\text{‰}$ (av. $0.1 \pm 1.4\text{‰}$), with a generally increasing trend from the bottom towards the top of the sediment core. The $\delta^{13}\text{C}_{\text{Ca}}$ ranges from -4.9 to $+7.0\text{‰}$ (av. $1.7 \pm 2.7\text{‰}$) and shows a strong positive correlation to the $\delta^{18}\text{O}_{\text{Ca}}$ ($r = 0.8$, $p < 0.05$). The $\delta^{18}\text{O}_{\text{Ct}}$ ranges from -3.6 to $+2.8\text{‰}$ (av. $-0.8 \pm 1.7\text{‰}$), and the $\delta^{13}\text{C}_{\text{Ct}}$ varies between -3.4 and $+4.6\text{‰}$ (av. $0.4 \pm 1.8\text{‰}$). Although the correlation between $\delta^{18}\text{O}_{\text{Ct}}$ and $\delta^{13}\text{C}_{\text{Ct}}$ is weak and not statistically significant ($r = 0.3$, $p > 0.05$), both isotopic records exhibit a generally increasing trend towards the top of the sediment core. Isotopic compositions of ostracod shells are most depleted in the early Middle Holocene, show enrichment during the Middle to Late Holocene, and display increased variability in the last 2000 cal yr BP.

5. Discussion

5.1. Modern limnology

The dominance of chloride and sodium in the lake water highlights the strong marine influence on the lake's chemistry, primarily through sea salt aerosols. Even during winter, when dilution by freshwater is highest, marine-derived ions remain dominant, indicating that sea spray deposition is a persistent and significant source of solutes. In contrast, stable water isotopes provide information on the source of lake water itself. Winter lake water isotopic composition plot close to the intersection of the local evaporation line (LEL) with the local meteoric water line (LMWL) (Fig. 2), suggesting that lake recharge is dominated by meteoric inputs (direct precipitation and groundwater). Given the shallow and well-mixed nature of the lake, a substantial contribution from seawater intrusion through the karstified bedrock would be expected to shift the lake water isotopic composition away from the LMWL towards more marine values, particularly during winter when evaporative enrichment is minimal. The absence of such a shift indicates that direct seawater intrusion is unlikely to be a dominant control on the lake's hydrological balance.

The contrasting seasonal patterns of calcium and magnesium point to the combined effects of marine and terrestrial sources. While magnesium largely follows the dilution of other marine ions, the relative stability or slight increase of calcium concentrations in winter reflects additional input from karstic groundwater, which is characteristically rich in calcium. An average pH of 8.4 indicates that dissolved inorganic carbon (DIC) is dominated by HCO_3^- (Appelo and Postma, 2005). The positive $\text{SI}_{\text{calcite}}$ throughout the year, especially during summer, suggests conditions favourable for carbonate precipitation (Appelo and Postma, 2005).

The offset of Lake Velo Blato samples from the LMWL and their alignment along the local evaporation line confirm that evaporation is a key process controlling the isotopic composition of lake water year-

round and is strongest in the summer, as reflected by the summer samples plotting furthest along the LEL (Fig. 2). During winter, evaporation is likely enhanced by Bora winds, which lower the humidity of the air above the lake water surface, despite the lower temperatures. This explains the position of winter lake water samples on the LEL (Fig. 2). However, since our samples represent seasonal snapshots of lake water isotopic composition, the LEL should be regarded as an approximation reflecting seasonal enrichment rather than a fully resolved evaporation model. The marked isotopic excursion observed in Lake Velo Blato during the summer highlights its sensitivity to hydroclimate changes.

5.2. Paleolimnological proxies

5.2.1. Interpretation of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of endogenic calcite and ostracods

The isotopic composition of surrounding rocks defines potential limestone and flysch marl end members, suggesting possible mixing with samples of lake carbonates (Fig. 8). Most samples cluster near the limestone, indicating a chemical signature of the carbonate bedrock and/or minimal detrital input from flysch marls. This is supported by SEM analysis of the $<80\ \mu\text{m}$ size fraction, which showed that most samples are composed of authigenic calcite covering minor tube-like biological fragments (Fig. 3a). Greater detrital influence is observed in lowermost samples and SEM analysis in this part of the core showed authigenic calcite covering larger detrital grains such as dolomite (Fig. 3b). Detrital dolomite is present only as an accessory mineral in the lower part of the sediment core (Ilijanić et al., 2022), where significant contamination from this marine-derived phase would have shifted the bulk carbonate isotopic signal towards higher values. This is inconsistent with the lowest $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of bulk carbonate and ostracods in the entire record (Fig. 7). Therefore, flysch marls are likely the predominant contaminant. Indeed, a previous study in Lake Velo Blato found higher magnetic susceptibility and higher content of clay minerals (smectite, illite, kaolinite) originating from flysch marls in the lower part of the sediment core, suggesting higher influx from the catchment and wetter climate conditions (Ilijanić et al., 2022). Thus, the lower $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of bulk carbonates could be the result of both past

climate changes and detrital contamination.

In hydrologically closed lakes, oxygen isotopic ratios are controlled by evaporation, temperature, seasonality, the amount effect, and changes in precipitation sources (Leng and Marshall, 2004; Zanchetta et al., 2007; Roberts et al., 2008). Aside from evaporation (Section 5.1), carbonate precipitating from lake water is affected by temperature-dependent fractionation between water and calcite (α_{w-c}), which has a gradient of around $-0.2\text{‰}/^{\circ}\text{C}$ in the range of ca. $10\text{--}30\ ^{\circ}\text{C}$ (Kim and O'Neil, 1997). However, temperature also affects the $\delta^{18}\text{O}$ of precipitation ($\delta^{18}\text{O}_p$), with a gradient of ca. $0.2\text{‰}/^{\circ}\text{C}$ established in Mediterranean stations (Bard et al., 2002; Zanchetta et al., 2012; Surić et al., 2025). This suggests that shifts in $\delta^{18}\text{O}_p$ due to changes in air temperature would likely cancel out the calcite-water fractionation. Thus, the $\delta^{18}\text{O}$ of endogenic calcite and ostracods primarily reflects changes in effective moisture (P/E), possibly modulated by changes in the “amount effect” (Bard et al., 2002; Bar-Matthews et al., 2000; Surić et al., 2025) and shifts in precipitation sources (Bard et al., 2002). Accounting for possible detrital contamination, higher $\delta^{18}\text{O}_c$ values likely indicate lower P/E and reduced detrital input, whereas lower $\delta^{18}\text{O}_c$ values seem to be associated with higher detrital input and indirectly imply higher P/E. The $\delta^{18}\text{O}$ of ostracods exhibits substantially greater variability than the $\delta^{18}\text{O}$ record of endogenic calcite (Figs. 7 and 9), reflecting species-specific and seasonally restricted calcification that captures short-term hydrological extremes. Nevertheless, the overall trend of ostracod $\delta^{18}\text{O}$ closely parallels that of calcite, especially in the basal part (Fig. 7), thus providing an independent proxy for paleoclimate changes.

Carbon isotope composition of endogenic calcite ($\delta^{13}\text{C}_c$) reflects the carbon isotopic composition of dissolved inorganic carbon ($\delta^{13}\text{C}_{\text{DIC}}$) in lake waters (Leng and Marshall, 2004). The primary controlling factors of $\delta^{13}\text{C}_{\text{DIC}}$ in lakes are the isotopic composition of the inflowing waters, CO_2 exchange with the atmosphere, and the photosynthesis/respiration of aquatic plants (Leng and Marshall, 2004). Inflowing waters (groundwaters and rivers) usually have lower $\delta^{13}\text{C}_{\text{DIC}}$ originating from the leaching of soil CO_2 . However, in karstic regions, groundwaters can carry higher $\delta^{13}\text{C}_{\text{DIC}}$ coming from the dissolution of carbonate rocks (Andrews et al., 1997; Leng et al., 1999). Today, Lake Velo Blato is

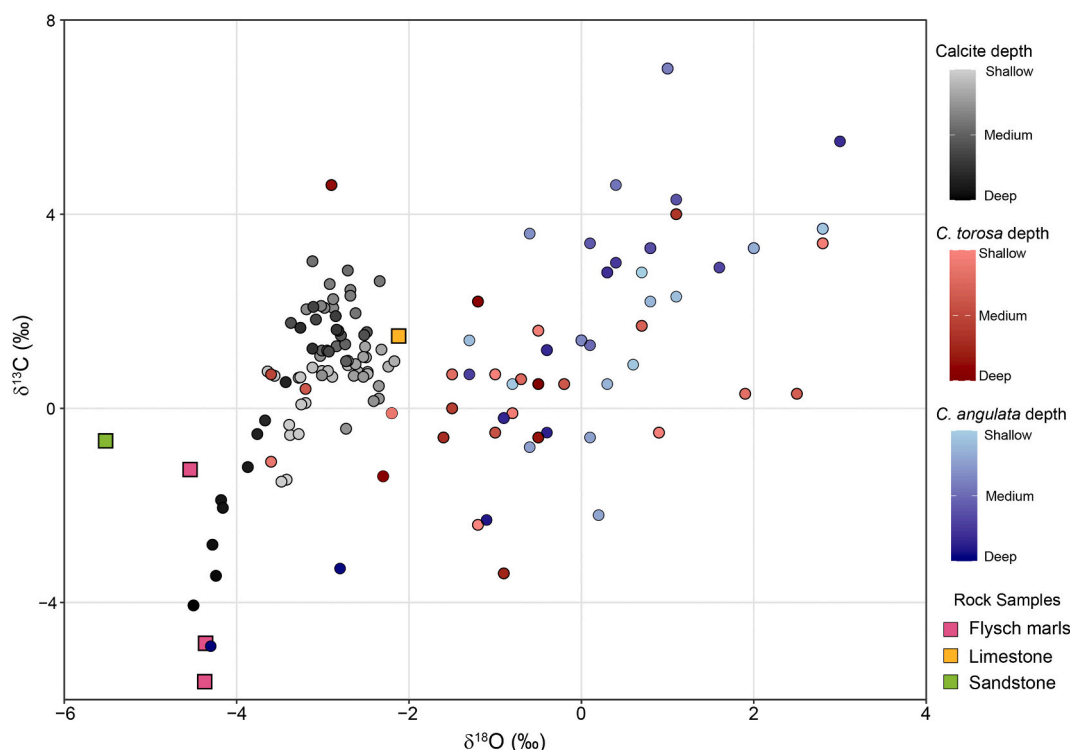


Fig. 8. The stable isotope ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) composition of lake carbonates, ostracods, and rock samples collected from the catchment (BGS © UKRI 2026).

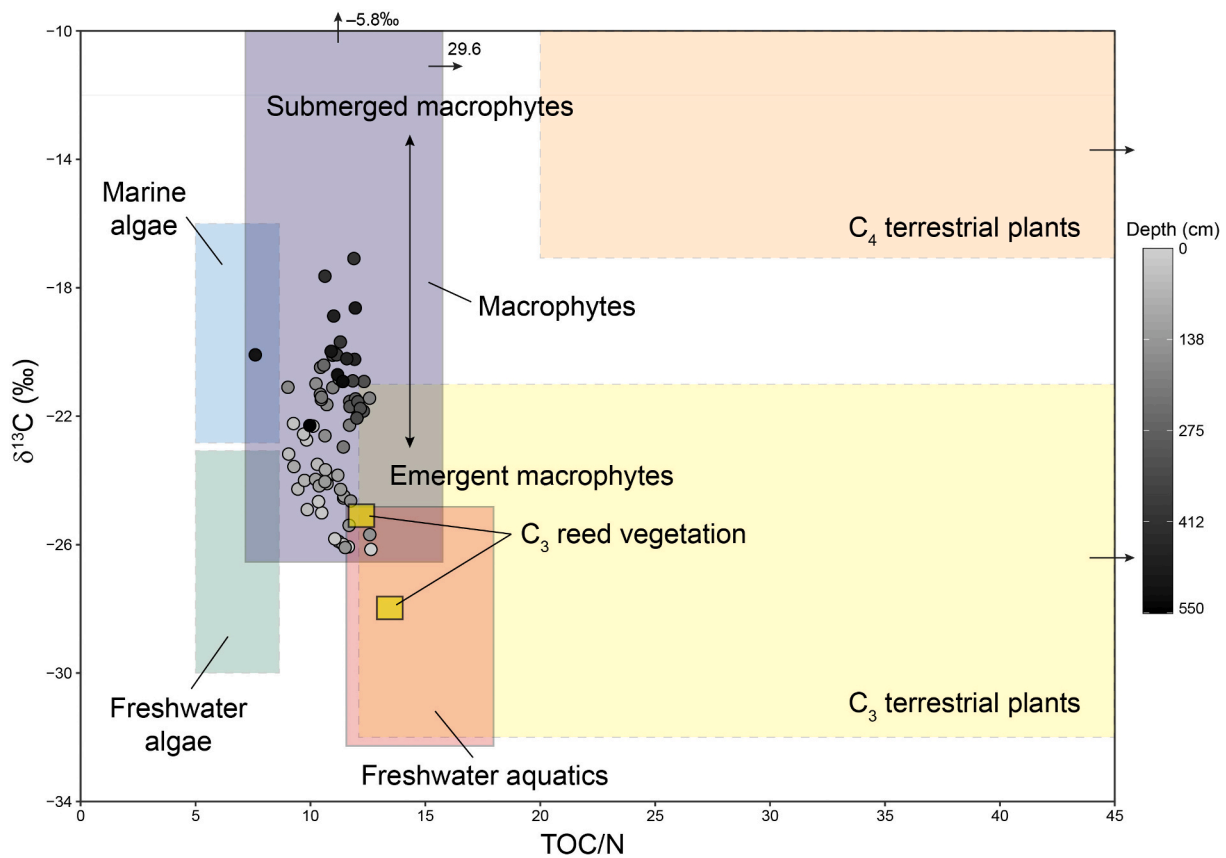


Fig. 9. The $\delta^{13}\text{C}_{\text{om}}$ versus TOC/N scatter plot showing a mixed source of organic matter coming from phytoplankton, macrophytes, and emergent vegetation (reeds). The reference fields for freshwater algae, marine algae, and C3-C4 terrestrial plants are taken from Lamb et al. (2006), with additional data for freshwater aquatics (macrophytes) and C₃ reed vegetation by Mackie et al. (2005), Aichner et al. (2010), and Khan et al. (2015). The $\delta^{13}\text{C}_{\text{om}}$ provided by BGS © UKRI 2026.

characterized by wetland vegetation and is surrounded by barren karst terrain (Fig. 2), with limited soils in the catchment. Therefore, carbon cycling in the lake is primarily associated with limestone dissolution, lake productivity, and the exchange of CO_2 with the atmosphere. The high positive correlation ($r = 0.7$) between $\delta^{13}\text{C}_c$ and $\delta^{18}\text{O}_c$ in the sediment core suggests similar controlling mechanisms for both isotopes and is often used as an indicator of hydrological closure (Talbot, 1990; Li and Ku, 1997). Thus, intervals with higher $\delta^{13}\text{C}_c$ likely reflect a higher degree of CO_2 exchange with the atmosphere, more ^{12}C consumption through photosynthetic activity, and hard waters from the karst bedrock. In contrast, intervals with lower $\delta^{13}\text{C}_c$ are probably associated with higher input from flysch deposits (Fig. 8) and higher productivity of organic matter. Similar to $\delta^{18}\text{O}$, the $\delta^{13}\text{C}$ of ostracods shows greater variability than the $\delta^{13}\text{C}$ of endogenic calcite (Figs. 7 and 8) due to the microenvironmental conditions at the sediment-water interface, such as decomposition of the organic matter and methanogenesis (Roberts et al., 2020; Curry et al., 1997).

5.2.2. Sources of organic matter

Without significant input of terrestrial organic matter from the catchment, the carbon isotope composition of organic matter ($\delta^{13}\text{C}_{\text{om}}$) from Velo Blato lake sediments can be used as a tracer of past changes in the aquatic carbon cycle (Leng et al., 2005). The $\delta^{13}\text{C}_c$ and $\delta^{13}\text{C}_{\text{om}}$ exhibit a weak positive correlation ($r = 0.3$, $p < 0.05$), indicating partially linked controls. If the organic matter and calcite originated from the same lacustrine DIC source, the $\delta^{13}\text{C}_{\text{om}}$ and $\delta^{13}\text{C}_c$ would show a strong positive correlation (Zanchetta et al., 2018, 2022). Such a correlation exists between 8100 and 6800 cal yr BP and from 2100 cal yr BP until present (Fig. 7), reflecting variable $\delta^{13}\text{C}_{\text{DIC}}$ throughout the Holocene. The TOC/N varies between 7.6 and 12.6 (Ilijanović et al., 2022),

suggesting mixed sources of organic matter (Meyers and Teranes, 2001). When plotting the $\delta^{13}\text{C}_{\text{om}}$ versus TOC/N values of lacustrine organic matter, using a published broader dataset by Lamb et al. (2006) and aquatic vegetation end members (Mackie et al., 2005; Aichner et al., 2010; Khan et al., 2015) (Fig. 9), it is possible to differentiate the main sources of organic matter in lake sediments. In general, samples from lower parts of the sediment core display higher $\delta^{13}\text{C}_{\text{om}}$ and trend towards submerged macrophytes, while samples from upper parts show lower $\delta^{13}\text{C}_{\text{om}}$ values and trend towards emergent macrophytes and reed vegetation. In coastal environments (e.g., estuaries, tidal marshes, lagoons, and isolation basins), the higher $\delta^{13}\text{C}_{\text{om}}$ is usually associated with more ^{13}C -enriched DIC coming from marine intrusions (Lamb et al., 2006; Mackie et al., 2005; Wilson et al., 2024). However, in Velo Blato lake sediments, the highest $\delta^{13}\text{C}_{\text{om}}$ values occur in ostracod zones O1 and O2, where freshwater species prevail (*C. neglecta*, *C. vidua*, *P. psammophila*), thus unlikely reflecting marine intrusion. Furthermore, the $\delta^{13}\text{C}_{\text{om}}$ ranges between -22.3‰ and -18.6‰ , which fits well with macrophyte ranges published in the literature. For example, Aichner et al. (2010) reported bulk $\delta^{13}\text{C}$ values from -18.1‰ to -5.8‰ in submerged aquatic macrophytes, while Herzschuh et al. (2010) reported values from -23‰ to -0‰ . Such enriched $\delta^{13}\text{C}$ of aquatic macrophytes is related to their ability to utilise HCO_3^- during periods when CO_2 is limited (Hollander and McKenzie, 1991). Thus, the basal part of the sediment core with higher $\delta^{13}\text{C}_{\text{om}}$ coupled with higher $\delta^{13}\text{C}_c$ most likely reflects progressive $\delta^{13}\text{C}_{\text{DIC}}$ enrichment from karst and higher evaporation (CO_2 outgassing). In contrast, lower $\delta^{13}\text{C}_{\text{om}}$ and $\delta^{13}\text{C}_c$ after ca. 2100 cal yr BP likely reflect increased emergent macrophyte and reed productivity (Fig. 9), with enhanced sediment respiration supplying ^{12}C -enriched CO_2 that lowers the overall $\delta^{13}\text{C}_{\text{DIC}}$, typical of organic-rich shallow lakes (Leng et al., 2005).

5.3. Paleoenvironmental and paleoclimatic interpretation

5.3.1. Middle Holocene (8100–4200 cal yr BP)

The onset of sedimentation in Lake Velo Blato corresponds to the early Middle Holocene (ca. 8100 cal yr BP), when global sea level was approximately 12 m lower than today (Lambeck et al., 2014). Between 8100 and 7500 cal yr BP, the ostracod assemblage is composed exclusively of freshwater species (*C. neglecta*, *C. vidua*, *P. psammophila*), corresponding to the ostracod biozone O1 (Fig. 5). Shannon diversity index is relatively high ($H = 1.5$), and adult to juvenile ratio is lower at the bottom and progressively increases towards the top of the zone, while larger species (e.g., *H. madaraszii*, *H. chevreuxi*) and gastropod shells are mostly fragmented. The relatively high number of juveniles compared to the adult valves suggests dynamic environmental conditions at the beginning of the record (Boomer et al., 2003; Lord et al., 2012). The stable isotope composition of calcite ($\delta^{18}\text{O}_c$ and $\delta^{13}\text{C}_c$) is the lowest in the record (Fig. 7) and possibly carries a signature of the flysch marls found in the catchment (Fig. 8), and thus cannot be readily interpreted as a paleoclimate proxy but rather as a proxy for higher detrital input. However, the lowest $\delta^{18}\text{O}_{Ca}$ and $\delta^{13}\text{C}_{Ca}$ of ostracod *Candona angulata* also occur in the basal part (Fig. 7), which indeed implies generally wetter climate conditions (higher P/E). This agrees with relatively lower temperatures and higher precipitation (peak between 8000 and 7500 cal yr BP) reconstructed from pollen in marine sediments from the Adriatic Sea (Comboureu-Nebout et al., 2013) and other Mediterranean paleoclimate records (Razum et al., 2021; Bar-Matthews et al., 2003; Roberts et al., 2008; Zanchetta et al., 2007; Lacey et al., 2015) (Fig. 10).

A period between 7500 and 6300 cal yr BP is marked by the first appearance of typical brackish ostracods in zone O2 (*C. torosa*, *C. angulata*, *H. salina*), which is interpreted as transitional (Fig. 5). Changes in salinity can also be inferred from the relative importance of the back-transformed ilr variables, from inv. ilr. 3 (freshwater) to inv. ilr. 1

(brackish) (Fig. 5). The $\delta^{18}\text{O}_c$ and $\delta^{13}\text{C}_c$ gradually increase between 8100 and 6700 cal yr BP (Fig. 7), probably reflecting the progressive ^{18}O - and ^{13}C -enrichment due to the lower P/E, increased CO_2 -outgassing, as well as lower detrital input from flysch marls. This trend is also seen in the $\delta^{18}\text{O}_{Ca}$ and $\delta^{13}\text{C}_{Ca}$ of ostracods, thus supporting the paleoclimate interpretation. The inferred lower effective rainfall (P/E) corresponds to the increasing aridity following the early Middle Holocene pluvial period (Comboureu-Nebout et al., 2013). A similar aridification trend was inferred from speleothem calcite from a nearby Modrić Cave on the eastern Adriatic Coast (Surić et al., 2025), as well as from Manita Peć Cave located in the Velebit Mts. (Surić et al., 2001). Increased salinity inferred from ostracod assemblages can be associated with the sea level rise and marine intrusion through karst (see Ilijanić et al., 2022), evaporative concentration of salts in summer (Tables 1 and 2), and the transport of sea salt aerosols, as lake water would be less diluted.

Between 8100 and 6800 cal yr BP, the TOC/N increases from 10 to 12, while $\delta^{13}\text{C}_{\text{com}}$ increases from -22.3‰ to -18.6‰ (Fig. 7), indicating higher proportions of aquatic macrophytes (Fig. 9). This is supported by high concentrations of organic detritus, large diatoms *Campylodiscus* sp., and charophyte remains found in the basal part during the ostracod analysis. Thus, relatively high $\delta^{13}\text{C}_{\text{com}}$ values in the basal, freshwater part cannot be attributed to marine intrusion through karstified bedrock, but rather to the progressive ^{13}C -enrichment of the lake water DIC. For example, Aichner et al. (2010) reported relatively high $\delta^{13}\text{C}$ values of the macroalga *Chara* sp., ranging between -16.8‰ and -13.1‰ , and generally higher values of submerged macrophytes (-18.1‰ to -5.8‰). The $\delta^{13}\text{C}$ values of aquatic macrophytes are frequently within the range of C_3 plants, but changes in lake water chemistry (e.g., high pH, alkalinity, and limited CO_2) can lead to more positive $\delta^{13}\text{C}$ values (Hollander and McKenzie, 1991; Ortiz et al., 2021). This reflects the ability of aquatic macrophytes to utilise bicarbonate during photosynthesis, as HCO_3^- is about 10‰ more enriched in $\delta^{13}\text{C}$ than CO_2 (Romanek

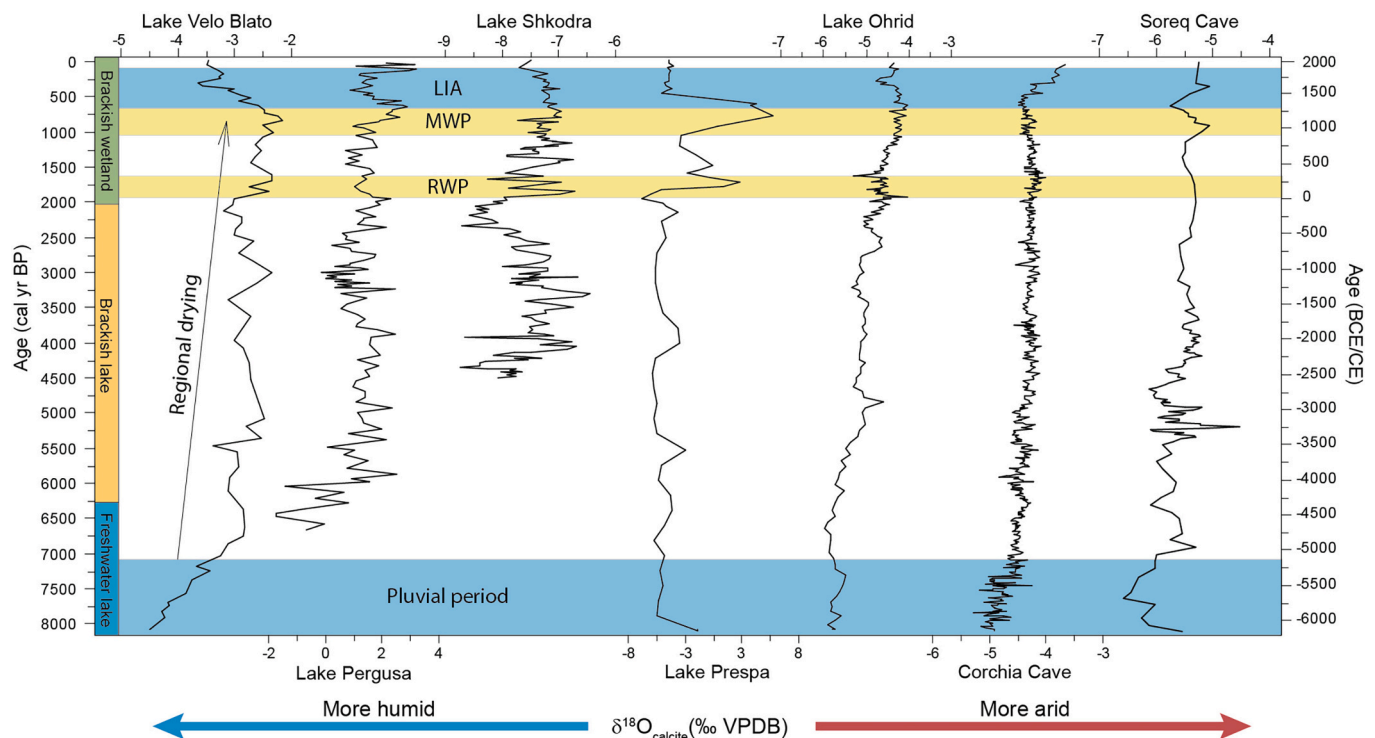


Fig. 10. Comparison of $\delta^{18}\text{O}$ record of endogenic calcite from Lake Velo Blato with other lacustrine and speleothem records from the Mediterranean region (Lake Pergusa, Zanchetta et al., 2007; Lake Shkodra, Zanchetta et al., 2012; Lake Prespa, Leng et al., 2013; Lake Ohrid, Lacey et al., 2015; Corchia Cave, Bajo et al., 2016; Zanchetta et al., 2007; Soreq Cave, Bar-Matthews et al., 2003). Pronounced wetter periods in Lake Velo Blato are marked in blue, while drier periods are marked in yellow. Time spans for the wet and dry periods: Pluvial period by Zhornyak et al. (2011), Roman Warm Period (RWP), Medieval Warm Period (MWP), and Little Ice Age (LIA) by Ljungqvist (2010). The $\delta^{18}\text{O}$ data from Velo Blato are provided by BGS © UKRI 2026 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 1992; Leng and Marshall, 2004).

The late Middle Holocene (6300–4200 cal yr BP) is characterized by true brackish conditions, as freshwater ostracods are replaced by typical brackish species in the zone O3 (Fig. 5). Moreover, all of the proxies continue to increase, except for $\delta^{13}\text{C}_{\text{om}}$, which starts to decrease from 6300 cal yr BP (Fig. 7) due to the overall higher productivity. Ostracod species diversity is highest in the zone O3 (Fig. 5), implying stable environmental conditions due to reduced stress (changes in salinity, water depth, temperature, and oxygen levels), which enabled the growth of the ostracod population. The stable environmental conditions roughly coincide with a substantial decrease in the rate of global sea level rise at around 6700 cal yr BP (Lambeck et al., 2014), supporting the interpretation that higher $\delta^{18}\text{O}_{\text{c}}$ and $\delta^{13}\text{C}_{\text{c}}$ originate from evaporated lake waters, rather than from more marine intrusion through karst. This interpretation also agrees with the increasing aridity pattern observed in other Mediterranean lakes (Roberts et al., 2008; Zanchetta et al., 2022; Lacey et al., 2015) (Fig. 10).

5.3.2. Late Holocene (4200 cal yr BP until present)

The early Late Holocene (4200–2100 cal yr BP) is broadly marked by environmental conditions similar to those of the late Early Holocene. The so-called “4.2 ka event”, a widespread aridification event in the Mediterranean region (Bini et al., 2019), cannot be adequately addressed due to the lower chronological resolution. However, alternate higher/lower salinities might have occurred at the Middle-Late Holocene transition, evidenced by pronounced shifts in relative abundances of *C. torosa*, when salinity (inv.ilr.1) was a dominant factor controlling the species distribution (Fig. 5). Thus, higher salinities are encountered between 4500 and 4000 cal yr BP, which might be due increased evaporation and sea salt aerosols. This drying is not particularly evident in the $\delta^{18}\text{O}_{\text{c}}$ and $\delta^{13}\text{C}_{\text{c}}$ of calcite, but there is a pronounced peak in $\delta^{18}\text{O}_{\text{ct}}$ and $\delta^{13}\text{C}_{\text{ct}}$ of *C. torosa* around 4000 cal yr BP (Fig. 7). Similar arid conditions around 4200 cal yr BP were inferred from ostracods in Lake Trasimeno (Marchegiano et al., 2018), from lake carbonates in Lake Shkodra (Zanchetta et al., 2012), Lake Pergusa (Zanchetta et al., 2022), and Lake Prespa (Leng et al., 2013). Bini et al. (2019) interpreted the “4.2 ka” event in the Mediterranean region as a period of reduced winter precipitation in addition to already dry summers.

A shift to lower $\delta^{13}\text{C}_{\text{c}}$ values occurs between 2100 and 1600 cal yr BP and correlates with lower $\delta^{13}\text{C}_{\text{om}}$. This is concurrent with elevated TOC and TOC/N values in the same interval, indicating higher organic matter productivity due to higher contribution from aquatic macrophytes and *C₃* reed vegetation (Fig. 9). This interval coincides with the decline in ostracod species diversity, suggesting less favourable conditions at the lake bottom. At the same time, the primary driver of species distribution shifts from salinity (inv.ilr.1) to processes associated with lake succession, such as lower lake levels, vegetation expansion, and eutrophication (the wetland inv.ilr.3) (Fig. 5). In other words, as oxygen becomes limited, the abundance of oxygen-dependent species *D. stevensoni* and *L. inopinata* starts to decline. The emergence of aquatic vegetation is also supported by the appearance of phytophilic species *M. cordata*, accompanied by *C. ovum* (Supplementary table) in ostracod zone O4. Overall, the proxy data suggest a transition from an open lake environment into a more stagnant, organic-rich wetland. Microbial decomposition of organic matter in anaerobic conditions leads to lower $\delta^{13}\text{C}_{\text{DIC}}$, driving $\delta^{13}\text{C}_{\text{c}}$ to lower values, while $\delta^{18}\text{O}_{\text{c}}$ continues to increase due to evaporation and reaches the highest values at around 840 cal yr BP. The environmental transition between 2100 and 1600 cal yr BP corresponds closely to the Roman Warm Period (RWP), and the highest $\delta^{18}\text{O}_{\text{c}}$ values imply peak aridity during the Medieval Warm Period (MWP) (Fig. 10). The Island of Pag was inhabited during the Roman and Medieval periods, with smaller settlements, pastoralism, and salt production activities (Rogić, 1971) potentially influencing the island's environment. Archeological remains from the Roman period are predominantly linked to coastal sites, such as the remains of a maritime villa and submerged ancient ships in Caska Bay (Radić Rossi and Boetto, 2020), reflecting the

island's maritime significance. Inland areas, particularly fertile lands lying on flysch deposits, have historically been used for agriculture and sheep grazing (Rogić, 1971). Therefore, localized human impact on freshwater reservoirs, such as Lake Velo Blato, may have occurred and interacted with climatic signals (e.g., through lake water extraction), and this possibility is considered here as a working hypothesis. However, the available evidence suggests that the pronounced peak aridity observed in the VB-2 sediment core is more consistent with regional climatic drying.

Following 840 cal yr BP, $\delta^{18}\text{O}_{\text{c}}$ trends to lower values and reach a minimum in the Late Holocene at around 350 cal yr BP, suggesting wetter conditions during the Little Ice Age (Fig. 10). During that time, there may have been a temporary restoration to more open water conditions, as suggested by increasing $\delta^{13}\text{C}_{\text{om}}$ and lower TOC/N (Fig. 7). The lake freshening coincides with the occurrences of noded valves of *C. torosa* (Fig. 4a), which is often used as an indicator of lower salinity (Marco-Barba et al., 2013; van Harten, 1975). Wetter climate conditions during LIA have also been inferred from other sites along the Eastern Adriatic Coast, e.g., from speleothem $\delta^{18}\text{O}$ from Modrić Cave (Rudžka et al., 2012), and a lake sediment $\delta^{18}\text{O}$ record from the Prokljan Lake (Smrkulj et al., 2025). Enhanced precipitation and sediment erosion are recorded in Lake Vrana on the Island of Cres during the LIA (Ilijanić et al., 2024). Furthermore, multiproxy data from a marine core from Modrić Bay imply maximum erosion from the catchment during the LIA, associated with intensive deforestation during the Venetian and Ottoman rules (Surić et al., 2025; Hasan, 2017). Records from the Western Adriatic Coast (Italy) suggest similar climatic conditions during the LIA, e.g., increased sea storm frequencies in Venice (Camuffo et al., 2000), and high frequencies of turbidity-tolerant foraminifera, implying enhanced rainfall and river runoff (Piva et al., 2008). In the northern Adriatic, a speleothem-based temperature reconstruction indicates that one of the coolest periods in the Holocene occurred during the LIA (Frisia et al., 2005). Therefore, the Velo Blato record corroborates that the Little Ice Age on the eastern Adriatic, as well as the wider Adriatic Region, was characterized by cooler and wetter climatic conditions.

Following the LIA, $\delta^{18}\text{O}_{\text{c}}$ values show an initial shift towards higher values, while the uppermost part of the core is characterized by generally lower $\delta^{18}\text{O}_{\text{c}}$ values. Although the resolution of the age-depth model decreases towards the core top, these lower values may indicate relatively wetter conditions during the most recent phase of sedimentation, in contrast to the drier conditions recorded in Lago Pergusa, Soreq Cave, Corchia Cave, and Lake Ohrid (Fig. 10). However, it could be that the isotopic composition of endogenic calcite carries a signature from the flysch marls, although less than in the basal part of the core (Fig. 8), but again associated with wetter climate conditions. Moreover, the $\delta^{13}\text{C}_{\text{om}}$ -TOC/N relationship from Velo Blato sediment core indicates a shift from mixed algal-macrophyte sources of organic matter to palustrine sources dominated by *C₃* reed community (Fig. 9). An earlier study revealed that the topmost sediment is rich in organic detritus and characterized by higher P, S, N, and TOC values, as well as occurrences of framboidal pyrites (Ilijanić et al., 2022). Furthermore, ostracod diversity sharply declines in biozones O5 and O6 (Fig. 5), while in the topmost sample (0–1 cm), only *C. torosa* and *C. ophthalmica* prevail, which could be due to their tolerance for hydrogen sulphide and hypoxia (Curry and Filippelli, 2010; Jahn et al., 1996). These geochemical and ostracod signatures indicate a highly productive, anoxic lake bottom. With continued accumulation of organic matter, oxygen depletion, and a lack of faunal diversity, the lake is likely to progress towards further infilling as part of natural lake succession, while future climatic conditions may intensify this process.

6. Conclusion

The paleoclimatic and paleoenvironmental reconstruction for coastal Lake Velo Blato covering the last 8100 cal yr BP indicates dynamic lake water conditions, from an open freshwater and brackish lake to

progressive lake infilling with wetland vegetation. Stable isotope data coupled with ostracod community analysis suggest that dynamic conditions were driven by regional climate and sea-level changes, while anthropogenic influences during the Roman and Medieval periods present a potential for future research. However, modern isotope hydrology and proxy data suggest that the climate was the dominant force behind paleoenvironmental changes, from wetter early Middle Holocene, drier Middle-Late Holocene, and again wetter late Late Holocene. In addition, this study highlights the challenges of interpreting the stable isotope data ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) of endogenic calcite in a coastal karst lake, such as disentangling marine intrusion from regional climate signals and contamination by detrital carbonates.

CRediT authorship contribution statement

Ivona Ivkić Filipović: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nikolina Ilijanić:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Conceptualization. **Ivan Razum:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Melanie J. Leng:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Jack H. Lacey:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Slobodan Miko:** Writing – review & editing, Writing – original draft, Resources, Project administration, Conceptualization. **Tamara Marković:** Writing – review & editing, Writing – original draft, Resources, Investigation, Formal analysis. **Martina Šparica Miko:** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.palaeo.2026.113702>.

Data availability

Data will be made available on request

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Supplementary material to research paper 2

Supplementary table - relative ostracod abundances in sediment core VB-2

Nr	Sample (cm)	Depth (cm)	<i>C. angulata</i>	<i>C. neglecta</i>	<i>P. marchica</i>	<i>Pseudocandona</i> sp. (juv.)	<i>C. kingsleii</i>	<i>C. torosa</i>	<i>D. stevensoni</i>	<i>H. salina</i>	<i>C. opthalmica</i>	<i>M. cordata</i>	<i>C. ovum</i>	<i>I. cf. gibba</i>	<i>I. bradyi</i>	<i>Ilyocypris</i> sp.	<i>Ilyocypris</i> sp. (juv.)	<i>C. vidua</i>	<i>L. inopinata</i>	<i>P. psammophila</i>	<i>C. bispinosa</i>	<i>H. madaraszii</i>	<i>H. chevreuxi</i>	<i>N. monacha</i>
1	0-4	0	0	0	0	0	0	78	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0
2	5-6	5	40	20	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	11-12	11	21	6	0	0	0	68	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0
4	14-15	14	32	5	5	0	0	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	20-21	20	24	1	1	0	0	72	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
6	23-24	23	26	1	0	0	0	72	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
7	26-27	26	14	0	0	0	0	86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	31-32	31	69	0	0	0	0	27	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
9	41-42	41	31	0	0	0	0	53	3	0	3	0	0	0	0	0	0	0	10	0	0	0	0	0
10	48-49	48	25	3	2	0	0	68	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
11	51-52	51	19	5	12	0	0	57	2	0	3	0	0	0	0	0	0	0	1	0	0	1	0	0
12	59-60	59	6	1	47	0	0	7	2	0	34	0	0	0	0	0	0	0	2	0	0	0	0	0
13	74-75	74	29	0	5	0	0	45	9	0	8	1	0	0	0	0	0	0	2	0	0	0	0	0
14	81-82	81	6	6	5	0	0	39	10	0	31	1	0	0	0	0	0	0	2	0	0	1	0	0
15	96-97	96	9	9	2	0	0	46	13	0	17	1	0	0	0	0	0	0	2	0	0	1	0	0
16	101-102	101	12	5	9	0	0	32	17	0	22	0	0	0	0	0	0	0	3	0	0	0	0	0
17	116-117	116	21	9	5	0	0	31	10	0	21	0	1	0	0	0	0	0	1	0	0	0	0	0
18	131-132	131	17	8	1	0	0	57	9	0	5	1	0	0	0	0	0	0	2	0	0	0	0	0
19	137-138	137	12	9	1	0	0	64	7	0	3	1	0	0	0	0	0	0	2	0	0	0	0	0
20	148-149	148	9	7	1	0	0	60	5	0	8	5	0	0	0	0	0	0	2	0	0	0	1	0
21	152-153	152	6	2	2	0	0	13	6	0	24	12	3	0	0	0	0	0	29	0	0	1	3	0
22	169-170	169	19	2	0	0	0	9	16	0	19	3	0	0	0	0	0	0	31	0	0	0	0	0
23	181-182	181	24	7	0	0	0	8	6	0	48	0	0	0	0	0	0	0	7	0	0	0	0	0
24	191-192	191	49	2	0	0	0	1	7	0	26	0	0	0	0	0	0	0	15	0	0	0	0	0
25	200-201	200	20	16	0	0	0	44	11	0	4	0	0	0	0	0	0	0	4	0	0	0	0	0
26	211-212	211	12	3	0	0	0	17	18	0	42	0	0	0	0	0	0	0	9	0	0	0	0	0
27	218-219	218	21	28	0	0	0	32	7	0	3	0	0	0	0	0	0	0	9	0	0	0	0	0
28	231-232	231	31	2	0	0	0	12	9	0	24	0	0	0	0	0	0	0	19	0	0	0	2	0
29	241-242	241	41	13	0	0	0	20	8	0	9	0	0	0	0	0	0	0	6	1	0	0	2	0
30	256-257	256	21	1	0	0	0	21	9	0	9	0	0	1	0	0	0	0	2	0	0	1	34	0
31	260-261	260	15	17	0	0	0	43	6	0	8	1	0	0	0	0	0	0	9	0	0	0	2	0
32	281-282	281	15	5	0	0	0	48	17	0	4	0	0	0	0	0	0	0	10	0	0	0	0	0
33	306-307	306	0	5	0	0	0	30	29	0	3	0	0	0	0	0	0	0	29	1	0	1	1	0
34	324-325	324	2	2	0	0	0	8	16	2	27	0	0	1	0	0	0	0	13	0	0	7	22	0
35	341-342	341	27	2	0	0	0	28	9	1	26	0	0	0	0	0	0	0	4	1	0	1	1	0
36	351-352	351	22	5	0	0	0	30	17	1	10	0	0	0	0	0	0	0	12	2	0	2	0	0
37	374-375	374	55	7	0	0	0	4	17	0	0	0	0	0	0	0	0	0	14	2	0	0	0	0
38	388-389	388	31	6	0	0	0	1	17	0	0	0	0	0	0	0	0	0	43	2	0	0	0	0
39	405-406	405	61	4	0	0	0	3	8	4	0	0	0	0	0	0	0	8	8	0	0	1	3	0
40	424-425	424	42	1	0	0	0	0	12	0	0	0	0	0	0	0	0	35	10	0	0	0	0	0
41	435-436	435	45	1	0	0	0	0	9	0	0	0	0	3	0	0	2	30	6	3	0	0	1	0
42	444-445	444	11	18	0	0	0	0	9	1	0	0	0	1	0	0	4	47	4	1	0	0	4	0
43	451-452	451	3	18	0	0	0	1	15	0	0	0	0	0	0	0	1	37	16	7	0	0	1	0
44	465-466	465	6	23	0	0	0	0	7	0	0	0	0	0	0	0	0	18	35	10	0	0	0	0
45	487-488	487	8	48	0	0	0	0	10	0	0	0	0	2	0	0	2	20	4	5	1	0	1	0
46	509-510	509	0	17	0	0	0	0	0	0	0	0	0	0	0	0	4	45	12	13	7	0	2	0
47	531-532	531	0	26	0	1	0	0	1	0	0	0	0	1	0	0	3	18	0	46	3	1	0	0
48	550-551	550	0	51	0	0	0	0	1	0	0	0	0	0	0	2	3	7	0	26	8	3	0	0

Research paper 3

Ilijanić, N., Ivkić Filipović, I., Miko, S., Hajek-Tadesse, V., Šparica Miko, M., McClure, S., Kennett, D., Hartke, E., Freeman, K.H., Sladović, Ž. & Podrug, E. (2026). Holocene paleolake evolution of the Bribir-Ostrovica karst polje (Dalmatia, Croatia): A multi-proxy lake sediment record. *Quaternary*. doi: 10.3390/quat9040048.

Article

Holocene Paleolake Evolution of the Bribir–Ostrovica Karst Polje (Dalmatia, Croatia): A Multi-Proxy Lake Sediment Record

Nikolina Ilijanić ¹, Ivona Ivkić Filipović ^{1,2,*}, Slobodan Miko ¹, Valentina Hajek-Tadesse ¹,
Martina Šparica Miko ¹, Sarah B. McClure ³, Douglas J. Kennett ³, Emma Hartke ⁴,
Katherine H. Freeman ⁴, Željka Sladović ⁵ and Emil Podrug ⁶

¹ Croatian Geological Survey, Milana Sachsa 2, 10000 Zagreb, Croatia; nilijanic@hgi-cgs.hr (N.I.); smiko@hgi-cgs.hr (S.M.); tadesse@hgi-cgs.hr (V.H.-T.); mtsparica@hgi-cgs.hr (M.Š.M.)

² Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, 10000 Zagreb, Croatia

³ Department of Anthropology, University of California, Santa Barbara, CA 93106, USA; mcclure@anth.ucsb.edu (S.B.M.); kennett@anth.ucsb.edu (D.J.K.)

⁴ Department of Geosciences, The Pennsylvania State University, University Park, PA 16802, USA; erh5454@psu.edu (E.H.); khf4@psu.edu (K.H.F.)

⁵ Geoda Consulting LLC, Kralja Zvonimira 13, 10000 Zagreb, Croatia; zeljka@geoda.hr

⁶ Šibenik City Museum, Gradska vrata 3, 22000 Šibenik, Croatia; emil.podrug@gmail.com

* Correspondence: iivkic@hgi-cgs.hr

Abstract

Karst poljes in the Dinaric karst are widely infilled with Quaternary sediments. In the Bribir–Ostrovica karst polje, these sediments were investigated using geomorphological mapping and multiproxy analysis of lake sediment cores, including grain size, mineralogical, total organic and inorganic carbon (TOC, TIC), and ostracod analyses, coupled with radiocarbon dating. A key sediment core (OSP-3) recovered a ~470 cm long sedimentary sequence dating back to 13,200 cal yr BP. The floodplain to wetland environment occurred at the Late Pleistocene to Holocene transition (ca. 12,100 cal yr BP), evident by the first appearances of ostracods and an increase in TOC. More stable lake conditions prevailed between 9600 and 7200 cal yr BP, with dominant carbonate deposition and abundant ostracods. During the Middle and Late Holocene, increased clastic input and reduced ostracod presence indicate a shallow, dynamic water body influenced by erosion and periodic flooding. Lake sedimentation was strongly controlled by local karst topography, with a maximum lake depth of ca. 6 m. The Bribir–Ostrovica paleolake represents a rare terrestrial Holocene paleoenvironmental record from the Dinaric karst of the eastern Adriatic coast and provides valuable context for interpreting the nearby Neolithic archaeological site of Krivače as a lakeside settlement.

Keywords: Dinaric karst; paleolimnology; paleoenvironment; geomorphology; ostracods



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1. Introduction

The eastern Adriatic karstic coast contains limited areas for the conservation of Quaternary deposits. They were mainly washed out due to erosional processes or, if closer to the coast, under the constant influence of sea-level changes. The most prominent areas for its deposition are karst poljes (Slavic term for flat-floor depressions in karst), which often contain lake sediments and represent paleolakes. The evidence of the Bribir–Ostrovica paleolake is important because it provides one of the few terrestrial Holocene paleoenvironmental records from the Dinaric karst on the eastern Adriatic coast. It provides a valuable

proxy for climate and ecosystem change, complementing marine and lake sediment records from Croatian karst systems, from the north to the south. The Holocene sedimentary archives used for paleoenvironmental reconstructions along the eastern Adriatic coast can be broadly classified into several types, including freshwater lakes, coastal lakes, isolated basins and karst poljes. Late Pleistocene to Holocene lake sediments were obtained from freshwater lakes and wetlands such as Lake Vrana on Cres Island [1], and the Bačina lakes—Crniševo [2]. Coastal lakes, such as Velo Blato on the Island of Pag [3,4], Lake Vrana near Biograd na Moru [5–8], estuarine lake Prokljan Lake [9,10] and marine lake Veliko Jezero on the Island of Mljet [11–13] record variable degrees of freshwater to brackish and marine influence associated with Holocene coastal evolution and transgression. Isolated basins, including the Lošinj Channel [14–16] and Koločep Bay [17], represent a distinctive type of sedimentary archive along the eastern Adriatic coast, which preserve evidence of alternating lacustrine, brackish, and marine conditions controlled by sea-level fluctuations and karst hydrology from MIS 3 to the Holocene. The Pirovac Bay [18] archives the sediments that represent the Holocene freshwater paleolake submerged during the Middle Holocene transgression. In contrast, karst poljes such as Čepić polje [19], Bokanjačko Blato [20], and Prološko Blato wetland [21,22] provide sedimentary archives that primarily record terrestrial Holocene paleoenvironmental change and hydrological variability within closed karst systems. Together, these archives reflect spatially heterogeneous but complementary responses of the eastern Adriatic landscape to postglacial sea-level rise, karst hydrology, and regional climatic variability.

Karst poljes in the Croatian coastal region are widespread, especially in northern Dalmatia (Ravni Kotari), where they represent fertile soils for agricultural activities. Quaternary gravel and sand, and alluvial and lake sediments predominantly cover most of the karst poljes in the lowlands of Ravni Kotari, according to a geological map of Croatia [23,24]. Karst poljes in Croatia predominantly preserve lake sediment records of Holocene environmental changes [19,22,25], whereas older Pleistocene sediments are rarely preserved. Lake sediments are widely distributed across the Ravni Kotari region, including the Bokanjačko blato [20], Vransko polje [26], Nadinsko polje, and Bribir–Ostrovica (B–O) and Žažvić poljes (this study) (Figure 1).

In the Bribir–Ostrovica polje, located in Šibenik County, the Middle Neolithic settlement Krivače occurs as archeological evidence of human occupation in Dalmatia on the Eastern Adriatic [27–31]. Krivače locality is situated on the SE edge of the Bribir–Ostrovica polje, along the Bribirčica stream and at the foot of the renowned archeological site of Bribirska Glavica spanning the prehistoric, Roman, and medieval periods [32]. A cultural horizon over 60 cm was identified above the sterile subsoil, belonging to the typical Danilo and Hvar culture. Radiocarbon dating on archeological remains (animal bones, human remains) suggests that occupation of the village began around 7300 cal yr BP [27]. Most of the Neolithic sites in northern Dalmatia, including the Krivače site, belong to farming societies that inhabited the area between 8000 and 6000 cal yr BP [27]. The duration of settlement at Krivače remains unresolved; however, paleoenvironmental changes in the Bribir–Ostrovica karst polje provide a valuable context [28]. Lake sediments provide indirect evidence of environmental changes near archeological sites, which may have affected past patterns of human movement [33]. Despite the geoarchaeological significance of the Krivače site, the evolution of the B–O karst polje has not been studied in detail. The initial studies were carried out in collaboration with archeologists [28,29]. This study aims to reconstruct the formation and evolution of the B–O paleolake, based on sedimentological, mineralogical, organic, and inorganic carbon content, coupled with micropaleontological analysis of ostracod assemblages. In addition, the study reevaluates the distribution of lake sediments in the Bribir–Ostrovica karst polje, using terrain prospection (GPR, GPS

mapping, and sediment coring) and sediment analysis, previously based solely on geological maps. The results highlight the valuable contribution of ostracods in reconstructing paleoenvironmental changes of lake sediments in karst poljes. Overall, the aim of this study is to provide new insights into the Holocene evolution of the B–O karst polje and to complement the archaeological knowledge of the Neolithic settlement at Krivače.

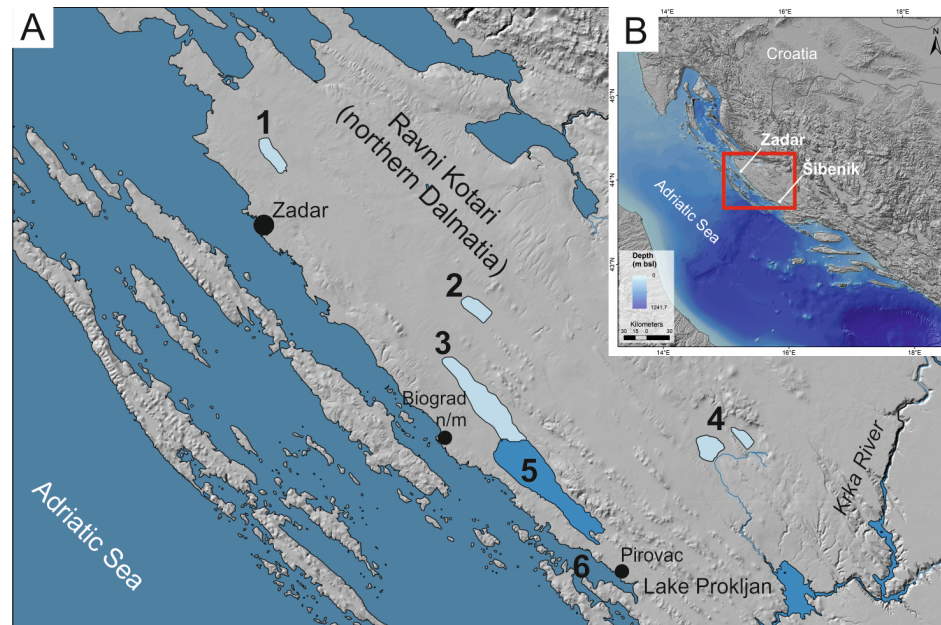


Figure 1. (A) Lake sediments in the mostly flat relief of the Ravni Kotari region. Numbers represent karst poljes and lake sediment locations: 1–Bokanjačko blato, 2–Nadinsko blato, 3–Vransko polje, 4–Bribir–Ostrovica (B–O) and Žažvić poljes, 5–Lake Vrana (near Biograd n/m), 6–Pirovac Bay. (B) Location of Ravni Kotari (northern Dalmatia) (red rectangle) in the central part of the eastern Adriatic coast in Croatia.

2. Geological Setting

The Bribir–Ostrovica (B–O) karst polje is located near the village of Bribir, north of Bribirske Mostine in the Ravni Kotari region of northern Dalmatia (the central part of the eastern Adriatic coast, Croatia). The topographical name of the B–O polje is Zblaće polje, which extends southeastward to Ćoraško polje. It is approximately 5 km long and up to 2 km wide, slightly elongated in the NW–SE direction, with a total surface area of ~5 km². The polje is divided by the Bribirčica stream into a larger northern section where the sediment cores are located and a smaller southern section (Ćoraško polje) with the Krivače archeological site (Figure 2). The Žažvić polje lies to the west of the B–O polje. It is much greater in size (11 km²), with the Bribirčica stream flowing along its southern margin. The polje itself consists of several smaller topographic poljes (Trolokva, Gornja bara, Donja bara, and Žažvićko polje).

The dominant rock types in the area of Ravni Kotari are Cretaceous and Paleogene (Eocene) carbonate rocks, followed by Eocene flysch deposits [34,35] (Figure 2A). The wider area of the B–O polje is composed of Cretaceous rudist limestones and alternations of limestones and dolomites. These are overlain by Eocene foraminiferal limestones, flysch deposits (marls and sandstones), and limestones, marls, and conglomerates. The southwestern slopes of the B–O polje are characterized by marl outcrops belonging to Eocene flysch deposits (Figure 3D). The specified geological units are covered by Quaternary sediments, which mainly consist of sand and fine gravel, lake sediments, and terra rossa soils. These Quaternary sediments consist of grey, muddy sediment containing sporadically occurring micropaleontological remains (mainly ostracods and gastropods visible to the

naked eye). The distribution of lake sediments is reassessed in the present study, which represents one of the key objectives of this work.

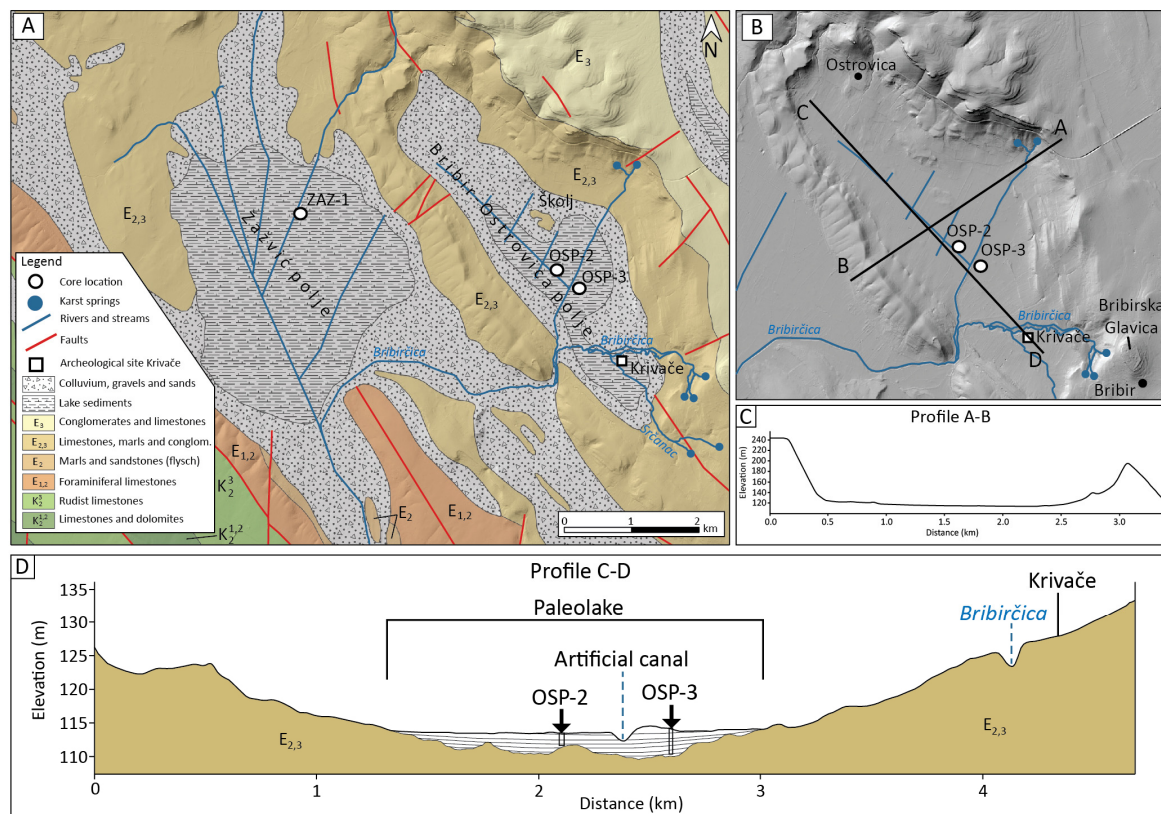


Figure 2. Geological map (A) of the Bribir–Ostrovica and Žažvić poljes [34,35]. Sediment core locations are marked (white circles), as well as the location of the archaeological locality Krivače (white square). (B) Digital terrain model map derived from LiDAR data [33] of the investigated area, highlighting its geomorphological characteristics, together with transversal (C) and longitudinal (D) profiles across the Bribir–Ostrovica polje.

The silty lake sediments in the B–O and Žažvić poljes are deposited mainly in the central part, while coarser sand, gravel, and pebbles, which represent colluvial and alluvial sediments, cover the marginal area. According to the geological map, lake sediments are widespread across the entire B–O polje [34,35], extending both north and south of the Bribirčica stream. The characteristic flat floor of the karst polje is evident in the LiDAR-derived [36] digital terrain model (DTM) (Figure 2B), as well as in the associated transversal (Figure 2C) and longitudinal profiles across the Bribir–Ostrovica polje (Figure 2D).

Significant hydrogeological features are freshwater springs along the edges of the polje (Figure 2). The springs become active during wet periods, when numerous streams form within the polje, leading to flooding. In addition, flooding occurs due to the rising groundwater levels, a common feature of Dinaric karst poljes [37]. The polje remains dry for most of the year, with flooding occurring during periods of heavy rainfall in the wet season, most commonly in late winter. Satellite images with Normalized Difference Water Index (NDWI) from Sentinel 2 [38] demonstrate the seasonal flooding of the polje in spring of 2016 (year of coring) (Figure 3A,B), which can extend even to early June. The dry period of the year was documented with drone images of the polje in September 2018 (Figure 3E). The seasonal stream Bribirčica dries out during hot and dry summer months, as well as the Srčanac stream near the Krivače site. In both B–O and Žažvić poljes, a network of canals and circular wells was constructed for agriculture and livestock (Figure 3F).

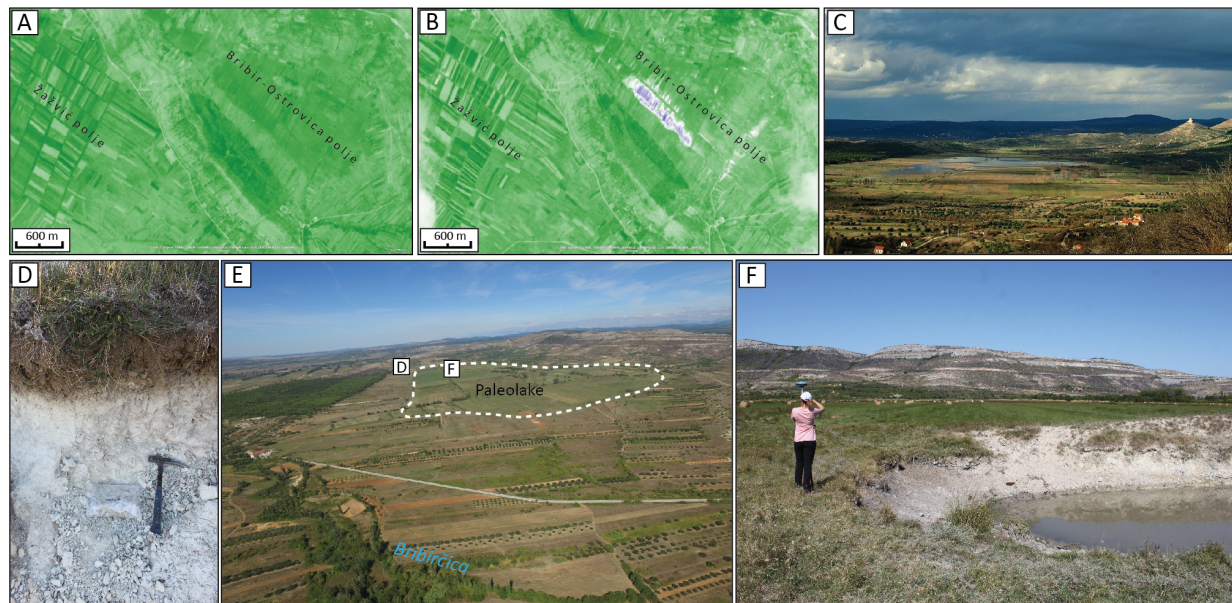


Figure 3. (A,B) Sentinel-2 satellite images (NDWI maps) [35] of Bribir–Ostrovica (B–O) and Žažvić poljes through the year 2016, when the coring was performed. The blue color in represents areas covered by surface water, while the green color represents dry land, soil, and vegetation clearly illustrating seasonal flooding of the B–O polje. (C) Image of Bribir–Ostrovica polje during the flooding season, taken from Bribirska Glavica (courtesy of Željko Krnčević). (D) Outcrop of Eocene flysch deposits in the catchment. (E) Drone image of the B–O karst polje with presumed paleolake boundary (white dashed line) and marked positions of images (D,F). (F) Paleolake sediments exposed in circular wells in the B–O polje.

3. Materials and Methods

Two sediment cores (OSP-2: 113.95 m a.s.l. 43°56'17" N, 15°48'47" E and OSP-3: 114.58 m a.s.l., 43°56'09" N, 15°49'0" E) were recovered in the Bribir–Ostrovica (B–O) polje, in the area north of the village Bribirske Mostine close to Bribir (Figure 2). The topographical name of the B–O polje is Zablache polje. The sediment core OSP-3 is located closer to the archaeological site Krivače (elevation 126.25 m a.s.l., coordinates 45°55'40" N, 15°49'25" E). The location of the additional core ZAZ-1 (elevation 100.18 m a.s.l., coordinates 43°56'39" N, 15°46'9" E) is in the Žažvić polje, west of the B–O polje and south of the village Lišane Ostrovičke. The lake sediment coring was performed during October 2016 using percussion drilling equipment Cobra TT (Eijkelpamp, Giesbeek, The Netherlands) (Figure 4A), with a 1 m long metal sediment corer. In the upper parts of the cores, the used metal core liner had a diameter of 100 mm, while the lower parts of the cores had diameters of 60 mm and 50 mm. Cores were photographed on the field after extraction, followed by sub-sampling in 1, 5, and 10 cm intervals. The upper part of the core OSP-2 is compiled from the upper 50 cm of the core OSP-1. The sediment core OSP-2 has a total length of 460 cm. The length of the core OSP-3 is 266 cm, while the rest is compiled from the parallel core OSP-3B 266–468 cm, which was collected in grey plastic tubes, 50 cm in diameter. This interval in the plastic core tube was cut in half in the laboratory, and the working and archive halves were sub-sampled in 1 cm intervals. Thus, the total length of the composite sediment core OSP-3 is 472 cm. The sediment core ZAZ-1 is 450 cm long. Sediment samples were sealed in plastic bags immediately after extraction. Material (organic material, charcoal) for radiocarbon dating was extracted in the plastic bags on site. The samples were transported and refrigerated in the cooling chamber (at 4 °C) in the laboratory at the Croatian Geological Survey and treated for further analysis. Selected samples were dried at 40 °C.



Figure 4. (A) Sediment coring in the Bribir–Ostrovica (B–O) karst polje using percussion drilling equipment Eijkelkamp Cobra TT. (B) Geophysical survey using GPR MALÅ georadar system.

A geophysical survey was conducted in 2019 using ground penetrating radar (GPR) with a MALÅ Geoexperience (GX) system (Guideline Geo, Stockholm, Sweden) equipped with a 450 MHz antenna (Figure 4B). The survey was carried out by Geoda Consulting LLC, covering a total of 6 km of profiles. The 450 MHz antennas allowed for a depth of penetration of approximately 5–8 m and were chosen because of their higher resolution compared to lower frequency antennas available for the same system [39]. The GPR datasets were processed using the ReflexW software (Version 10.5). The processing followed a standard workflow, similar to that applied in the karst polje Prološko blato [21]. The distribution of lake sediments in the Bribir–Ostrovica polje was additionally evaluated in detail based on geological and geomorphological field prospection, as well as spatial analysis tools in ArcGIS software (version 10.2.1). Both sediment cores and geological prospection allowed reassessment of sediment distribution in the studied part of the polje, thus enabling the observation of paleoenvironmental changes in the BO polje.

Magnetic susceptibility was measured with a Bartington magnetometer (Bartington Instruments Ltd., Oxon, UK) using the MS2E surface sensor and the MS2B dual-frequency sensor (4.7 and 0.47 kHz). The MS2E surface sensor was used to obtain high-resolution measurements at 1 cm intervals of samples in plastic bags for all three cores. Selected samples throughout the sediment core OSP-3 were homogenized and powdered with a pestle in an agate mortar, weighed, and packed in plastic 10 cm³ pots (total 51 samples) for measurements using the MS2B dual-frequency sensor. Results are presented in SI units, volume κ_{lf} (10^{−5}) and mass-weighted χ_{lf} (10^{−8} m³/kg) for MS2E and MS2B measurements, respectively.

Particle-size analysis was performed on a small portion of samples (0.2 g) using a Shimadzu-SALD 2300 laser diffractometer (Shimadzu Corporation, Kyoto, Japan) at the Croatian Geological Survey, measuring between 0.17 μ m and 2 mm particle size. Samples were pre-treated with 30% H₂O₂ on a hot plate at 80 °C to remove the organic matter. Next, 2 mL (Na₄P₂O₇) was added as a dispersant, then the samples were sonicated before being analyzed. The obtained result for every sample is the average of three measurements. Data were processed using the software GRADISTAT v8 [40]. A total of 52 samples were analyzed from the sediment core OSP-2, 35 samples from the core OSP-3, and 42 samples from the sediment core ZAZ-1.

The mineralogy of the sediments was examined by X-ray diffraction (XRD) with a PANalytical X'Pert Powder X-ray diffractometer (Malvern Panalytical, Almelo, The Netherlands) at the Croatian Geological Survey, equipped with a PIXcel detector, using Ni-filtered Cu-K α radiation (45 kV and 40 mA), 1/4° divergence and 1/2° anti-scatter slits, and a step size of 0.02°2 θ , with counting time 4 s per step. Data were evaluated with

HighScore X'Pert Plus software (Version 4.5) using the ICDD database (PDF-4/Minerals). The bulk mineralogy was determined on random powders prepared after grinding with an agate pestle and mortar and mounting by backside loading on Al-holders. In total, 27 samples from the OSP-2, 20 samples from the OSP-3 and 10 samples from the ZAZ-1 sediment cores were analyzed. The clay mineralogy was determined from <2 µm clay fractions separated from suspension by centrifuge, spread onto glass slides and allowed to dry at room temperature. The clay minerals were identified after carbonate removal using buffered sodium acetate (NaOAc) solutions, on oriented slides from air-dried (AD), ethylene glycol (EG)-solvated, and heated at 400 °C and 550 °C states. Clay mineralogical analyses were performed on 6 samples from the sediment core OSP-2 and 11 from the OSP-3 core. Additionally, a sample of marl from the outcrop in the SW part of the polje was analyzed to characterize the flysch deposits. Clay mineral phases were identified by changing basal reflections on XRD patterns based on diagnostic tests [41].

Elemental analyses of carbon and nitrogen were done on a Thermo ScientificTM Flash 2000 NC Analyzer (Thermo Fisher Scientific, Waltham, MA, USA) at the Croatian Geological Survey. Total carbon (TC) and nitrogen (TN) were measured on powdered samples packed into tin capsules, while total organic carbon (TOC) was measured after carbonate removal with 4M HCl and heating for 2 h. Total inorganic carbon (TIC) was calculated as the difference between TC and TOC. The C/N ratio was calculated by dividing the TOC and TN. Insoluble residue was calculated as the mass difference between the HCl-treated sample and the initial (untreated) sediment mass. The analytical precision was controlled by the measurements of the standard reference material, Soil NC Reference Material (N = 0.21% and C = 2.29%). In total, 52 samples were analyzed from the core OSP-2, 51 samples from the core OSP-3, and 42 samples from the core ZAZ-1.

For the ostracod analysis, 26 samples were taken from sediment core OSP-2, 33 from OSP-3, and 6 from ZAZ-1. In the sediment core OSP-2, sampling resolution was generally 1 cm, except for the topsoil (0–45 cm) and intervals with redeposited flysch (387–460 cm), where 5 cm sample resolution was used. In the sediment core OSP-3, samples were taken at 1 cm resolution between 52 and 266 cm, and at 3 cm resolution between 267 and 466 cm, due to the lower core diameter and limited material available for ostracod analysis. Although differences in sampling resolution may introduce bias when comparing changes in species abundances by attenuating higher-frequency fluctuations, the paleoenvironmental interpretations in this study are based on long-term trends and major assemblage changes that occur over intervals longer than the sampling interval. Freeze-dried samples were soaked in distilled water until they disintegrated. Samples were further wet-sieved using 466 µm, 263 µm, 122 µm, and 63 µm meshes, and then oven-dried at 40 °C. Quantitative analysis was performed in sediment cores OSP-2 and OSP-3 by hand-picking ostracods from 466 µm and 263 µm size fractions, while the lower fractions were examined qualitatively to estimate the in situ fauna. Ostracods from the sediment core ZAZ-1 were examined only qualitatively to confirm the presence of a lake environment in the adjacent Žažvić polje. The sediment fractions from which ostracods were picked were weighed, and abundances were normalized to 1 g of dry-sieved sediment. The ostracod analysis was performed under a stereomicroscope (Am Scope) and with the aid of scanning electron microscopy (SEM; JEOL JSM-35CF) (JEOL, Tokyo, Japan). Species identification was based on Fuhrman [42] and Meisch [43].

AMS radiocarbon dating was carried out at Penn State University, at the AMS ¹⁴C facility (University Park, PA, USA) of the Institute of Energy and the Environment. It was performed on two samples from the sediment core OSP-2 and five samples from the sediment core OSP-3. The material for all the samples was uncharred organics (plant material). The results were calibrated using the IntCal20 calibration curve [44], and a depth–age model was constructed in the R package rBacon (Version 3.5.2.) [45].

4. Results

4.1. Ground-Penetrating Radar (GPR) Profiles

GPR profiles over the sediment cores in the Bribir–Ostrovnica polje have been used to analyze the meaning of changes in GPR profiles and the sensitivity of GPR to potential sedimentological changes. GPR allows the imaging of changes in electrical properties in the subsurface by recording the reflections of an emitted electromagnetic pulse [39]. These results from core locations OSP-2 and OSP-3 permitted us to analyze a broad correlation between sediment cores and GPR profiles, in order to characterize the stratigraphic architecture in the subsurface. The geophysical survey revealed a well-developed karst paleorelief, with bedrock consisting of weathered marls (Figure 5, orange line). This occurs at a shallow depth (~4 m) in the profile near core location OSP-2 (Figure 5A), where the sediment core reached hard, compacted weathered marls interpreted as bedrock (Figure 6). In contrast, the profile near sediment core OSP-3 (Figure 5B) indicates that the bedrock lies relatively deeper in the subsurface (>5 m).

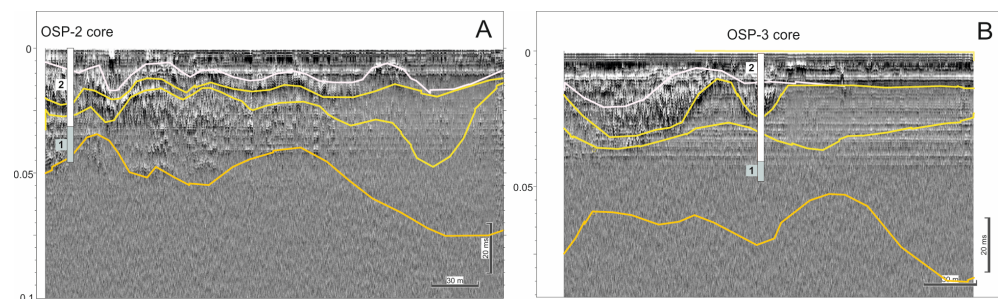


Figure 5. GPR profiles near sediment core locations OSP-2 (A) and OSP-3 (B), with well-developed paleorelief (orange line) and rough correlation of sediment core lithologies (1–weathered marl, clayey with clasts; 2–lake silty sediments).

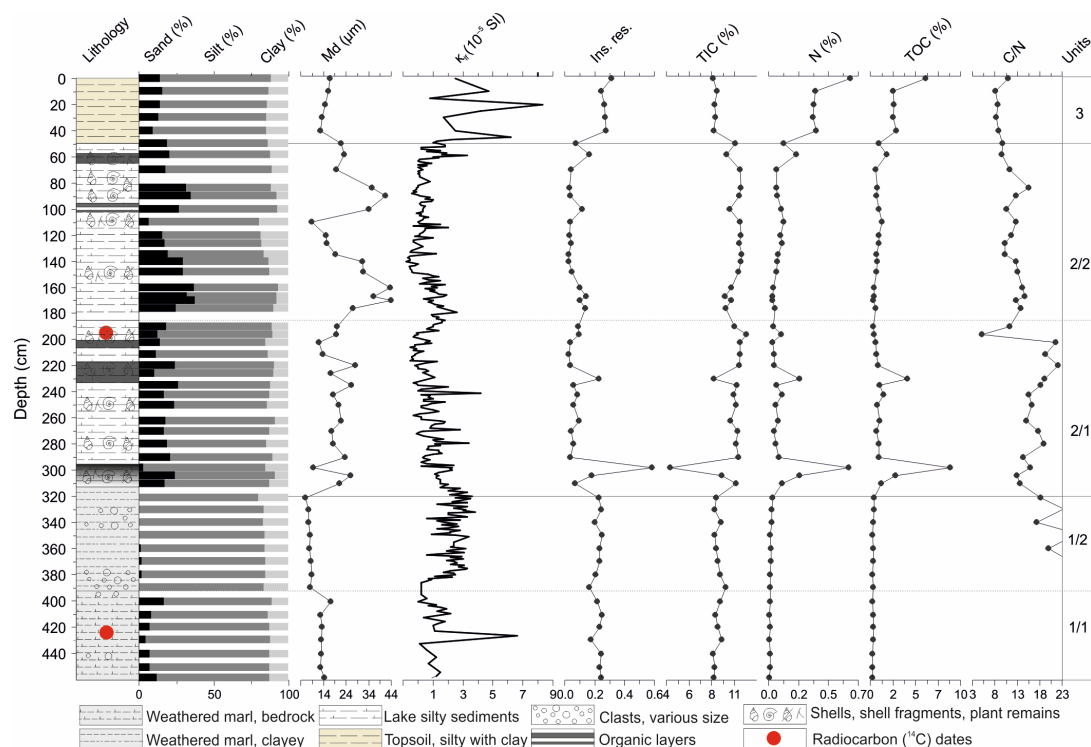


Figure 6. Lithological units of the OSP-2 sediment core from Bribir–Ostrovnica polje, based on grain-size distribution and median grain size (Md), volume magnetic susceptibility (κ_{lf}), insoluble residue and TIC, N, TOC, and C/N logs (artificially inflated ratio in Unit 1, therefore reduced results are shown).

4.2. Sediment Core Lithologies and Chronologies

Using detailed sedimentological descriptions, smear-slide microscopic observations, grain size, mineralogical composition, and TIC and TOC core logs, we defined the units in the studied sediment cores. Photographs of all recovered sediment cores are provided in the Supplementary File S1. The sediment core OSP-2 (460 cm long) consists of the base of the core, which is composed of bright grey sediments up to 320 cm (Unit 1) interpreted as weathered marls being the bedrock (Figure 6). The lower Subunit 1/1 (460–390 cm) comprises very hard and compact sediments. In grain size, the silt fraction is dominant (med. 79.9%), with clay (med. 12.6%) and sand (med. 7.7%) fractions in lower amounts. The upper Subunit 1/2 (390–320 cm) contains more clay fraction (med. 16.2%) and less sand fraction (med. 0.5%), with a lot of plant remains and organic material, as well as occasional clasts. Both subunits are composed of dolomite, calcite, and quartz as major mineral phases, and muscovite/illite, kaolinite, and 14 Å clay mineral as minor mineral phases. The XRD mineralogical composition is presented in Supplementary File S2 (Table and XRD patterns of selected samples). Diagnostic tests on oriented mounts revealed the presence of following clay minerals: smectite, chlorite, illite, and kaolinite. This composition corresponds to the clay mineral composition of weathered marls exposed along the margins of the polje. Volume magnetic susceptibility (κ_{lf}) amounts to a median 2.1×10^{-5} SI in this whole unit, being somewhat lower (med. 1.2×10^{-5} SI) in the lower subunit, except for one peak at 6.6×10^{-5} SI. The TIC concentrations are constant to med. values of 8.9%. Very low N and TOC concentrations mark this whole unit (0.01% and 0.3%, respectively), and thus C/N values reflect analytical constraints associated with very low TN concentrations near the detection limit, resulting in artificially inflated ratios.

The gradual transition into the next Subunit 2/1 (320–185 cm) is marked by a slight increase in N and TOC (0.07% and 1.0%, respectively), with two prominent peaks at intervals 298–299 cm and 226–233 cm. The high concentrations of N and TOC at 298–299 cm (0.6% and 8.5%, respectively) appear in the dark grey interval from 310 cm, which turned to almost black sediment from 301 cm to 296 cm with a lot of plants and shell fragments. A dark organic layer appears again from 233 cm to 217 cm (N: 0.3%; TOC: 4.0%), and between 202 cm and 195 cm (N: 0.1%; TOC: 0.4%). The C/N ratio median values are 15.6, with a lower value at the end of the unit, at the organic layer at 196–197 cm interval. The median grain size ($Md = D_{50}$) increases to the med. values of 20.0 μm due to the increase in sand fraction in this unit (med. 17.8%), with silt being the dominant fraction (med. 70.2%). The values of TIC slightly increased (med. 11.0%), followed by lower volume magnetic susceptibility values (med. 0.7×10^{-5} SI) and calcite as the dominant mineral, while small amounts of quartz are also present. The calcite predominates in the next Subunit 2/2 (185–50 cm), while quartz appears as minor in several intervals (166–181 cm, 100–101 cm, 58–59 cm). This is supported by the lowest volume magnetic susceptibility values (med. 0.3×10^{-5} SI) and the highest TIC values (11.3%). Slightly lower TIC and higher insoluble residue are observed in the interval between 181 and 166 cm. In this unit, there is the highest sand fraction (med. 26.0%), and the lowest clay fraction (med. 11.8%). The interval between 135 cm and 110 cm has, in contrast, low amounts of sand fraction (16.5%). The high amount of shell fragments appears between 125 cm and 103 cm, and 90 cm and 75 cm. Black and grey laminations are observed between 103 cm and 94 cm in various thicknesses (up to 1 cm), not detected in elevated TOC values (med. 0.7%). C/N values (12.2) are somewhat lower than in the previous Subunit 2/1. At the topsoil Unit 3 (50–0 cm), the sediment shifts to slightly clayey (med. 14.2%), with the highest volume magnetic susceptibility values (med. 2.5×10^{-5} SI). Total N and TOC are also the highest (0.4% and 2.6%, respectively), with a C/N ratio of 8.2.

The composite core OSP-3 (Figure 7) has a total length of 472 cm, and up to 430 cm (Unit 1) the sediment is bright grey silty sediment (med. silt = 86.2%), with up to 13.8% of clayey fraction and an absence of sand fraction (weathered marl, clayey). In mineralogical composition, dolomite and calcite dominate, with minor quartz, muscovite/illite and 14 Å clay mineral. Detailed analysis of clay minerals on oriented mounts allowed identification of smectite, chlorite, illite and kaolinite in clay fraction. The TIC content is 10.6%, N and TOC concentrations are low (med. 0.03% and 0.4%, respectively). The appearance of sand (med. 10.1%) and larger median grain size (med. 16.0 µm) in silty sediment (med. silt = 78.4%) marks the next Subunit 2/1, from 430 cm up to 350 cm. The sediment is dark grey in colour, additionally characterized by the higher TOC concentrations (med. 2.2%), and in the black layers it reaches up to 11.6% and 19.7% (intervals 405–407 cm and 382–384 cm, respectively). The median CN values are 14.7. In the lower part of the subunit, calcite, quartz and dolomite are still present, as well as the same clay minerals as in the previous unit, while in the upper section of the subunit, chlorite is absent—only smectite, illite, and kaolinite prevail. The clay mineral composition remains unchanged up to the top of the core. In Subunit 2/2, from 350 cm to 270 cm, the sediment is brighter grey and homogeneous with occasional dark grey layers, although median concentrations of TOC are 1.1%, and C/N values are 15.4. The TIC content is the highest in the core (med. 12.0%), and calcite is the dominant mineral phase. Volume magnetic susceptibility values become negative in this interval (med. $\kappa_{lf} = -0.4 \times 10^{-5}$ SI), while mass magnetic susceptibility is the lowest within the core (med. $\chi_{lf} = 2.0 \times 10^{-8}$ m³/kg). From 270 cm to 100 cm (Subunit 2/3), sediment converts into homogeneous silty sediments (med. 84.3%), with a very small amount of sand fraction (med. 0.8%), which continues to the top of the core. The shells, shell fragments, and plant remains occasionally appear. The TIC content decreases (med. 7.9%), while TOC is the lowest in the core (med. 0.3%), but without significant changes in C/N values (med. 14.6). Generally, higher values of magnetic susceptibility, both volume (med. 3.0×10^{-5} SI) and mass (med. 3.8×10^{-8} m³/kg), can be observed. This is in line with higher insoluble residue, and quartz and muscovite/illite that appear next to the calcite as mineral phases. The upper part of the core, Subunit 2/4 (100–50 cm), is described as bright-grey-coloured silty sediment (med. 81.2%), with slightly higher values of clay fraction (med. 16.5%) and smaller median grain size (med. 8.0 µm). The TIC value is low (8.0%), while the insoluble residue is elevated. TOC shows constant values (med. 1.2%), while C/N reaches 13.1 and 14.1 in the middle part of the subunit. The shell fragments and occasional clasts are also present. In the topsoil (50–0 cm), magnetic susceptibility increases to the maximum values of volume ($\kappa_{lf} = 26.7 \times 10^{-5}$ SI) and mass magnetic susceptibility ($\chi_{lf} = 30.9 \times 10^{-8}$ m³/kg). Here, the TIC is the lowest (med. 7.3%) in the core, while the TOC (med. 2.6%) slightly increases. The total N is the highest in the core (med. 0.4%), and C/N (8.2) is lower than in the previous subunit.

In the core ZAZ-1, bright-yellow-to-grey-coloured carbonate sediments between 450 and 200 cm represent the lowest Unit 1 of the core (Figure 8). It is subdivided into lower (1/1) and upper (1/2) subunits at a depth of 370 cm. The lower Subunit 1/1 (450–370 cm) is characterized by a harder, compact material with high values of TIC (11.2%) and the low values of insoluble residue and negative values of volume magnetic susceptibility. Calcite is the major and quartz is the minor mineral phase, while in the upper Subunit 1/2 (370–200 cm), calcite and quartz are major mineral phases, and muscovite/illite and a 14 Å clay mineral appear as minor minerals. The increased values of insoluble residue and decreased TIC content (med. 9.1%) support this change, as well as increased values of volume magnetic susceptibility (med. 1.8×10^{-5} SI). The clasts and concretions can also be observed throughout this subunit. Generally, the unit can be defined as weathered marls redeposited from the geological bedrock, which corresponds to marls in the outcrops of the

polje. This unit is overlain by brighter grey homogenous carbonate lake sediments further up the core, up to 50 cm. In the Subunit 2/1 (200–110 cm), sediments are silty (med. 80.0%), with 17.8% of clay fraction and very low sand fraction, which increases towards the top of the core. Calcite is the dominant mineral phase. TIC, TOC, and N concentrations, as well as C/N, slightly increase in this unit. Another significant change in sediment composition occurs between 110 cm and 50 cm (Subunit 2/2), described as grey lake sediments, with high carbonate (calcite and TIC) content and subordinate quartz. Magnetic susceptibility values are somewhat higher in the interval between 85 and 50 cm, but the median value for this unit is relatively low (0.7×10^{-5} SI). The contents of N and TOC have an increasing trend towards the top of the core. Occasional occurrences of gastropod shell fragments are visible. In this interval, there is an increased trend of N and TOC towards the top of the core. At the topsoil interval (50–0 cm), the sediments have the highest values of TOC and N values (3.0% and 0.5%, respectively). Sediments are coarser, sandy, with increased median grain size, and alternating silty layers.

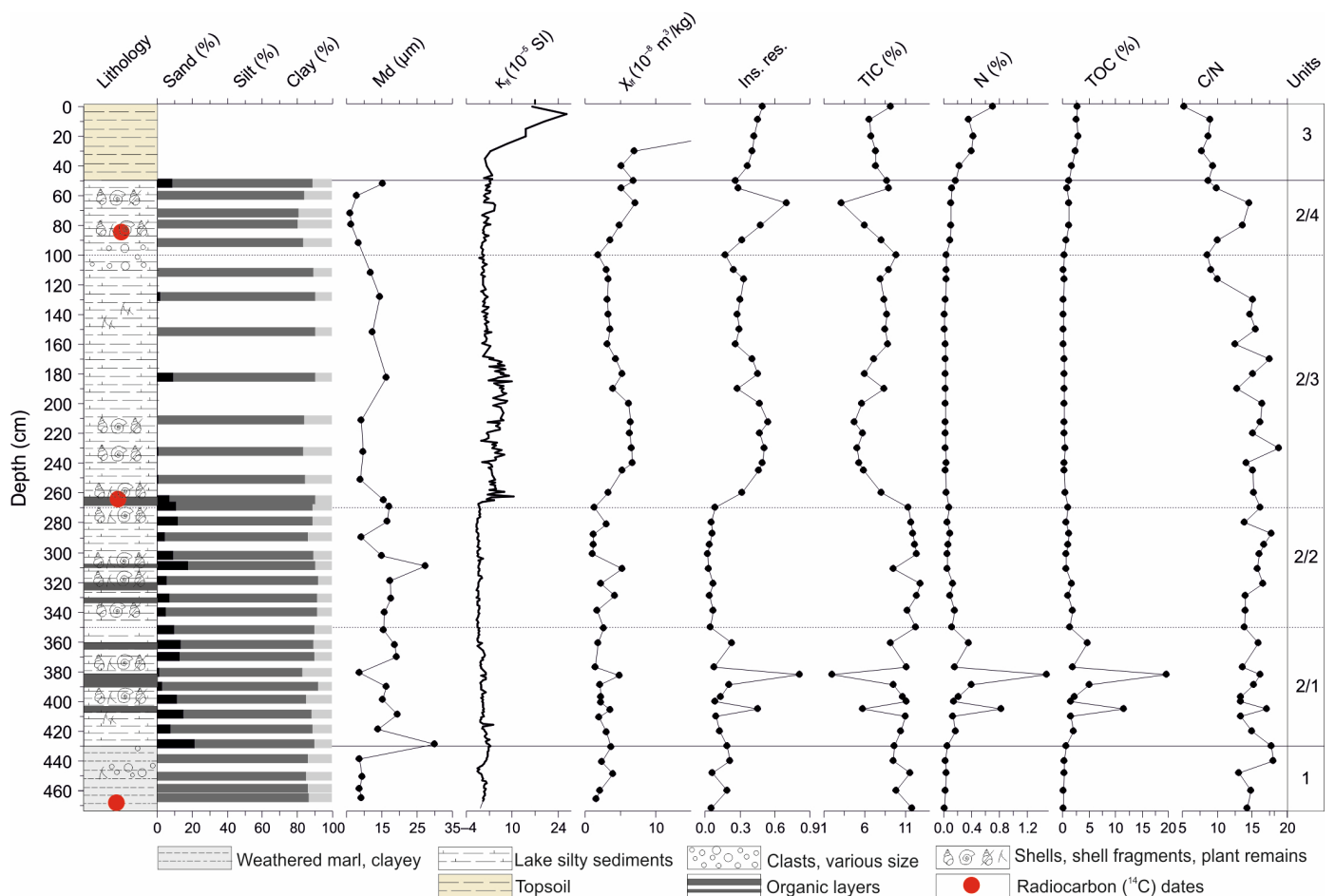


Figure 7. Lithological units of the OSP-3 sediment core from Bribir–Ostrovica polje, based on grain-size distribution and median grain size (Md), volume (κ_{lf}) and mass magnetic susceptibility (χ_{lf}), insoluble residue and TIC, N, TOC and C/N logs.

The radiocarbon chronology of cores OSP-2 and OSP-3 is based on two and three dates, respectively, all obtained from the sample organic material (Table 1). Given that the study area is characterized by carbonate-rich bedrock and karst hydrology, the potential influence of a reservoir effect (old carbon) on the obtained radiocarbon ages cannot be excluded [46]. The incorporation of dissolved ancient carbon derived from carbonate dissolution may result in apparently older radiocarbon ages. Due to the limited number of

dated samples, the reservoir effect should therefore be considered when interpreting the age–depth models and sedimentation history. The radiocarbon dates and the produced age–depth models should therefore be considered as preliminary ages for these sediment cores from the Bribir–Ostrovnica polje (Figure 9). The 472 cm long composite OSP-3 core spans the last 13,200 cal yr BP and exhibits more pronounced variability in sedimentation rates, particularly around 100 cm, as indicated by a shift in the age–depth model slope. The 460 cm long core OSP-2 spans the last 11,300 cal yr BP, and the age–depth model indicates broadly uniform sedimentation rates.

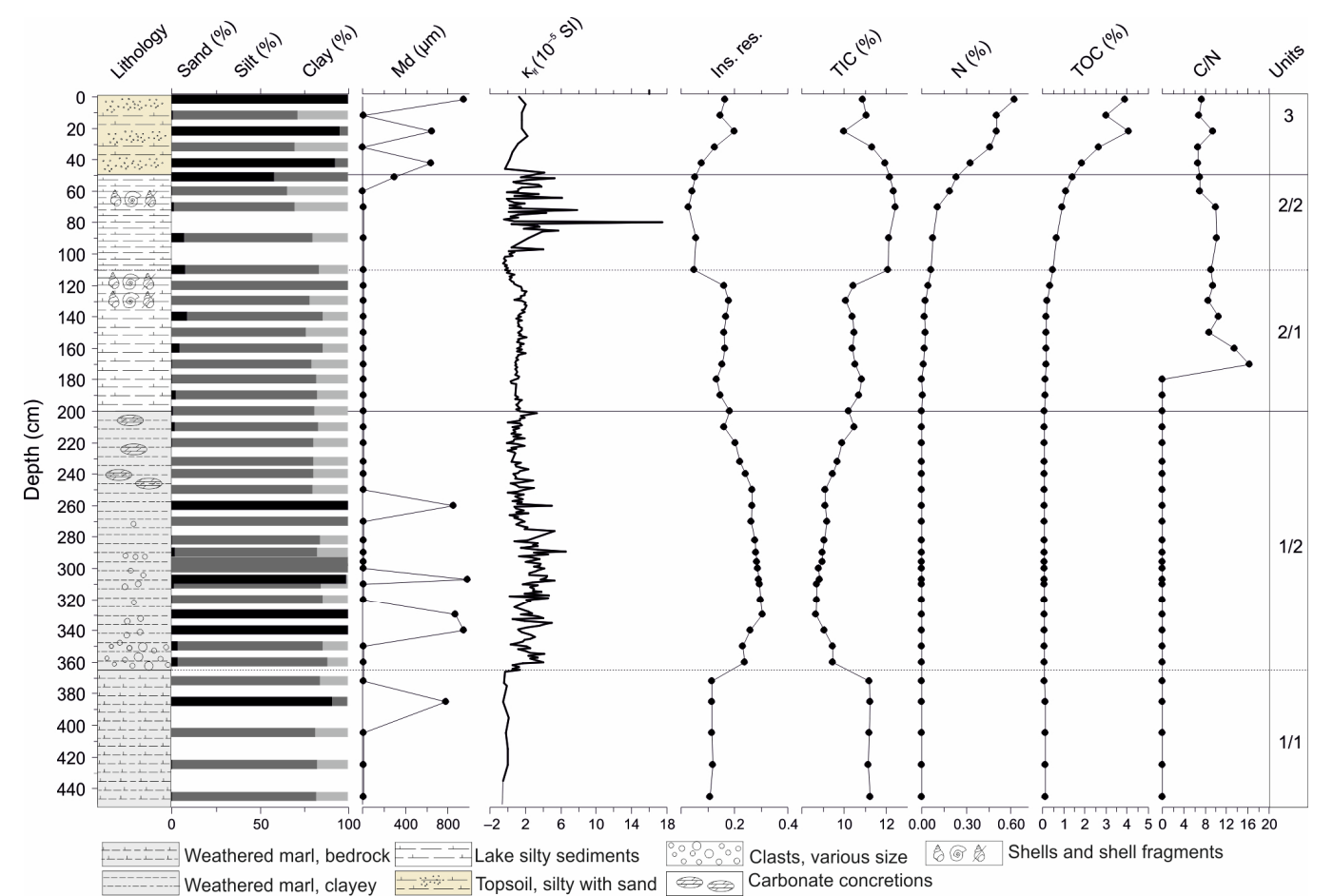


Figure 8. Lithological units of the ZAZ-1 sediment core from Žažvić polje, based on grain-size distribution and median grain-size (Md), volume magnetic susceptibility (κ_{f}), insoluble residue and TIC, N, TOC, and C/N logs.

Table 1. Radiocarbon ^{14}C dating results of the studied sediment cores from Bribir–Ostrovnica polje. The samples were analyzed using AMS at Penn State University (PSU AMS).

Core	Depth Interval (cm)	Lab ID	Material	Radiocarbon Age (BP)	Calibrated Age (2σ, cal BC)	Calibrated Age (2σ, cal BP)
OSP-2	195–196	PSUAMS-1802	uncharred organics	4890 ± 30	3712–3637	5662–5587
OSP-2	420–425	PSUAMS-1806	uncharred organics	9345 ± 35	8725–8488	10,675–10,438
OSP-3	84–85	PSUAMS-1801	uncharred organics	4030 ± 25	2620–2475	4570–4425
OSP-3	265–266	PSUAMS-1804	uncharred organics	6175 ± 40	5226–5000	7176–6950
OSP-3B	468–469	PSUAMS-1807	uncharred organics	11,350 ± 60	11,355–11,132	13,305–13,082

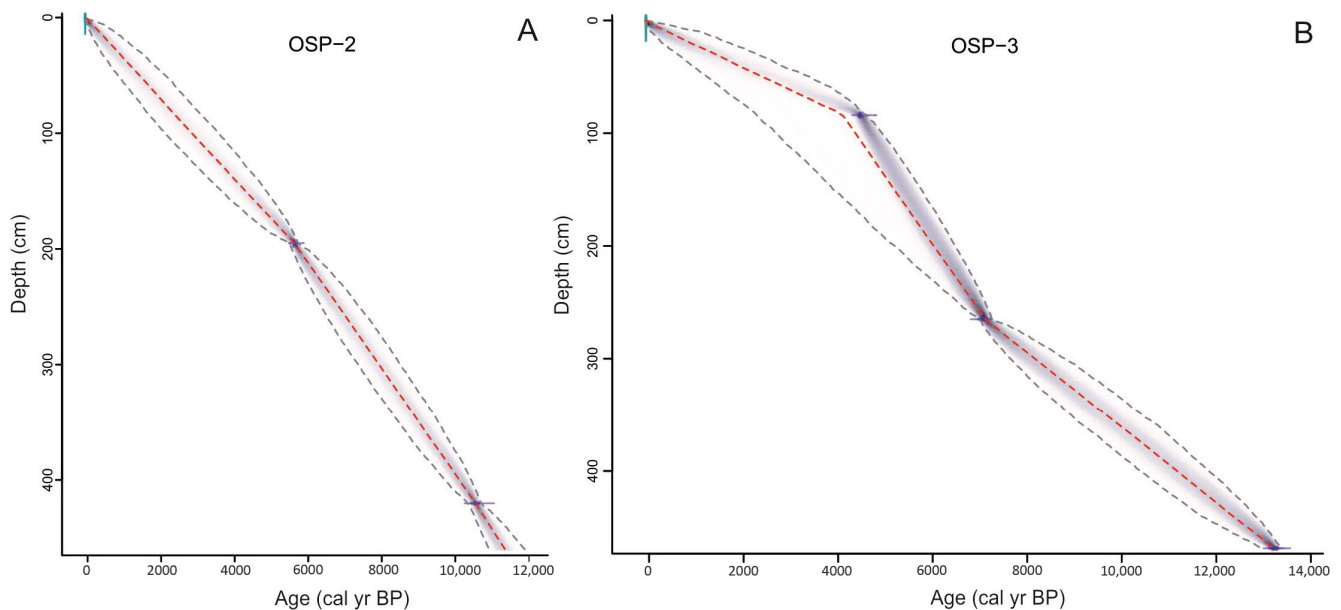


Figure 9. Radiocarbon dating and age–depth models OSP-2 (A) and OSP-3 (B) sediment cores from Bribir–Ostrovica karst polje. The grey shading represents the probability density with black dotted boundaries marking the 95% confidence interval, while the red dotted line represents the single “best-fit” chronological model based on weighted mean.

The estimated sedimentation rates of the OSP-3 core are lower in the top and bottom parts (0.2–0.4 mm/year) and higher in the middle part of the core (0.8 mm/year), in line with the shifts in the slope of the age–depth model. In sediment core OSP-2, estimated sedimentation rates are constant, between 0.4 and 0.6 mm/yr, in agreement with a relatively smooth age–depth relationship.

4.3. Ostracod Assemblages in Analyzed Sediment Cores

In sediment core OSP-2, located in the central part of the paleolake (Figure 2), a total of 14 species were identified, belonging to 13 genera: *Candona neglecta*, *Fabaeformiscandona fabaeformis*, *Candonopsis kingsleii*, *Pseudocandona marchica*, *Metacypris cordata*, *Cyclocypris ovum*, *Cypridopsis vidua*, *Heterocypris reptans*, *Hungarocypris madaraszi*, *Ilyocypris* cf. *bradyi*, *Paralimnocythere psammophila*, *Paralimnocythere* cf. *relicta*, *Notodromas monacha*, and *Cypria ophtalmica* (Figures 10 and 11). The most abundant species are *C. neglecta*, *Cyc. ovum*, and *M. cordata*, while subordinate species are *P. marchica*, *P. cf. relicta*, and *I. cf. bradyi*. Other species are rare and contribute <10% to the assemblage, except for *H. reptans*, which shows a short-lived increase to 15% at 85–86 cm. The large species *Hun. madaraszi* was recorded only qualitatively (presence/absence), as most valves were fragmented. The core was subdivided into four zones, each defined by distinct changes in species composition and relative abundances (Figure 10). Ostracod zone O1 (460–350 cm; 11,350–9030 cal yr BP) is the lowermost zone in the sediment core OSP-2, composed of bright grey sediment (weathered marls). The zone is barren of ostracods, and only one broken valve—probably of *C. neglecta*—is present in sample 371–372 cm. However, this zone is rich in plant remains and abraded foraminifera, such as *Globigerina* sp., *Nummulites globulus*, and *Vulvulina* cf. *pennatula*, which are redeposited from Eocene limestone and flysch deposits in the paleolake’s catchment (Figures 2 and 3). Ostracod zone O2 (350–175 cm; 9030–5000 cal yr BP) is characterized by the highest species richness and diversity. The lower part of the zone still contains Eocene foraminifera (351–321 cm), while ostracods begin to appear from 331 cm and are dominated by *C. neglecta*. The very high total ostracod count between 300 and 301 cm is due to normalization of raw counts and reflects a high number of *C. neglecta*

juveniles, although adults are also present. This sample was taken from an organic-rich layer between 301 and 296 cm, which is very rich in gastropod shells and opercula (Figure 6), as well as *Chara* gyrogonites and numerous fragments of *Hun. madaraszi*. Between 300 and 200 cm, the total number of ostracods declines, although it is still relatively high, while *C. neglecta* is replaced by *M. cordata*. In ostracod zone O3 (175–40 cm; 5000–1100 cal yr BP), the total ostracod number is relatively low, although with a partial recovery between 120 and 100 cm. Ostracod assemblages are dominated by *Cyc. ovum*, *M. cordata*, and *P. marchica*, while *C. neglecta* is subordinated and mostly juveniles. However, the sediment is still rich in gastropods, bivalves, and *Chara* gyrogonites and thalli. The last zone, O4 (40–0 cm; 1100 cal yr BP–present), is characterized by only four valves of *Cyc. ovum* and a few fragmented candonid juveniles (not counted) in the lower part, and a complete absence of ostracods in the upper part. Eocene foraminifera reappear, while gastropods are less abundant and more fragmented.

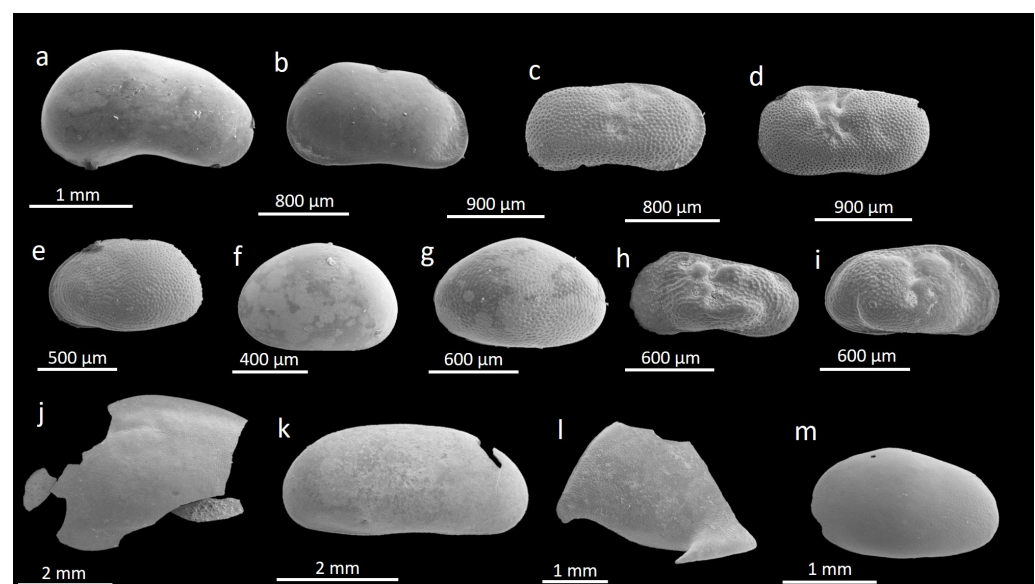


Figure 10. SEM photographs of ostracod species identified in sediment core OSP-3: (a) *C. neglecta*, male right valve, (b) *P. marchica*, male right valve, (c) *I. inermis*, female right valve, (d) *I. cf. bradyi*, female left valve, (e) *M. cordata*, female left valve, (f) *Cyc. ovum*, female left valve, (g) *Cyp. vidua*, female left valve, (h) *P. psammophila*, female left valve, (i) *P. cf. relict*, female right valve, (j) *Hun. madaraszi*, fragmented valve, (k) *Herpetocypris* sp., female right valve, (l) *Cypris bispinosa*, fragmented valve with spine-like lateral projection, (m) *H. reptans*, partially fragmented female right valve.

In sediment core OSP-3, located in the presumed shallower part of the paleolake (Figure 2), a total of 19 species were identified, referable to 15 genera: *Candona neglecta*, *Mixtacandona* sp., *Candonopsis kingsleii*, *Fabaeformiscandona fabaeformis*, *Pseudocandona marchica*, *Pseudocandona* sp., *Heterocypris reptans*, *Cypris bispinosa*, *Metacypris cordata*, *Ilyocypris* cf. *bradyi*, *Ilyocypris inermis*, *Ilyocypris* sp. (juveniles), *Cypria ophtalmica*, *Cyclocypris ovum*, *Cypridopsis vidua*, *Hungarocypris madaraszi*, *Herpetocypris* sp., *Paralimnocythere* cf. *relict*, *Paralimnocythere psammophila*. The most abundant species are *C. neglecta*, *M. cordata*, and *Cyc. ovum*, while *I. cf. bradyi*, *P. marchica*, *Cyp. vidua*, *P. cf. relict*, *P. psammophila*, *F. fabaeformis* are subordinate (Figure 10). Although the entire core is characterized by relatively high species richness, the rest of the species are scattered and/or contribute less than 10% to the assemblage (e.g., *I. inermis*, *Mixtacandona* sp., *H. reptans*, *Cypris bispinosa*, *Ca. kingsleii*, and *Cy. ophtalmica*), in comparison to the sediment core OSP-2, where ostracods are more evenly distributed. Three valves belonging to the family Candonidae could not be identified to the genus and species level, but were counted. As in the previous core, valves of *Hun.*

madaraszi were mostly fragmented and excluded from the count. The sediment core OSP-3 was subdivided into the following three zones.

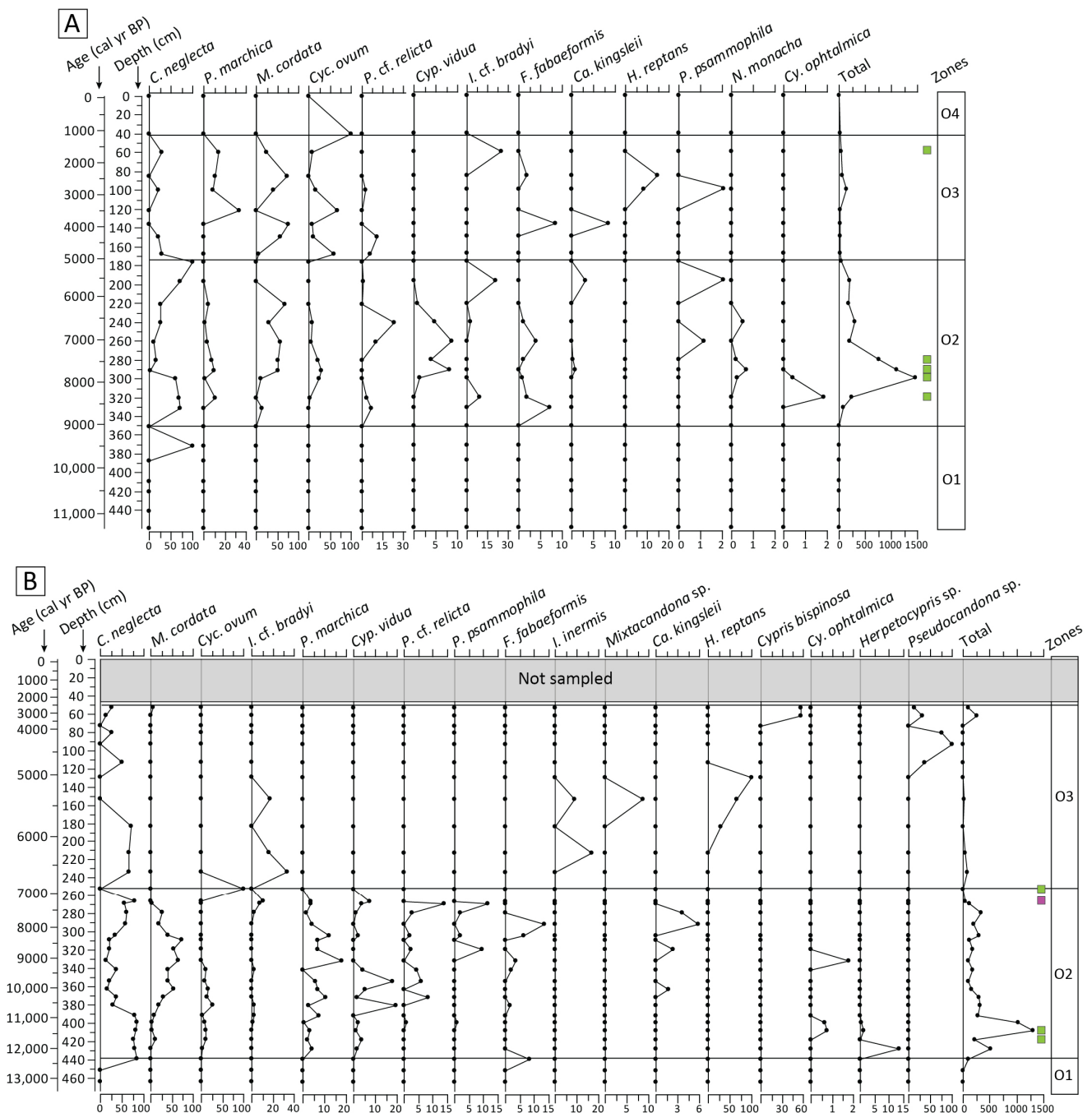


Figure 11. Ostracod assemblages in sediment core OSP-2 (A) and OSP-3 (B) from Bribir-Ostrovica polje. Green squares mark the occurrences of *Hun. madaraszi*, and purple square marks *Candonidae* indet.

Ostracod zone O1 (470–438 cm; 13,200–12,300 cal yr BP) comprises two lowermost samples, which are barren of ostracods but rich in abraded Eocene foraminifera. Ostracods first appear in the second zone O2 (438–265 cm; 12,300–7100 cal yr BP), characterized also by the greatest species diversity and maximum total counts (Figure 9). The lower part of the zone (438–390 cm) is dominated by *C. neglecta*, and Eocene foraminifera still appear at 417 cm. Species diversity increases in the upper part of the zone (390–265 cm), and assemblages are dominated by *M. cordata*. The upper part of the zone is also rich

in gastropods, bivalves, and *Chara* gyrogonites, as well as encrusted *Chara* thalli. Total ostracod count decreases towards the top of the zone. The third zone, O3 (265–50 cm; 7100–2500 cal yr BP), is characterized by a generally low ostracod count, with only short-lived recovery between 233 and 211 cm—dominated by *C. neglecta* and *I. cf. bradyi*—and between 61 and 52 cm, dominated by *C. neglecta*, *Pseudocandona* sp., and *Cypris bispinosa* (Figure 9). These intervals are also rich in gastropod shells and encrusted *Chara* thalli.

In sediment core ZAZ-1, ostracods occur between 201 and 87 cm, and are represented by *C. neglecta*, *Ilyocypris* sp., *Herpetocypris* sp., *Hun. madaraszi*, *Mixtacandona* sp., and *Pseudocandona* sp. Between 87 and 10 cm, ostracods are absent.

5. Discussion

5.1. Paleoenvironmental Reconstruction of the Bribir–Ostrovnica Karst Polje

The analysis of sediment cores OSP-2 and OSP-3 from the Bribir–Ostrovnica polje, encompassing sedimentological and mineralogical data, TOC and TIC contents, and micropaleontological (ostracod) distribution, supported by radiocarbon dating, provides a comprehensive reconstruction of past environmental dynamics influencing the Bribir–Ostrovnica paleolake during the Holocene. Given the relatively deeper paleorelief in the subsurface near sediment core OSP-3, the depositional environment is inferred to have developed earlier than at the location of sediment core OSP-2, as reflected by the greater sediment thickness. This type of depression (sinkholes or dolines) in the karst paleorelief is well documented along the eastern Adriatic coast, where they form freshwater environments or are submerged by seawater [1,11,14,16,21]. The main difference lies in the bedrock composition, which is either weathered flysch or red paleosols, such as in the karst polje Bokanjačko blato in northern Dalmatia [20], controlled by the local geology. Karst poljes are generally characterized by a relatively flat floor in carbonate terrain, filled with sediments [47]. In the Dinaric karst, sediment infillings are largely composed of Quaternary deposits, as observed in the present study.

The sediment core OSP-3 records the period between 13,200 and 12,100 cal yr BP at its base (472–430 cm), corresponding to the weathered marls of the Eocene flysch bedrock. These sediments extend to a depth of 320 cm in core OSP-2 and were deposited between 11,300 and 8300 cal yr BP (460–320 cm). In the core ZAZ-1 from Žažvić polje, weathered marls reach a depth of 200 cm. The mineralogical composition corresponds to the marls that occur in the outcrops on the edges of the polje, in bulk (major calcite, quartz, and dolomite in OSP cores) and clay mineral assemblages (smectite, chlorite, illite, and kaolinite). The flysch marl-derived carbonate contributes to relatively high TIC content (Figures 5 and 6), especially in lower Subunit 1/1 in ZAZ-1 core (Figure 8). In ZAZ-1 Subunit 1/2, the higher insoluble residue, followed by the presence of quartz and muscovite/illite as major minerals, lowers TIC values and increases magnetic susceptibility. It is observed that low concentrations of N and TOC characterize these sediments. This is supported by the absence of ostracods in sediment cores OSP-2 and OSP-3 (Zone O1). In contrast, foraminifera species were recorded, and they were significantly abraded. These foraminifera are probably of Eocene age (e.g., *Nummulites globulus*) and represent the weathered Eocene flysch marls as bedrock.

We presume that the wetland to shallow lake was formed at 12,100 cal yr BP (430 cm), evident in the sediment core OSP-3, and at 8300 cal yr BP (320 cm) as evidenced by the sediment core OSP-2. This is marked by the first appearances of ostracod species (*C. neglecta*), as well as increased N and TOC contents, slightly less pronounced in the ZAZ-1 sediment core. However, in ZAZ-1, the interval between 200 and 110 cm is the richest in ostracods (*C. neglecta*, *Ilyocypris* sp., *Pseudocandona* sp., *Herpetocypris* sp., *Hun. madaraszi*), suggesting the formation of a shallow lake environment. In OSP-3, within the

period between 12,100 and 9600 cal yr BP (430–350 cm), several darker grey organic layers occurred, with very high N and TOC concentrations and a relatively high C/N ratio, as well as insoluble residue. This indicates sediment runoff and organic matter originating from both algal- and land-derived organic matter [48]. The paleoenvironmental conditions in the lake sediment core from Bokanjačko Blato near the city of Zadar point to increased erosion and input of siliciclastic material from the catchment from 10,300 cal yr BP up to 4200 cal yr BP [20]. Between 12,100 and 11,000 cal yr BP, the normalized total ostracod count is substantially high (Figure 9) and reflects high raw counts of *C. neglecta* juveniles, possibly reflecting dynamic environmental conditions and transport of juveniles [49]. However, adult specimens are also present, along with a high abundance of gastropods, bivalves, and encrusted *Chara* thalli and gyrogonites, strengthening the interpretation of in situ fauna and development of lacustrine conditions. The richness and dominance of *C. neglecta* at the onset of lacustrine conditions may be due to the low nutrient content (lower TOC and N) and lake water temperatures balanced by surrounding karst springs. Similar conditions were inferred from Holocene paleolake sediments in Prološko Blato karst wetland, where *C. neglecta* is the dominant species throughout the record [22]. However, at around 11,000 cal yr BP, TOC and N increase considerably, corresponding to the occurrence of organic-rich layers in the sediment core OSP-3 (Figure 7). This is accompanied by changes in ostracod assemblages, with the dominance of *C. neglecta* declining and being replaced by *M. cordata* (Figure 10). Other species also appear in relatively high abundances, such as *Cyc. ovum*, *Cyp. vidua*, and *P. marchica*. The ecological preferences of *M. cordata* are relatively well-known. They inhabit shallow, warm freshwater bodies such as small lakes, ponds, marshes, and wetlands, as well as the littoral zones of lakes, where they thrive among aquatic vegetation [43,50]. In Quaternary sedimentary records, they are often used as indicators of lake succession from open-lake environments to shallow wetlands encroached by vegetation, reflecting changes in lake levels, temperature, and trophic status [43]. For example, in Europe, *M. cordata* is an important time marker for post-glacial deposits [51–54], and its appearance is typical for the intervals associated with lake-level lowering and/or change in the trophic status, and its occurrence is contemporaneous with the onset of the deposition of calcareous mud [54]. In Croatia, *M. cordata* occurs in Holocene records from shallow coastal lakes along the eastern Adriatic coast, which are rich in aquatic vegetation [4,6]. Particularly, in Lake Velo Blato on Pag Island, *M. cordata* appears during the Roman Warm Period, along with *P. marchica* and *C. ovum*, an interval associated with lake-level lowering and the emergence of aquatic vegetation (emergent macrophytes and reeds), as evidenced by stable isotope records of lake carbonates and organic matter [6]. Similarly, in shallow Lake Vrana near Biograd na Moru, *M. cordata* co-occurs with *P. marchica* during the early Middle Holocene, suggesting the development of a warm, shallow freshwater environment with rich vegetation [4]. Thus, its dominance between 10,500 and 8000 cal yr BP in B–O polje, accompanied by the highest TOC and N contents, most likely suggests a decrease in lake level, expansion of aquatic vegetation, and possibly warmer conditions.

The lake sedimentation in OSP-3 core from the B–O polje between 9600 and 7200 cal yr BP (350–270 cm) is marked by the deposition of lake silty sediments, with high carbonate content as reflected by high TIC values and calcite as the dominant mineral phase. The deeper, more stable lake conditions prevailed, as evidenced in the re-emergence of *C. neglecta* between 8500 and 7200 cal yr BP (Figure 9). The C/N values were relatively high (~15) and represent the mixture of terrestrial and aquatic origins of organic matter [44]. Slightly higher median grain size in both subunits suggests an increase in catchment runoff and an overall more humid hydroclimatic regime, which resulted in deeper paleolake formation during this period. This interpretation is consistent with biomarker data from core OSP-2,

where soil transport played a major role in the observed distribution patterns [46]. These findings provide indirect evidence of human occupation, in the sense of soil disturbances and enhanced soil erosion within the catchment. The upper part of the ostracod zone O2, particularly around 7200 cal yr BP, is characterized again by the dominance of *C. neglecta*, which appears along with *P. cf. relict*a and *P. psammophila*, whose ecological preferences are less well known than those of *M. cordata* and *C. neglecta*. Meisch [43] reports that the *P. cf. relict*a prefers small water bodies, particularly those that dry up in early summer. However, it is also found in littoral zones of lakes, similar to *P. psammophila*. A later one is also reported from a small, temporary pool in Scotland, where mud cracks on the bottom indicated desiccation, thus confirming that limnocytherids are drought resistant [55]. In the lake sediment record from coastal Lake Velo Blato, developed under the influence of Holocene sea-level rise, the lower part of the sediment core is characterized by the *C. neglecta*-*Cyp. vidua*-*P. psammophila* association, indicating an early freshwater phase during the generally wetter early Middle Holocene [6]. At the same time, the stable isotope record of lake carbonates and organic matter suggests that the lake water dissolved inorganic carbon (DIC) was strongly influenced by groundwater flowing through the karst [6]. With limited information about the ecological preferences, we tentatively propose that the upper part of the ostracod zone O2 is characterized by lower water temperatures balanced by the surrounding karst springs, as evidenced by the dominance of *C. neglecta*, with possible seasonal desiccation in marginal parts of the lake, as evidenced by the higher abundances of drought-resistant limnocytherids, particularly *P. cf. relict*a.

The paleolake in OSP-2 core is recorded from 8300 cal yr BP (320 cm). Up to 5300 cal yr BP (185 cm), it also contains occasionally darker grey, high TOC layers of various thickness, and overall high C/N values (~15) and increased median grain size. This indicates a dynamic environment and increased delivery of the material from the catchment. The concentrations of N-alkane and PAH in core OSP-2 increased between 8000 and 6000 cal yr BP, indicating increased input of soil-derived materials from the catchments during wetter climate conditions and enhanced human activity by soil disturbances [56]. The interval represents the period when ostracods appear in the core (Zone O2) (Figure 10). Variations in ostracod assemblages are similar to the previous core OSP-3, with *C. neglecta* dominating in the lower part of the zone O2 (8600–7900 cal yr BP) and *M. cordata* prevailing between 7900 and 6200 cal yr BP. This suggests similar environmental conditions at both coring sites, although asynchronous, probably due to the morphological characteristics of the karst polje. In sediment core OSP-2, total ostracod count sharply declines around 5000 cal yr BP, possibly suggesting the onset of seasonal desiccation in this part of the paleolake, likely due to the lake recession towards the lower (western) parts of the karst polje (Figure 12).

From 7200 to 4600 cal yr BP (OSP-3 270–100 cm), the C/N values remain similar to those in the previous period, with a decreasing trend towards the top of the core. In contrast, TIC and median grain size decreased, while insoluble residue and magnetic susceptibility increased, indicating higher siliciclastic input. They are the highest in the next period between 4600 and 200 cal yr BP (OSP-3 100–50 cm). Here, the TIC content is very low. In both subunits, increased delivery of siliciclastic material from the catchment, related to soil erosion, is suggested. This interpretation is consistent with biomarker data from core OSP-2, where soil transport played a major role in the observed distribution patterns [56]. These findings provide indirect evidence of human occupation, in the sense of soil disturbances and enhanced soil erosion within the catchment.

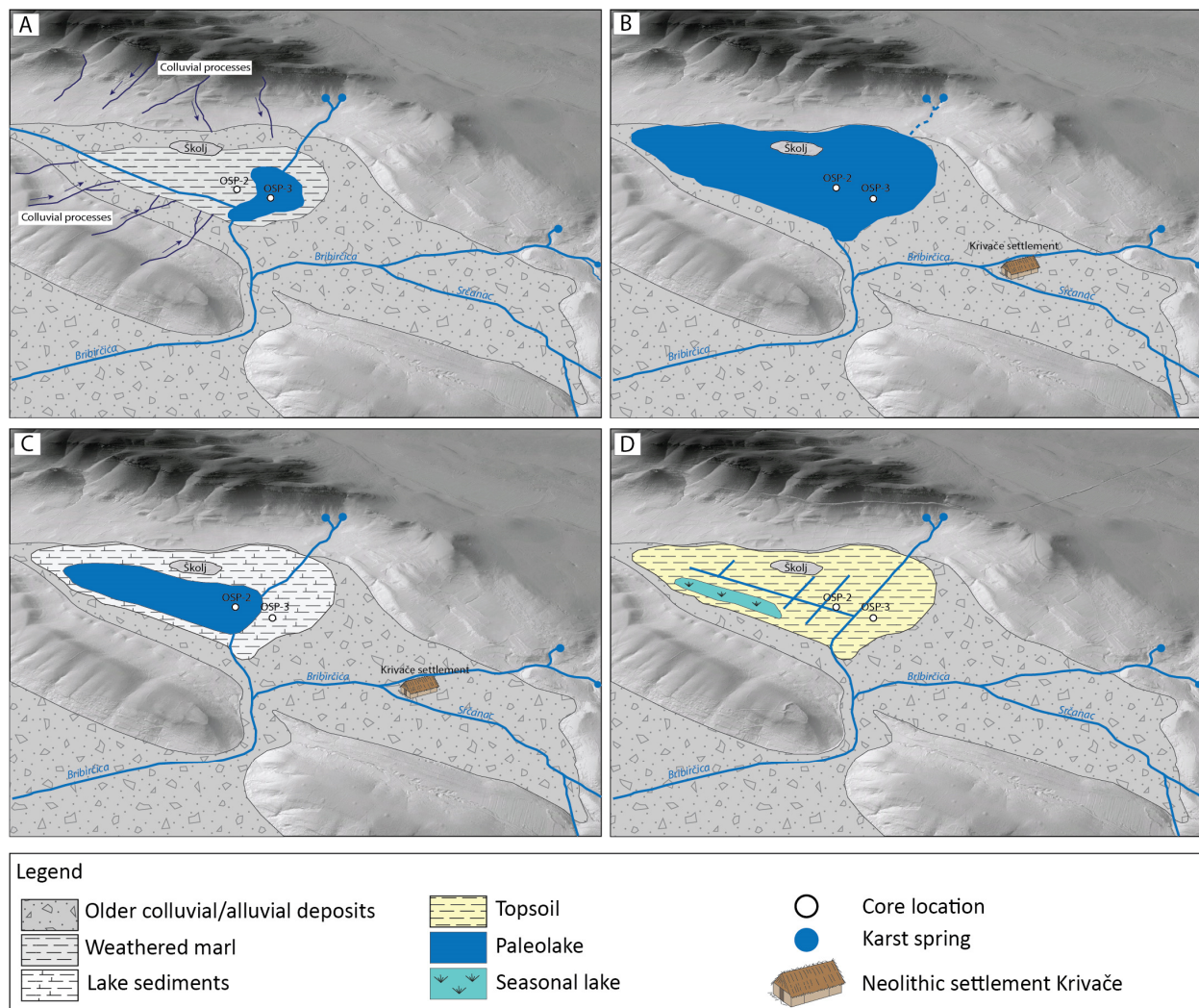


Figure 12. Paleoenvironmental reconstruction of the Bribir–Ostrovica polje based on key sediment core OSP-3. (A) Wetland to shallow lake between 12,100 and 9600 cal yr BP. (B) A deeper and stable lake between 9600 and 7200 cal yr BP. (C) A shallower lake with a dynamic environment between 7200 and 200 cal yr BP. (D) The present seasonally flooded karst polje, covered by topsoil.

In the period from 5300 to 1400 cal yr BP, as indicated by the OSP-2 core interval 185–50 cm, the lower C/N values (~12) and insoluble residue are in contrast to elevated grain size, which again would support a more dynamic depositional environment. Species richness in ostracod zone O3 is relatively high; however, most taxa show discontinuous distributions and occur sporadically in higher abundances, particularly in sediment core OSP-3 (Figure 10). *C. neglecta* is accompanied by *I. cf. bradyi*, a species associated with springs and water bodies fed by springs [43], suggesting the development of a fluvial environment in this part of the B–O karst polje, which is fed by the surrounding karst springs (Figure 2). This is supported by the presence of stygobitic *Mixtacandona* sp. around 5400 cal yr BP, as well as *H. reptans* between 6000 and 5000 cal yr BP, which is commonly found in springs and waters fed by springs [43]. It seems that such conditions appeared later in sediment core OSP-2, where *H. reptans* occurs around 3000 cal yr BP (Figure 10), in line with the notion of lake recession (Figure 12). The last ostracod zone O4 is marked by the complete absence of ostracods in the last ca. 1000 cal yr BP, probably suggesting the complete desiccation of the paleolake in this part of the B–O karst polje, and intensified colluvial processes, as evidenced by the reappearance of Eocene foraminifera.

At present, the Bribir–Ostrovica polje is a seasonally flooded karst polje covered by topsoil.

The lake sediment record from the Bribir–Ostrovica karst polje is in line with other paleoenvironmental interpretations of the eastern Adriatic karst region and central Mediterranean. The Holocene sequence in Lake Vrana on Cres Island (northern Eastern Adriatic coast) indicates an increasing trend of siliciclastic sediments delivered into the lake during the Early and Middle Holocene, dominantly in the interval from 8000 to 4400 cal yr BP [1], which coincides with the humid and pluvial period recorded in the central Mediterranean region [13,57–61]. Stable isotopes from lake sediments and ostracods in Velo Blato on Pag Island (northern Eastern Adriatic coast) indicate wetter climate conditions between 8100 and 7500 cal yr BP, coinciding with the development of a freshwater lake [3,4]. In Pirovac Bay (central Dalmatia), the lake sediments in the freshwater environment were deposited in Early to Middle Holocene prior to being submerged by the marine transgression at 7300 cal yr BP, which suggests high freshwater input from the karstified underground from the adjacent Lake Vrana (Biograd na Moru) and wetter climate conditions [18]. The flooding of calcareous tufa barriers in karst estuary of Lake Prokljan (central Dalmatia) occurred in the period from 8400 to 7500 cal yr BP [9]. The high-resolution Sr/Ca ratios of the bulk lake sediments originating from needle-like aragonite in Lake Veliko Jezero on Mljet Island (southern Dalmatia) enabled the use of this proxy as paleotemperature and paleohydrology indicators, and allowed to distinguish four major (and six minor) cold and dry events, centred at 8300, 6000, 4250 and 2900 cal yr BP [13]. In contrast, the predominance of Mg-calcite over aragonite suggested the opposite [13], i.e., to wetter climate conditions, which are also observed in the wider Mediterranean region during this time period, from 7700 to 7000 cal yr BP [57–60].

Karst poljes Bokanjačko blato (northern Dalmatia) and Prološko Blato (southern Dalmatia) indicate intermittent lake conditions [20–22] during the generally wetter Early–Middle Holocene in central Mediterranean, recorded in Lake Shkodra [62], Lake Ohrid [63], Lake Prespa [64], Lake Dojran [65], Lake Butrint [66], Soreq Cave [57], and the Adriatic Sea [58–61]. In the lake sediments of Bokanjačko Blato and Lake Vrana near Biograd na Moru [6–8], the discrepancy between wetter climate conditions and lower lake levels are supported by the lower sea levels during the Early–Middle Holocene. In the Prološko Blato lake sediment record in the southern Dalmatian hinterland, during the Middle–Late Holocene (8000–2100 cal yr BP), the geochemical and ostracod proxies indicated formation of a deeper lacustrine environment and decreased sediment run-off [22]. This contrasts with other lake sediment records, probably related to enhanced surface and subsurface connectivity within the karst [22]. In the Bribir–Ostrovica karst polje the evolution starts at the Late Pleistocene to Holocene transition (12,100 cal yr BP) with the formation of wetland to shallow lake, progressing to deeper lake between 9600 and 7200 cal yr BP, while during the Middle and Late Holocene it becomes shallower, with a slight shift to increased sediment input towards the last 200 cal yr BP. In the OSP-2 sediment core, lake conditions are evident from 8300 cal yr BP.

5.2. Delineation of the Bribir–Ostrovica Paleolake Extent

The geological map [34,35,67,68] distinguishes the rock units (lithologies) within the polje, emphasizing the Quaternary deposits in both the Bribir–Ostrovica and Žažvić poljes, showing a progressive accumulation of finer lake sediments toward their central parts (Figure 2). The marginal zones of the poljes and the Krivače archaeological site are characterized by colluvial and alluvial deposits. The lake sediment distribution in Žažvić polje is relatively uniform and roughly circular, covering most of the polje. In the B–O polje, the Bribirčica stream is located in the southern part, where it divides the spatial distribution

of lake sediments into a smaller southern and a large northern part. The sedimentological evidence of the lake sediments proved the paleolake's existence from the beginning of the Holocene based on core OPS-3 located in the central part of the B-O polje, north of the Bribirčica stream. The thickest lake sediments are interpreted to occur in the lowest parts of the polje basin, west of the hill Školj, where seasonal flooding is presently observed.

We infer that a paleolake did not form in the south of the Bribirčica stream in the southern part of the polje due to its higher elevation (122–132 m a.s.l.). This area, topographically referred to as Ćoraško polje, is characterized by numerous springs which, during wet seasons, likely played a significant role in increasing water discharge toward the Bribirčica stream. The area probably consisted of a cascade system of small ponds separated by tufa barriers, with high-energy streams and flood events forming a fluvial system. These conditions facilitated the development of tufa deposits, as observed in the area of the Krivače archaeological site, where calcareous tufa was deposited over cultural material [31]. The authors concluded that this horizon indicates prolonged flooding of this part of the polje by the Bribirčica stream, resulting in the partial calcification of fine-grained sandy sediments above the cultural layers. This suggests that a permanent paleolake did not develop at the Krivače settlement, but rather in its vicinity, north of the Bribirčica stream. Therefore, the integration of the geological and geomorphological data from Holocene sediments in the Bribir–Ostrovia and Žažvić poljes enabled the reconstruction of the extent and spatial distribution of lake sediments (Figure 13). The resulting synthesis map provides an important framework for assessing the surface archaeological potential and will be a valuable tool for future archaeological investigations.

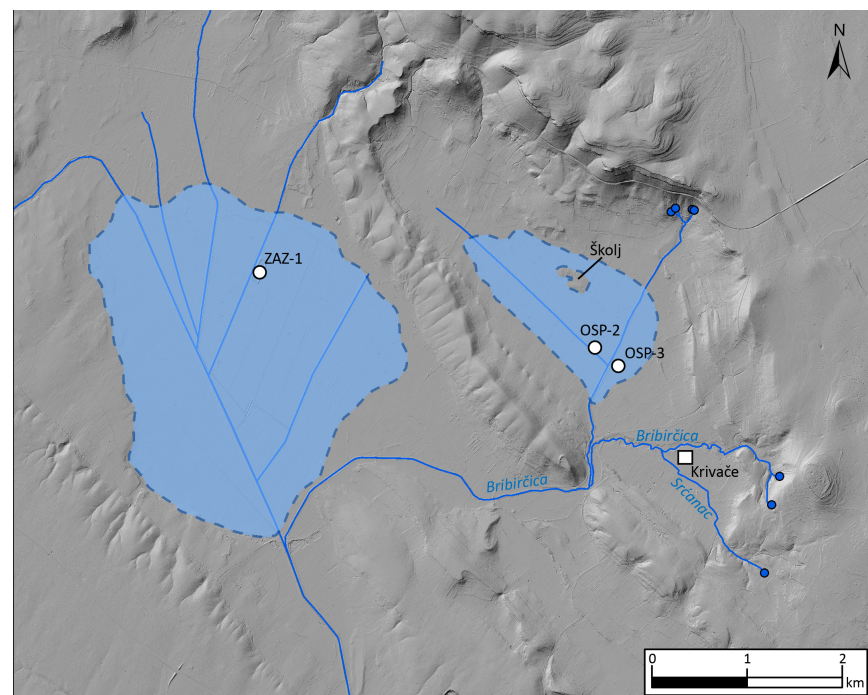


Figure 13. Reconstructed extent of the Holocene paleolakes in Bribir–Ostrovia and Žažvić poljes based on sediment core analysis (white circles) and geomorphological characteristics of the investigated area (the background map is a hillshade map generated from LiDAR-derived DTM [36]). The distribution of lake sediments is restricted to the area north of the Bribirčica stream and did not reach the Krivače archeological site (white square). The hill Školj existed as an island during the paleolake in B-O polje. The blue dots represent karst springs.

Considering that Bribirske Mostine are located at an elevation of 115 m a.s.l., while the OSP-3 sediment core site lies at 114 m a.s.l. and consists of lake sediments over the length

of 4.3 m, it can be assumed that the palaeolake in the Bribir–Ostrovnica polje reached a maximum depth of approximately ~5.5–6 m. This estimate is based on the assumption that the lake surface was hydraulically controlled by the outlet elevation at Bribirske Mostine, which is interpreted as the spillover threshold. Under these conditions, the lake likely attained a water level of around 115 m a.s.l. at approximately 12,100 cal yr BP.

5.3. Archaeological Context of the Krivače Settlement Within the Bribir–Ostrovnica Karst Polje

The eastern Adriatic coast plays a crucial role in understanding the spread of agriculture into Europe from the beginning of the Neolithic period, approximately 8000 years ago, based on identified domesticated plants and animals, and associated pottery [27,28,69–72]. There are indications that the Krivače site occupation within the Bribir–Ostrovnica karst polje spans the entire Neolithic period [73–76], although the Middle Neolithic period is determined in recent studies [27,30,31].

Lake formation in the Bribir–Ostrovnica polje began at ~12,100 cal yr BP, initially as a wetland that evolved into a shallow lake, as evidenced by core OSP-3. Stable lake conditions prevailed between 9600 and 7200 cal yr BP, extending to 4600 cal yr BP, until it was dried out. This overlaps chronologically with the Krivače Middle Neolithic site that was occupied somewhere between 8000 and 6000 cal yr BP [25]. At the site, this was a period characterized by intensive agriculture, settlement growth, and slope disturbances across the edges of the paleolake. These processes are reflected in increasingly dynamic depositional environments and enhanced siliciclastic input from 7200 cal yr BP. This coincided with the onset of settlement around 7300 cal yr BP [27]. However, this increase in terrigenous input may also reflect regional climate changes towards increased precipitation and wetter climate conditions during the mid-Holocene. Therefore, combined climate–human impact could be responsible for this depositional change, rather than attributing it solely to human activity. To further evaluate this interpretation, biomarker analyses were conducted on sediment core OSP-2 [56]. The abundance and distribution patterns of lipid biomarkers, including n-alkanes (plant wax compounds) and polycyclic aromatic hydrocarbons (PAHs; fire indicator compounds) in sediment core OSP-2, are evidence of elevated N-alkane and PAH concentrations between 8000 and 6000 cal yr BP, which could be the result of both changing climate and human activity [56]. The two possible drivers of depositional changes in this interval remain unresolved until further analyses.

The greater thickness in core OSP-2 of the clayey, weathered marls derived from the bedrock reflects a well-developed paleorelief. Therefore, interpretations in karst settings based on sediment cores should be made with caution due to their complex geomorphology. As shown by this example, two nearby sediment cores yielded different depositional ages. We interpret this difference as a result of shallow paleorelief, where sediments were more prone to erosion, in contrast to the deeper paleorelief at the OSP-3 location, which favoured sediment accumulation and earlier lake formation (Figure 12).

The identification of Holocene lake sediments in the Bribir–Ostrovnica polje, near the Krivače site provides strong evidence for favourable paleoenvironmental conditions that supported settlement development. This setting offers an excellent example of the nature of Neolithic ways of life, particularly the importance of close access to water resources. The Krivače faunal assemblage points out the increase in cattle during the Middle and Late Neolithic periods, and pigs in the Late Neolithic [28], which require significantly more water than sheep or goats. Therefore, the environmental conditions may have supported larger cattle herds once established.

The presence of Holocene paleolakes, beyond the Bribir–Ostrovnica and Žažvić poljes in the Ravni Kotari region, northern Dalmatia (Figure 2), significantly enhances our un-

derstanding of past land-use dynamics. This implies potential new settlement locations, transportation routes, and resource availability during prehistoric periods.

5.4. Shortcomings and Prospects

Future research will explore the possibility of a correlation between paleoenvironmental reconstructions derived from the presented sediment cores and additional cores to be collected from the Bribir–Ostrovica and Žažvić karst poljes, given their importance as locations of nearby Neolithic settlements. Since the carbonate-rich geological setting of the study area may influence radiocarbon ages through the potential incorporation of old carbon (reservoir effect), future work will include additional dating of different materials and alternative dating methods to develop an unambiguous chronology of environmental changes. Further investigation will focus on analyses of lipid biomarkers, including glycerol dialkyl glycerol tetraethers (GDGTs), which can be used as paleotemperature proxies. Carbonate clumped isotope proxy is based on the temperature-dependent abundance of the heavier isotopes of carbon (^{13}C) and oxygen (^{18}O) when forming carbonate minerals, and is expressed as the $\Delta 47$ parameter; it can be used to reconstruct past environmental temperatures. A detailed ostracod study will provide complementary paleoenvironmental data, enabling a more robust reconstruction of past environmental changes. These efforts will greatly improve our understanding of the interactions between climatic variability and human activities during the Holocene in this region.

6. Conclusions

The study of sediment cores from the Bribir–Ostrovica and Žažvić karst poljes evidences the presence of a paleolake developed during the Holocene. Sediment cores OSP-2 and OSP-3 from the Bribir–Ostrovica polje provide a comprehensive reconstruction of Holocene environmental dynamics in the Bribir–Ostrovica paleolake, based on sedimentological, mineralogical, geochemical (TOC, TIC), micropaleontological (ostracods), and radiocarbon data. The GPR data reveal a pronounced karstic paleorelief, implying that these two closely spaced cores do not differ substantially in depositional environment, but only in the difference in the timing of the onset of sedimentation. The spatial distribution of the lake sediments shown on the geological map was evaluated and is limited to the area north of the Bribirčica stream in the Bribir–Ostrovica polje. Based on geomorphology and sedimentology, the paleolake was relatively shallow, with maximum water depths likely not exceeding ~6 m. Upland and peripheral areas away from the basin centre mainly contain colluvial and alluvial deposits, reflecting stream and runoff activity rather than a continuous and permanent lake environment.

The sediment core OSP-3 reveals a dynamic environmental history of the lake, marked by distinct phases. The oldest sediments in the core were weathered marls that date back to at least 13,200 years BP, interpreted as bedrock flysch deposits. Between 12,100 and 9600 cal yr BP, the core is characterized by lake silty sediments with organic layers that could have been formed in wetland to shallow lake environments, with high sediment input from the catchment, indicated by high insoluble residue. In the period between 9600 and 7200 cal yr BP, the TIC content increases, with ostracod species indicating the stable lake conditions. During the period from 7200 cal yr BP to 200 cal yr BP, the relatively higher siliciclastic sediment input into the lake is evident by the elevated insoluble residue and magnetic susceptibility, and supports a more dynamic depositional environment.

Our results show that the Holocene lake sediment record from the Bribir–Ostrovica karst polje intersects with the Neolithic archaeological site Krivače, whose human occupation occurred close to this paleolake environment. Based on these findings, the present research proposes further improvements in chronology and additional analyses of lake

sediment cores using both organic and inorganic paleotemperature proxies. Such research will be essential for a more detailed reconstruction of environmental conditions during Neolithic human habitation. In conclusion, the integration of geological, geomorphological and paleoenvironmental data enables precise paleoenvironmental reconstructions, an approach that may contribute to a better understanding of human settlement patterns at the Krivače archaeological site.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/quat9040048/s1>, Supplementary File S1: Sediment core photographs: Sediment core OSP-2 50–460 cm, Sediment core OSP-3 0–266 cm, Sediment core OSP-3B 266–472 cm, Sediment core ZAZ-1 0–450 cm. Supplementary File S2: XRD Mineralogical composition (Table of XRD mineralogical composition and XRD patterns of selected samples), Table S1. Bulk XRD mineralogical composition of all analyzed samples from sediment cores OSP-2, OSP-3 and ZAZ-1, with identified major and minor mineral phases, as well as identified clay minerals on oriented mounts. Figure S1. XRD patterns of selected samples from sediment core OSP-2. Figure S2. XRD patterns of selected samples from sediment core OSP-3. Figure S3. XRD patterns of selected samples from sediment core ZAZ-1.

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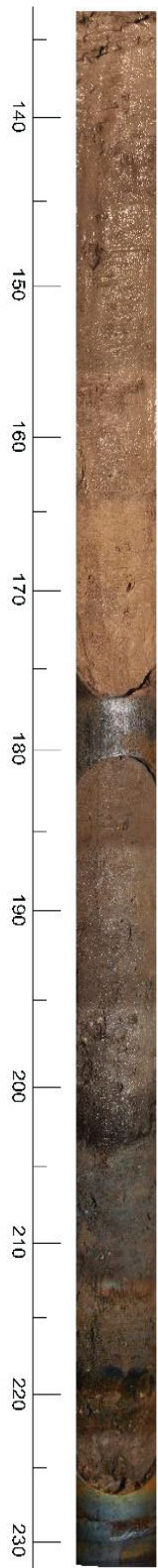
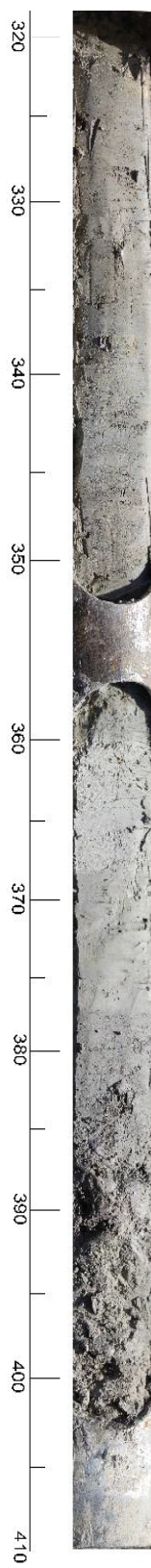
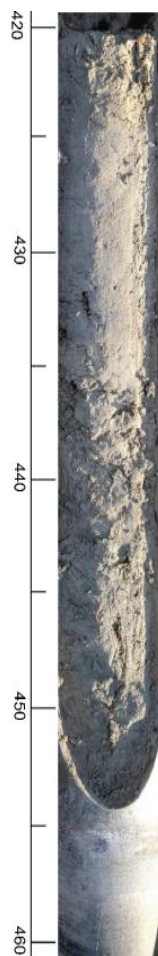
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Supplementary material to research paper 3

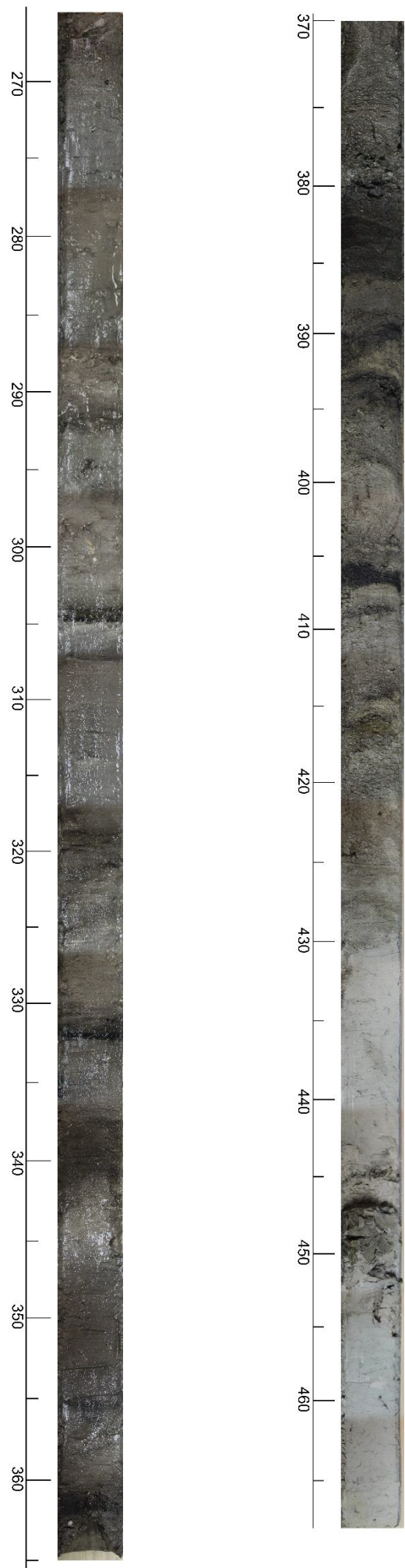
Sediment core OSP-2 50–460 cm



Sediment core OSP-3 0–266 cm



Sediment core OSP-3B 266–472 cm



Sediment core ZAZ-1 0–450 cm

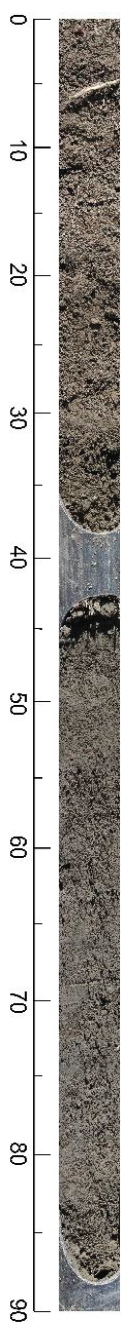
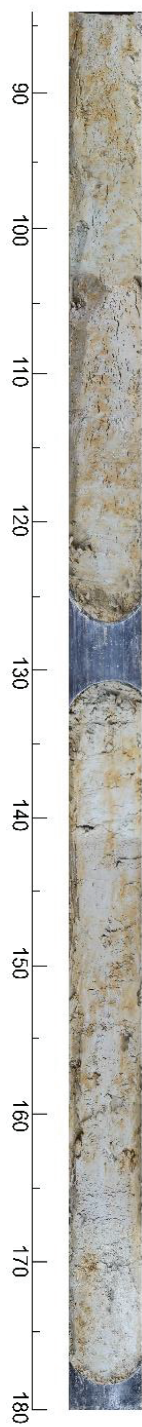
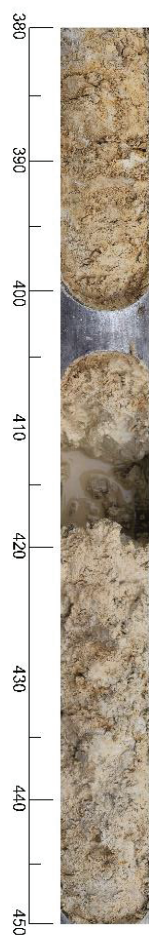


Table S1. Bulk XRD mineralogical composition of all analyzed samples from sediment cores OSP-2, OSP-3 and ZAZ-1, with identified major and minor mineral phases, as well as identified clay minerals on oriented mounts. Mineral abbreviations: Cal: calcite, Dol: dolomite, Qtz: quartz, Ms/I: muscovite/illite, Sm: smectite, Chl: chlorite, Kln: kaolinite.

Nr.	Sediment core	Sample (cm)	Sed. units	XRD Mineralogical composition		Identified clay minerals
				Major mineral phases	Minor mineral phases	
1	OSP-2	0-5	3	Cal	Qtz	Sm, Ill, Kln
2	OSP-2	40-45	3	Cal	Qtz	
3	OSP-2	50-51	3	Cal		
4	OSP-2	58-59	2/2	Cal	Qtz	Sm, Ill, Kln
5	OSP-2	84-85	2/2	Cal		
6	OSP-2	100-101	2/2	Cal	Qtz	
7	OSP-2	120-121	2/2	Cal		
8	OSP-2	135-136	2/2	Cal		
9	OSP-2	148-149	2/2	Cal		
10	OSP-2	166-167	2/2	Cal	Qtz	
11	OSP-2	176-181	2/2	Cal	Qtz	Sm, Chl, Ill, Kln
12	OSP-2	196-197	2/1	Cal		
13	OSP-2	220-221	2/1	Cal		
14	OSP-2	242-243	2/1	Cal	Qtz	
15	OSP-2	262-263	2/1	Cal	Qtz	Sm, Chl, Ill, Kln
16	OSP-2	280-281	2/1	Cal	Qtz	
17	OSP-2	290-291	2/1	Cal		
18	OSP-2	297-298	2/1	Qtz, Cal	Sm, Chl, Ms/I, Kln	
19	OSP-2	321-322	1/2	Cal, Qtz, Dol	Sm, Chl, Ms/I, Kln	
20	OSP-2	330-331	1/2	Cal, Qtz, Dol	Sm, Chl, Ms/I, Kln	
21	OSP-2	350-351	1/2	Cal, Qtz, Dol	Sm, Chl, Ms/I, Kln	Sm, Chl, Ill, Kln
22	OSP-2	370-371	1/2	Cal, Dol, Qtz	Sm, Chl, Ms/I, Kln	
23	OSP-2	387-392	1/2	Cal, Dol, Qtz	Sm, Chl, Ms/I, Kln	
24	OSP-2	409-412,5	1/1	Cal, Dol, Qtz	Sm, Chl, Ms/I, Kln	
25	OSP-2	420-425	1/1	Cal, Dol, Qtz	Sm, Chl, Ms/I, Kln	
26	OSP-2	441-446	1/1	Cal, Dol, Qtz	Sm, Chl, Ms/I, Kln	Sm, Chl, Ill, Kln
27	OSP-2	459-460	1/1	Cal, Dol, Qtz	Sm, Chl, Ms/I, Kln	
28	OSP-3	0-5	3	Cal, Qtz		Sm, Ill, Kln
29	OSP-3	50-51	3	Cal, Qtz		
30	OSP-3	80-81	2/4	Cal, Qtz		Sm, Ill, Kln
31	OSP-3	116-123	2/3	Cal, Qtz		
32	OSP-3	150-151	2/3	Cal, Qtz		Sm, Ill, Kln
33	OSP-3	180-181	2/3	Cal, Qtz	Ms/I	
34	OSP-3	200-201	2/3	Cal, Qtz	Ms/I	
35	OSP-3	230-231	2/3	Cal, Qtz	Ms/I	Sm, Ill, Kln
36	OSP-3	260-261	2/3	Cal, Qtz		Sm, Ill, Kln
37	OSP-3B	270-272	2/2	Cal, Qtz		
38	OSP-3B	300-302	2/2	Cal		Sm, Ill, Kln
39	OSP-3B	320-322	2/2	Cal	Qtz	
40	OSP-3B	350-352	2/1	Cal		Sm, Ill, Kln
41	OSP-3B	376-378	2/1	Cal		
42	OSP-3B	389-390	2/1	Cal	Qtz, Dol	Sm, Ill, Kln
43	OSP-3B	400-401	2/1	Cal	Qtz, Dol	
44	OSP-3B	420-421	2/1	Cal	Qtz, Dol	Sm, Chl, Ill, Kln
45	OSP-3B	440-441	1	Cal, Dol, Qtz	Ms/I, Sm, Chl, Kln	Sm, Chl, Ill, Kln

46	OSP-3B	460-461	1	Dol, Cal, Qtz	Ms/I, Sm, Chl, Kln	Sm, Chl, Ill, Kln
47	OSP-3B	467-468	1	Dol, Cal, Qtz	Ms/I, Sm, Chl, Kln	
48	ZAZ-1	0-5	3	Cal	Qtz	
49	ZAZ-1	51-52	3	Cal	Qtz	
50	ZAZ-1	60-61	2/2	Cal	Qtz, Ms/I, Sm, Chl, Kln	
51	ZAZ-1	87-96	2/2	Cal	Qtz	
52	ZAZ-1	110-111	2/1	Cal	Qtz	
53	ZAZ-1	210-211	1/2	Cal	Qtz, Ms/I, Sm, Chl, Kln	
54	ZAZ-1	250-251	1/2	Cal	Qtz, Ms/I, Sm, Chl, Kln	
55	ZAZ-1	300-301	1/2	Cal	Qtz, Ms/I, Sm, Chl, Kln	
56	ZAZ-1	370-375	1/1	Cal	Qtz, Ms/I	
57	ZAZ-1	440-450	1/1	Cal	Qtz, Ms/I	

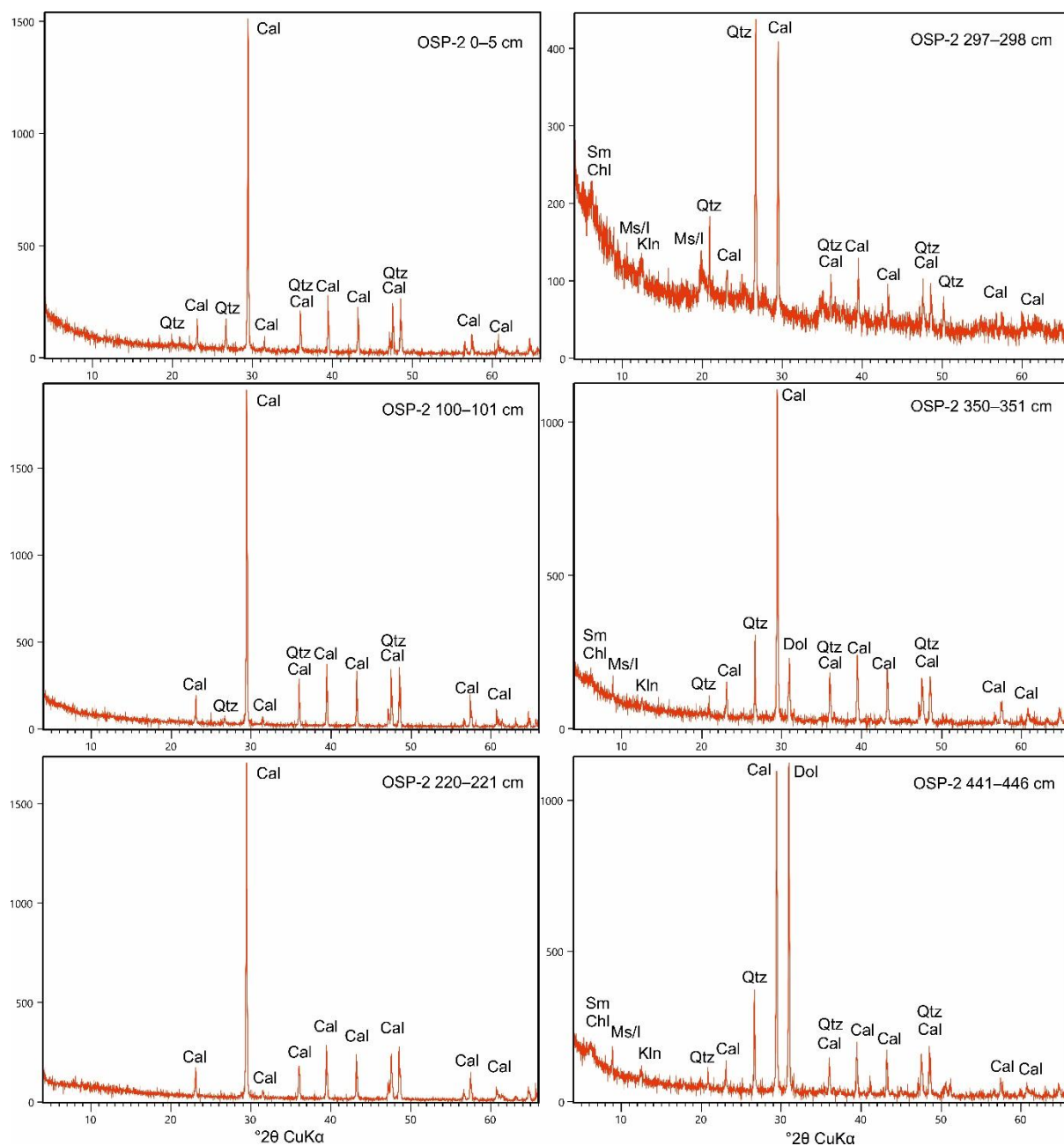


Figure S1. XRD patterns of selected samples from sediment core OSP-2. Mineral abbreviations: Cal: calcite, Dol: dolomite, Qtz: quartz, Ms/I: muscovite/illite, Sm: smectite, Chl: chlorite, Kln: kaolinite.

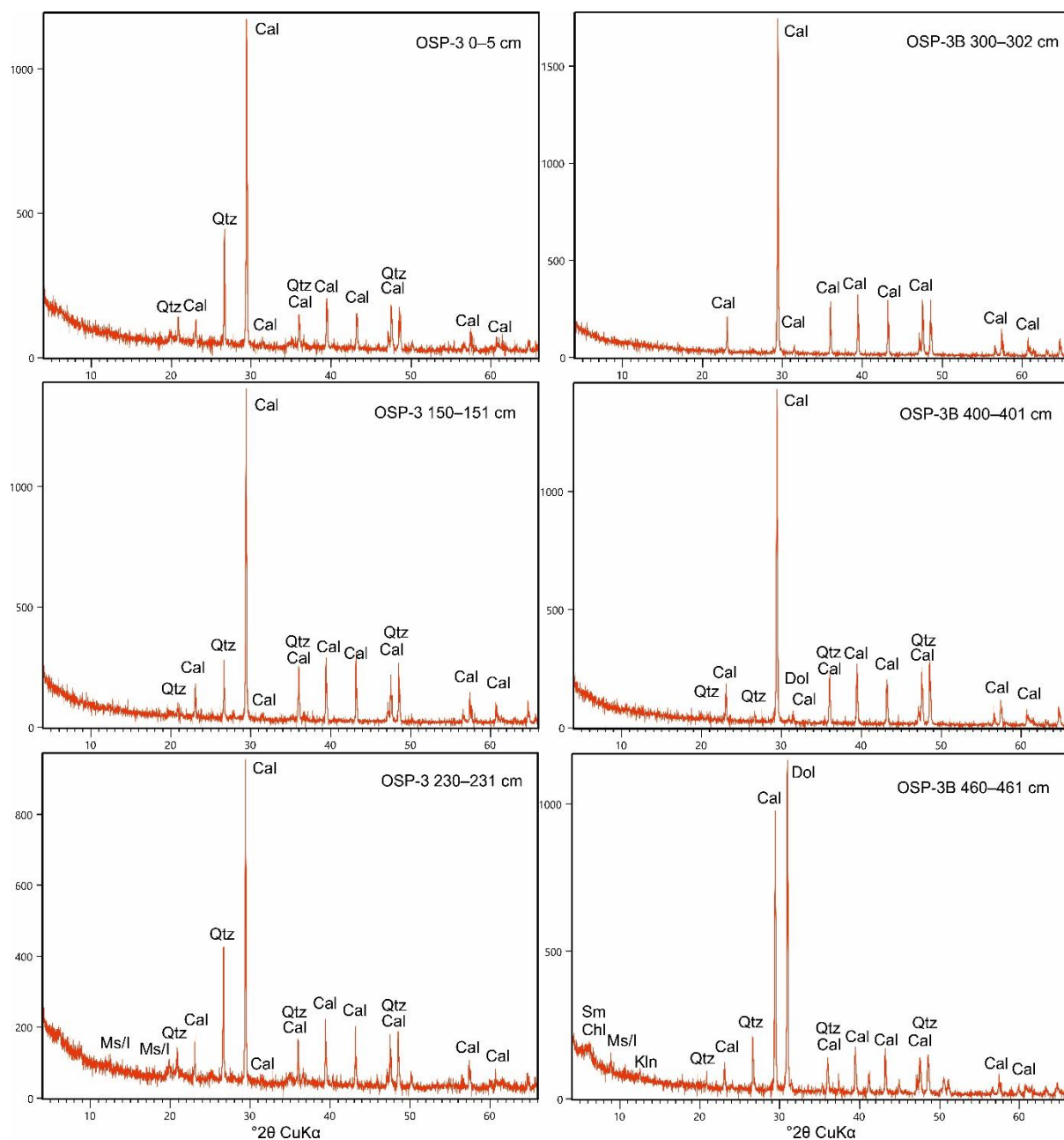


Figure S2. XRD patterns of selected samples from sediment core OSP-3. Mineral abbreviations: Cal: calcite, Dol: dolomite, Qtz: quartz, Ms/I: muscovite/illite, Sm: smectite, Chl: chlorite, Kln: kaolinite.

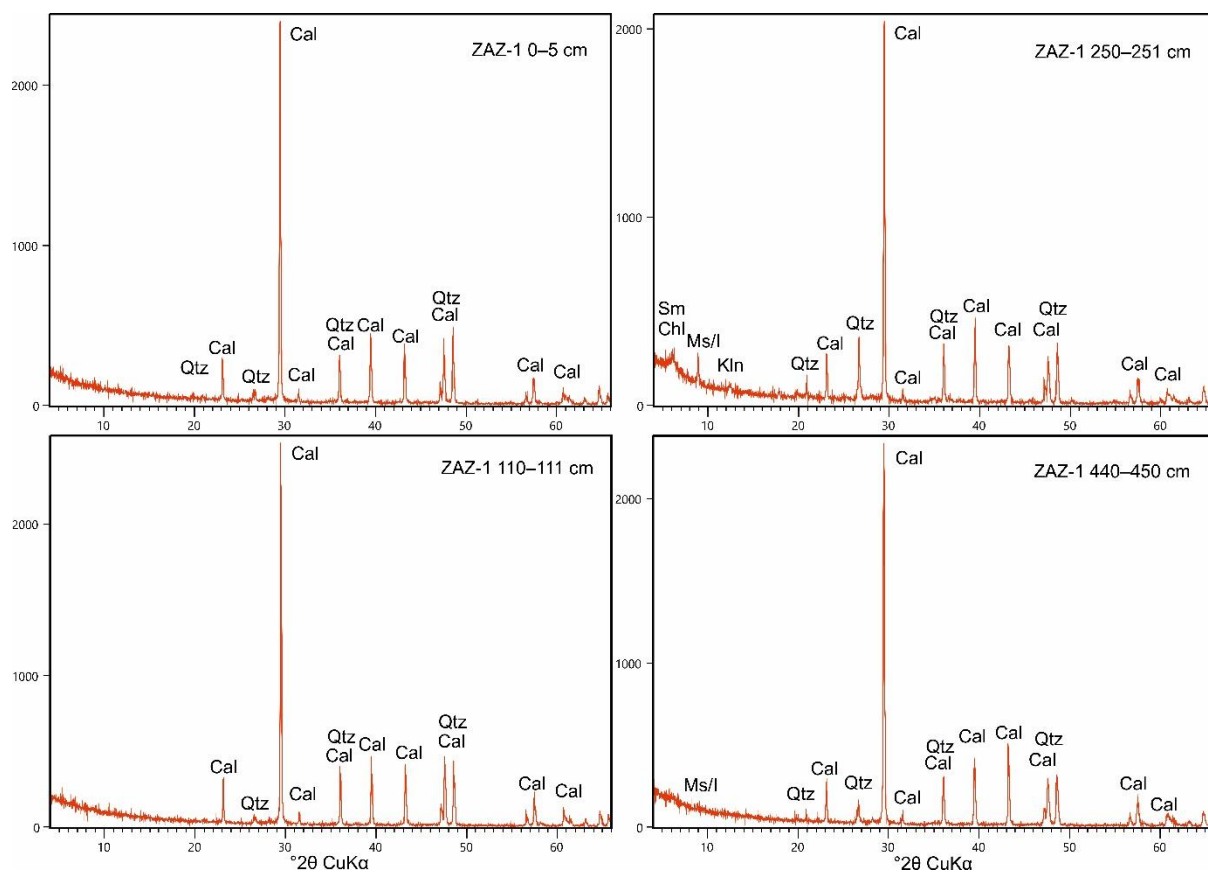
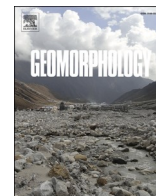


Figure S3. XRD patterns of selected samples from sediment core ZAZ-1. Mineral abbreviations: Cal: calcite, Qtz: quartz, Ms/I: muscovite/illite, Sm: smectite, Chl: chlorite, Kln: kaolinite.

Research paper 4

Ivkić Filipović, I., Ilijanić, N., Miko, S., Hasan, O., Brunović, D., Kordić, B., Barudžija, U. & Sladović, Ž. (2025). Late Quaternary geomorphology and sedimentary processes in the Prološko Blato karst wetland (Imotsko Polje, Croatia). *Geomorphology* 482, 109765, Copyright Elsevier. doi: 10.1016/j.geomorph.2025.109765.



Late Quaternary geomorphology and sedimentary processes in the Prološko Blato karst wetland (Imotsko Polje, Croatia)[☆]

Ivona Ivkić Filipović^a, Nikolina Ilijanić^{a,*}, Slobodan Miko^a, Ozren Hasan^a, Dea Brunović^a, Branko Kordić^a, Uroš Barudžija^b, Željka Sladović^c

^a Croatian Geological Survey, Milana Sachsa 2, 10 000 Zagreb, Croatia

^b University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10 000 Zagreb, Croatia

^c Geoda Consulting LLC, Ul. kralja Zvonimira 13, 10 000, Zagreb, Croatia

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ABSTRACT

Karst polje depressions are particularly well-known in the Dinarides. Here we present the results of comprehensive research in Prološko Blato karst wetland situated in one of the largest karst poljes in Croatia – Imotsko Polje. The Prološko Blato is characterized by sinkholes filled with water (karst lakes) and seasonally flooded karst polje. The sediments were retrieved using coring and profile sampling in erosional channels during the dry season. Geomorphological characteristics were analyzed using the digital elevation model (DEM), Unmanned Aircraft System (UAS) and ground penetrating radar (GPR). Morphology and bathymetry of karst lakes were investigated using sub-bottom profiling and sidescan sonar survey. The evolution of the Prološko Blato can be tracked from the Last Glacial Period when alluvial fan sedimentation was the dominant process in the karst polje. The alluvial sedimentation ceased with coarse-grained (gravel) deposition in the distal part of the alluvial fan during the deglaciation period (after ~19,000 cal yr BP). During the Early Holocene, a progressive deepening of the basin enabled the development of a shallow lake/wetland characterized by enhanced detrital input, thus suggesting wetter climate conditions between ca. 9000 and 8000 cal yr BP. This is followed by a relatively long period (from ca. 8000 to 800 cal yr BP) of lacustrine carbonate sedimentation in a deeper lacustrine environment. Around 800 cal yr BP, sediments are characterized by disturbed clayey/carbonate sediments with numerous intercalations, pointing to a disturbance in the paleolake. At the same time, geomorphological characteristics of the area suggest sinkhole formation in the paleolake's marginal part, which hypothetically led to the desiccation of the paleolake and the establishment of a modern seasonally flooded karst wetland. This research demonstrated the existence of Holocene paleolake sediments in Prološko Blato, thus confirming that karst poljes contain valuable terrestrial paleoclimate/paleoenvironmental sediment archives.

1. Introduction

Karst poljes are one of the largest surface karst landforms and are defined as flat-floored enclosed depressions in limestone karst (Bonacci, 2004; Ford and Williams, 2007). They are very common in the Dinaric karst belt, especially in the central Dinarides, where they are distributed in a cascading manner from the highest peaks (higher poljes) to the Adriatic Sea (lower poljes) (Mijatović, 1984). A polje depression is usually bounded by major faults in the NW–SE direction known as the “Dinaric strike”, implying a tectonic influence on its formation. However, paleoclimatic changes in Oligo-Miocene and Quaternary led to

alternating chemical and mechanical erosion that shaped the karst poljes into modern landscapes (Mijatović, 1984). Hence, various depositional environments were formed, of which the Miocene Dinaride Lake System is best known (e.g., de Leeuw et al., 2011, 2012; Jiménez-Morero et al., 2009; Mandić et al., 2009). Dinaric karst poljes are characterized by complex hydrological and hydrogeological features, such as springs, losing and sinking rivers (ponornica), swallow holes (ponors) and estavelles (Bonacci, 2013). Moreover, they are regularly flooded in the cold and wet part of the year due to the rising groundwater level and/or when the inflow exceeds the maximum capacity of the ponors (Bonacci, 2013). Thus, poljes represent important natural retentions of

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* Corresponding author.

E-mail address: niljanic@hgi-cgs.hr (N. Ilijanić).

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water and as such, they are thoroughly studied in terms of their hydrology and hydrogeology (e.g., Mayaud et al., 2019; Bonacci and Roje-Bonacci, 2000; Kovačić and Ravbar, 2010; Ravbar et al., 2021; Filipović et al., 2023).

Despite the long tradition of karst research in the region, Quaternary sedimentary deposits of Dinaric karst poljes remain poorly investigated in terms of their occurrence, thickness, and origin. Comprehensive studies of these deposits, formed in the latest phase of the polje formation, might provide critical information on the complex genesis of karst poljes. Moreover, the deposition of these sediments was highly influenced by dynamic climate and environmental changes throughout the Quaternary, and these sediments most likely capture valuable information about the Quaternary paleoenvironmental changes via their physical, biological and geochemical proxies.

In this study, we present the results of research undertaken in one of the largest karst poljes in Croatia, the Imotsko Polje, located in the Dalmatian hinterland. The Imotsko Polje is best known for its karst lakes, which are in fact sinkholes filled with water. The area is home to one of the largest sinkholes in the world, the Red Lake (Crveno jezero) and Blue Lake (Modro jezero), near the city of Imotski. Red Lake is particularly well known in the karst literature as an example of a >500 m deep cylindrical chasm with a depth of 6 m below the sea surface (Bonacci and Andrić, 2014; Ford and Williams, 2007; Kranjc, 2013; Williams, 2004). Less famous, although still impressive, is a group of sinkholes and karst lakes situated in the NW part of the polje and called the Lokvičići Lake System. This lake system hosts our research area, a seasonally flooded karst wetland called the Prološko Blato. Seasonal fluctuations in the local water table change the environment of Prološko Blato from wetland to dry polje and leave behind distinctive erosional channels with exposed successions of Late Quaternary sediments. Thus, it is an ideal site to study the latest phases of karst polje evolution. This study has four main aims: 1) to characterize the Prološko Blato

geomorphological setting via DEM, UAS, and bathymetry and morphology of karst lakes using the sub-bottom profiling and side-scan sonar survey, 2) to provide lithological description and age of the Late Quaternary sediments of the Prološko Blato using the sediment cores and exposed profiles in erosional channels, coupled with radiocarbon dating 3) to confirm the extent of Late Quaternary sediments in the subsurface using the GPR method, and 4) to reconstruct the Prološko Blato paleoenvironmental evolution throughout the Late Quaternary.

2. Study area

2.1. Geological setting

The Imotsko Polje is one of the largest Dinaric karst poljes, with a surface area of 95 km², length of 33.3 km, and width of 1 to 6 km. The polje is situated in the Dalmatian hinterland, with 45 km² in Croatia and 50 km² in western Herzegovina (Fig. 1A). The wider area of the polje is surrounded by the Biokovo mountain (1762 m above sea level (asl)) in the SW part, Zavelim (1347 m asl) in the NE part, and Čvrsnica (2228 m asl) further NE in Herzegovina. This region belongs to the central part of the Dinarides known as the Dinaric high karst zone, built of Cretaceous carbonates, Paleogene clastic deposits (marls, sandstones, conglomerates) known as flysch and Promina beds, Miocene marls, and various types of Quaternary sediments (Korbar, 2009; Raić and Papeš, 1978) (Fig. 1B). Bauxite deposits can be found in a wider area. The region is structurally deformed and seismically active as a result of compressional tectonic movements associated with the collision of the Adriatic microplate and the Dinarides (Dragičević et al., 1999; Kuk et al., 2000). The polje is bounded by the main fault zones stretching in the NW–SE direction (Dinaric strike), which are crucial in the structural development of the depression (Dragičević et al., 1999). However, Quaternary erosional and depositional processes (mainly alluvial) shaped the

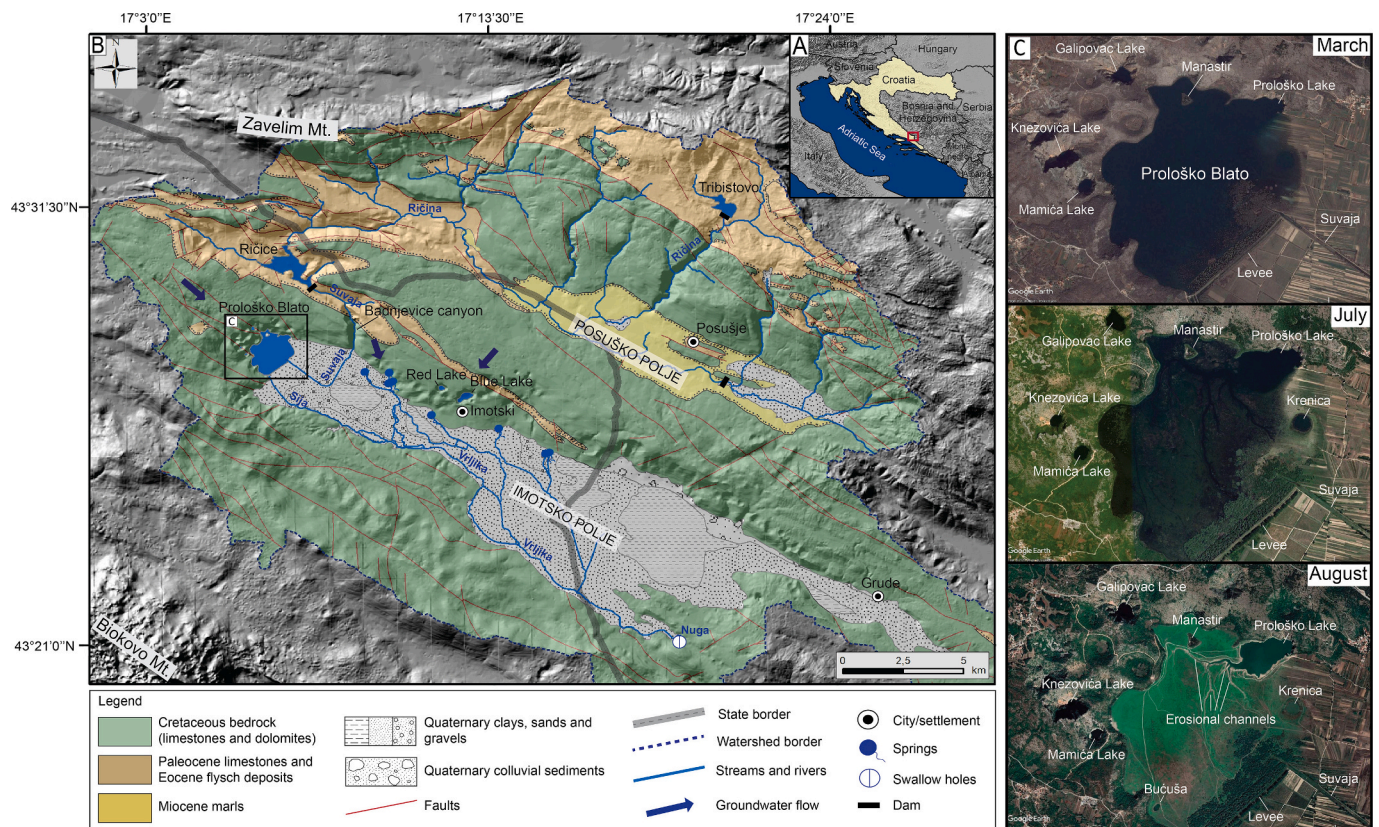


Fig. 1. (A) Geographical position of the study site, (B) geology and hydrogeology of the Imotsko Polje catchment area (modified after Bonacci and Roje-Bonacci, 2000; Raić et al., 1976; Roglić, 1938), and (C) Google Earth satellite images of seasonal flooding in the Prološko Blato karst wetland.

depression into the modern karst polje (Roglić, 1938). Earlier research drilling in the polje revealed that the Quaternary infilling is 105 m thick in the SE part and 145 m thick in the NW part and is composed of various alluvial sediments with occasional bituminous clays (Sakač and Jović, 1958). The lack of Neogene deposits, which are present in many other Dinaric basins (e.g., Sinjsko polje, Livanjsko polje, Duvanjsko polje) (see de Leeuw et al., 2012), suggests a younger age of formation of the Imotsko Polje (Raić and Papeš, 1978; Sakač and Jović, 1958).

2.2. Karst hydrology and hydrogeology

The hydrogeology of the Imotsko Polje is complex due to the karstified nature of limestone bedrock. Quaternary sediments in the polje represent a partial barrier for groundwater flow, affecting the occurrence and distribution of hydrogeological features and flow regimes (Bojanić et al., 1981). Major features include karst springs and ponornica rivers, ponors (swallow holes), estavelles, sinkholes (dolines), and karst lakes. Most karst springs are distributed along the N–NE margin of the polje (Fig. 1B), where major faults meet Quaternary sediments (Bojanić et al., 1981). The hydrology of the polje is controlled by the precipitation rates in the mountainous region of western Herzegovina. The major ponornica river, the Ričina, flows from the Tribistovo dam (901 m asl) through the Posuško polje (570–620 m asl) into the Ričice retention basin. From here, the river is called Suvaja and flows through the Badnjevice Canyon into the Imotsko Polje (250–300 m asl), where it meets the river Vrljika and sinks into the Nuga ponor (Fig. 1B). The many names of this same river are a result of a cascading drainage path typical of the central Dinarides (Bonacci and Roje-Bonacci, 2008; Ford and Williams, 2007). As with many other karst poljes, the Imotsko Polje is regularly flooded in the wet part of the year, although this flooding is limited to the margins of the polje, such as the Prološko Blato in its NW part. Before the 20th century, flooding was severe, especially at the Suvaja River's mouth, where flash floods often caused damage to houses and crops and consequently famine and diseases (Ujević, 1991). Flooding was regulated in the 20th century with the construction of many artificial channels and, most importantly, the Ričice retention basin (dam) in 1987 (Fig. 1B).

2.3. The Prološko Blato

The Prološko Blato is a seasonally flooded karst wetland in the NW part of the Imotsko Polje. It is part of the Lokvičići Lake System, a group of karst lakes interconnected via groundwater, which includes Galipovac Lake, Knezovića Lake and Mamića Lake (Fig. 1C). The area is protected as a significant landscape and is part of the Natura 2000 network due to its rich bio- and geo-diversity. Prološko Blato is mostly fed by groundwater and partially by the Suvaja River (Bonacci and Roje-Bonacci, 2000). Groundwater discharge occurs in early winter through many estavelles along the NW margin of the polje. The major estavelle is Prološko Lake in the NE, which is directly connected to the groundwater (Bonacci and Roje-Bonacci, 2000). Seasonal flooding turns the area into a larger but relatively shallow (1–6 m) lake with wetland vegetation (Fig. 1C), overflowing two smaller lakes, Krenica and Bućuša, locally known as oka (eyes). One small, isolated hill called the Manastir in the northern part remains above the water level as an island. The island contains ruins of the 16th-century Franciscan monastery, i.e., from the time of Ottoman occupations of SE Europe. The Franciscans used this natural phenomenon for protection from Ottoman attacks. According to the local folklore, they managed to keep the water level high by burying the estavelles along the margins of the Prološko Blato to incapacitate their function as ponors (Ujević, 1991). Nevertheless, the area today is seasonally flooded. The water level is regulated with the construction of an artificial levee and Sija outflow channel, which eventually merges with the Vrljika River in the central part of the Imotsko Polje (Fig. 1B).

3. Methods

3.1. Field methods

A bathymetric survey of the lakes in Prološko Blato was conducted with the Humminbird 999 HD SI combo echo sounder and side-scan sonar in combination with a Humminbird AS + GPS HS precision GPS receiver with a heading sensor. The obtained side-scan images were analyzed in the Reef Master 2.0 software package. A high-resolution seismic survey was carried out in Prološko Lake using the Innomar SES-2000 dual frequency sub-bottom profiler (SBP), using two low frequencies of 4 kHz and 6 kHz. In total, 32 seismic profiles were obtained covering the entire Prološko Lake area. For time-depth conversion, we assumed a constant sound velocity of 1500 m sec^{-1} . Seismic data were converted into SEG-Y format and processed and interpreted using Geo-Suite Allworks software.

Ground penetrating radar (GPR) was used on the land surfaces during the dry season (October 2020) to obtain more extensive information on the subsurface features present in the area. It was a complemented method to traditional surveying methods (outcrop sampling and coring), as it is faster and requires significantly less time for a larger surface area. GPR emits short pulses of electromagnetic waves into the subsurface and detects reflected signals at the interfaces between materials with different electromagnetic properties (Blindow et al., 2007). Although the GPR is widely used in karst environments, mainly for the detection of caves and subsidence areas, the penetration of the GPR signal can be affected by complex conditions in the field (Čeru and Gosar, 2019). For example, the penetration depth is greatly affected when dealing with materials with high conductivity (e.g., clays), which can attenuate radar energy and reduce exploration depth (Barr, 1993).

GPR profiles were acquired using the MALÅ GX (ground explorer) equipment, which contains two separate components: the GX Controller and the GX antenna connected through a single data/power cable. Geopositioning was obtained through inbuilt DGPS and external GPS. The frequency of 80 MHz was used, as we presumed it would provide better penetration depth to detect the boundaries between lacustrine and underlying coarser alluvial sediments (up to 25 m). Georadar signal processing was performed with Reflexw software. The workflow includes data sorting, profile summation, velocities calculation based on hyperbolas, time-zero correction, background removal, gain correction, bandpass filtering, static topography correction, and 2D filtering (xy average) (Figs. S2 and S3 in Supplementary material).

UAS missions for geomorphological characterization were conducted in the autumn of 2020. The SfM technique was employed to build a classified point cloud and generate a digital surface model (DSM) and orthophoto of the Prološko Blato research area ($\sim 4.2 \text{ km}^2$). The orthophoto image and DSM with a 5 cm Ground Sample Distance (GSD) were created using the eBee Plus RTK/PPK Fixed Wing UAS, equipped with senseFly S.O.D. A 3D camera, and eMotion 3 software for mission planning and aircraft control. The orthophoto and DSM were generated with Pix4D software version 4.0.18 and displayed in the HTRS96/TM reference coordinate system. The orthophoto image was used for visual characterization of geomorphological features and processes, such as capturing the erosional processes in the area and spring activity in flooding period, while the DSM was used for detailed surface visualization of the terrain.

Sediments of the Prološko Blato were drilled in the polje and sampled from outcrops within erosional channels during the dry season. The cores were drilled with Eijkelpkamp Cobra TT drilling equipment with a core diameter of 10 cm. Each core was sectioned into 10 cm intervals in the field, stored in plastic core boxes, and transported to the Croatian Geological Survey. Core PB-1 ($43^\circ 28' 23'' \text{N}$, $17^\circ 7' 5'' \text{E}$) is located on the southern shore of the Prološko Lake (Fig. 2), where we presumed lower thickness of the paleolake sediments. The core was drilled with Cobra TT (October 2018) up to a depth of 4 m, while the rest of the sediment (4–6.5 m) was sampled from the exposed outcrop (Profile PBP), and

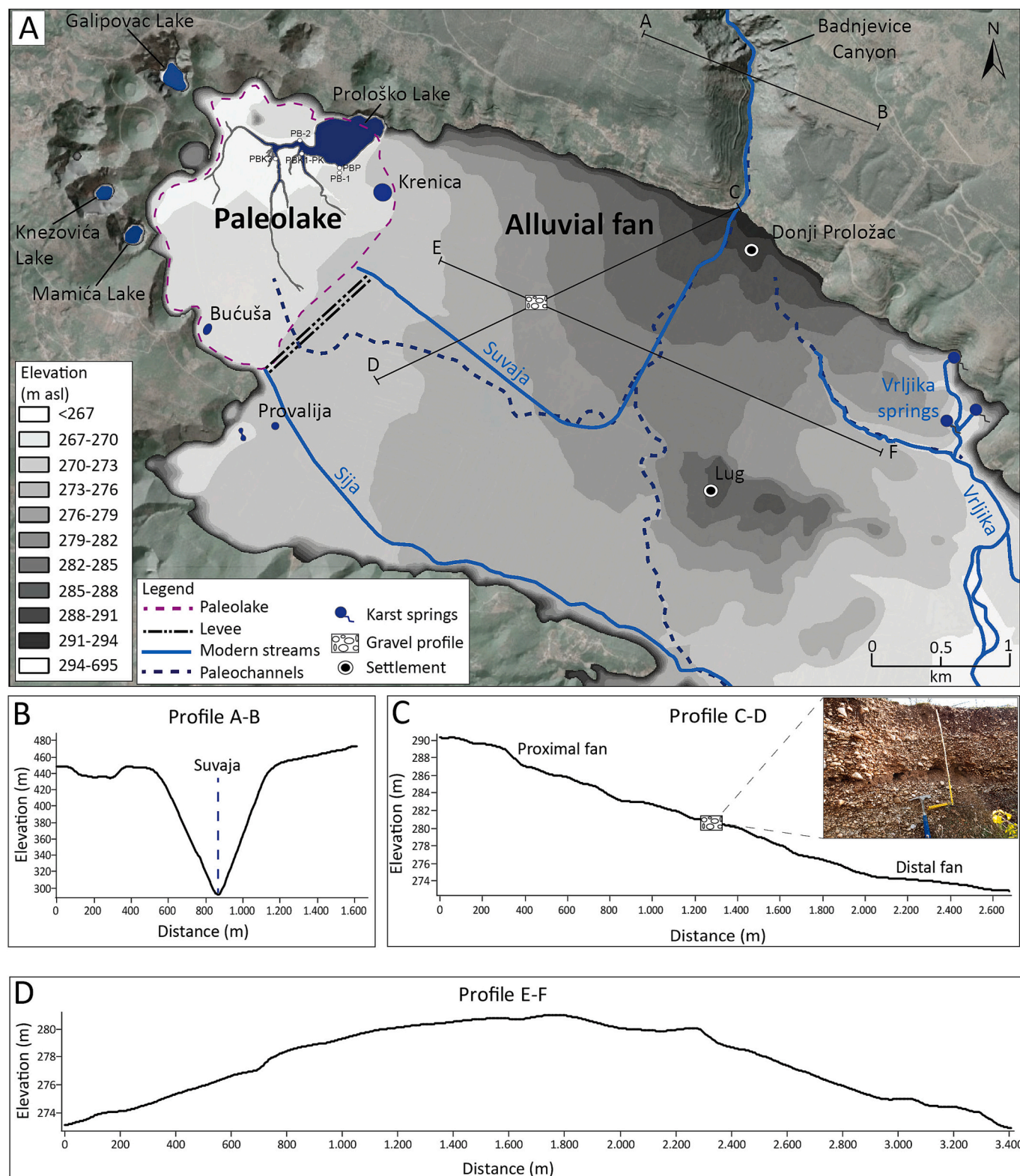


Fig. 2. (A) Geomorphological setting of the research area, (B) the cross profile of the incised feeder channel (Badnjevice Canyon), (C) radial profile and (D) cross profile of the alluvial fan. The DEM is overlapped with the hillshade map and orthophoto image (Geoportal of the State Geodetic Administration). Elevations 294 to 695 m asl are transparent to enhance the hillshade effect of sinkholes and Badnjevice Canyon. Suvaja paleochannels were mapped from historical cadastral maps (Cadastral Maps of the Habsburg Empire, 1835). Note the gravels on radial profile C—D.

master core is designated as PB-1. Core PB-2 (43°28'30"N, 17°6'54"E) is located on the northern shore of the main erosional channel (Fig. 2). It was drilled with Cobra TT (October 2020) up to 6.2 m, while the deeper sediments from 6.2 m to 7.5 m were sampled in an exposed outcrop, and from 7.5 m up to 9.2 m it was drilled again. The total composite core consists of four segments: PB-2 A, PB-2B, PB-2 PROFILE, PB-2C, and the master core is designated as PB-2. The profile PBK1-PK (43°28'27"N, 17°6'53"E) was sampled up to a depth of 6.3 m from an erosional channel, 279 m away from the PB-1, while PBK3 (43°28'26"N, 17°6'45"E) in another larger erosional channel 452 m away from the PB-1 (Fig. 2). Profile PBK1-PK was lithologically described and sampled in lower resolution, while the profile PBK3 was sampled for radiocarbon dating. Both profiles were used for correlation with defined sedimentary units in PB-1 and PB-2, to confirm the extent and thickness of paleolake sediments.

3.2. Laboratory analysis

The initial core description was used for overlapping individual core segments and for the correlation of the cores and profiles. Core PB-1 was sliced at a 1 cm resolution, except in disturbed intervals (topsoil, sand, gravel). Core PB-2 was subsampled every 10th cm, while the rest of the core was preserved in cold storage. Samples taken for further analysis were freeze-dried and crushed in an agate mortar.

Magnetic susceptibility was measured using the Bartington MS2E surface sensor and the MS2B dual-frequency sensor. The MS2E surface sensor was used for surface sediment core samples and the measurement resolution was every cm. The results were expressed as volume magnetic susceptibility, measured at low frequency (κ_{lf} , 10^{-5} SI). For measurements of magnetic susceptibility using the dual-frequency sensor (MS2B), samples were packed in 10 cm³ plastic pots and weighed before measurement at two frequencies (0.46 kHz and 4.6 kHz). The obtained results were presented as the mass magnetic susceptibility (χ_{lf}) and dual frequency mass magnetic susceptibility (χ_{fd}). The color of the sediments was determined with a Munsell Color Chart (Munsell Color, 1994) and measured with an X-rite spectrophotometer (X-Rite DTP22/Digital Swatchbook); the results were expressed in $L^*a^*b^*$ color space.

Grain-size analysis was performed on a Shimadzu SALD-2300 laser diffraction particle size analyzer, capable of measuring particles from 0.017 μ m to 2 mm. Sample pretreatment included removal of the organic matter with 30 % hydrogen peroxide (H₂O₂) and particle dispersion using sodium hexametaphosphate ((NaPO₃)₆). The main statistical parameters were determined using the GRADISTAT software package (Blott and Pye, 2001). Gravels, if present, were described visually.

Mineralogical analyses were performed on PANalytical X'Pert Powder diffractometer (XRD) with Ni-filtered CuK α radiation generated at 45 kV and 40 mA. It is equipped with a vertical goniometer of θ/θ geometry and a PIXcel detector. Scanning parameters were as follows: divergence slit 1/4°, antiscatter slit 1/2°, sample mask of 10 mm, 0.04° Soller slits inserted into the primary and diffracted beam path, scanning step 0.02°2 θ , and 4 s time per step. Processing and interpretation of collected data were done using X'Pert Highscore Plus software and the associated International Centre for Diffraction Data (ICDD) mineral database (PDF-4/Minerals). Bulk mineralogical analyses were performed on fine powdered samples in the range between 4°2 θ and 66°2 θ , on total 23 samples from composite core PB-1, 14 samples from profile PBK1-PK, and 26 samples from composite core PB-2. The clay minerals were analyzed using oriented glass slides of the separated clay fraction (<2 μ m) by centrifugation after carbonate removal using buffered sodium acetate (NaOAc) solutions, in air-dried (AD) and ethylene glycolated (EG) states, and heated to 400 °C and 550 °C. Their measurements ranged between 4°2 θ and 30°2 θ , after each treatment. The clay mineral identification was done according to the following criteria (Moore and Reynolds, 1997): illite was distinguished by a 10 Å peak that does not shift upon treatments; chlorite was identified by 14 Å, 7 and 3.5 Å peaks

that do not change intensity after treatments; kaolinite was confirmed by 7 Å peak that disappears after heating to 500 °C and a steady peak at 3.5 Å; smectite was recognized by shift of 14 Å peak to higher d-spacings at 17–18 Å upon EG and collapse to 10 Å after heating; illite/smectite was identified by maximum between 10 Å and 14 Å which shifts toward higher d-values in glycolated samples; the presence of vermiculite was identified by 14 Å peak that collapses to 13–12 Å after heating. Selected samples from core PB-1 were used to identify clay mineral phases, as well as individual samples from the lake (grab samples) and greyish-blue clayey sediments from the lower (Pleistocene) sections from the profiles in the erosional channel, together with collected marl samples from flysch deposits from the catchment (Ričice retention basin) to reveal their sediment source via clay mineral composition.

The age control of paleolake sediments was based on accelerator mass spectrometry radiocarbon (¹⁴C) dating at Beta Analytics Laboratory (Miami, USA) and at Radiocarbon Laboratory, Institute of Physics, Centre for Science and Education, Silesian University of Technology (Gliwice, Poland). Cores and profiles were carefully examined for suitable material for radiocarbon dating. Mollusk shells were abundant, while charcoal and plant material were scarce or absent. Given the karstic nature of the Prološko Blato and its catchment, any calcareous fossil remains used for ¹⁴C dating must be corrected for the freshwater reservoir effect (FRE) (Philippsen, 2013). One way to correct this error is to date FRE-independent, terrestrial material from the same stratigraphic position to determine the offset between terrestrial and aquatic radiocarbon ages (Philippsen, 2013). Thus, an additional profile, PBK3 (43°28'26"N, 17°6'45"E), was investigated within erosional channels to find suitable material for FRE correction. Two crucial lithological boundaries contained abundant terrestrial and aquatic remains, which were used for FRE calculation (see Section 4.2.1). Radiocarbon data were calibrated using Calam 2.4 (Blaauw, 2010), the IntCal20 calibration curve (Reimer et al., 2020) and calculated reservoir effect.

3.3. Data management and ArcGIS analyses

Data collected from previous studies were georeferenced and combined with this research using ArcGIS software (version 10.2.1). The regional catchment area of the Imotsko Polje was generated through Hydrology Spatial Analyst Tools using a 25-m resolution Digital Elevation Model (DEM). The results were combined with the Basic Geological Map of SFRY (1:100.000) Sheet Imotski (Raić et al., 1976) to show the geological setting of the obtained drainage basin, supported with hydrological data from Bonacci and Roje-Bonacci (2000). The geomorphological setting of the wider area of the Prološko Blato was characterized with a 5-m resolution DEM created by contour vectorization of the Croatian base map (1:5000) (Geoportal of the State Geodetic Administration of the Republic of Croatia, 2022) and subsequent hillshade and slope analysis. The former hydrology of the polje was determined by georeferencing historical cadastral maps (Cadastral Maps of the Habsburg Empire, 1835) that predate major human interventions, such as the construction of the Ričice dam, artificial channels in the Imotsko Polje and a levee in the Prološko Blato.

4. Results

4.1. Geomorphological setting of the Prološko Blato

DEM analysis, satellite and field observations revealed two major geomorphic units, each defined by specific processes and landforms, which affected the Prološko Blato evolution. These are a) the alluvial fan of the Suvaja River and b) the sinkholes of the Prološko Blato (Fig. 2A).

4.1.1. Alluvial fan

The alluvial fan of the Suvaja River was formed by sediment discharge in the upland drainage basin (see Fig. 1B) and accumulation in the karst polje. The fan is readily observed in the DEM by its arcuate

shape in the plan view, spanning outward from the alluvial fan apex in a nearly 180° semicircle, which is typical for alluvial fans (Blair and McPherson, 2009) (Fig. 2A). The fan is made of coarse-grained clastic sediments (mostly gravels) detected at the fan surface (Fig. 2C). The radial profile of the fan exhibits a consistently narrow incline, not exceeding 5° (Fig. 2C), whereas its cross profile demonstrates a downward concave shape (Fig. 2D). Generally, it is possible to detect the end point of an alluvial fan, usually at the intersection of the alluvial fan and distant alluvial plain (Norini et al., 2016). However, the Suvaja alluvial fan is confined by the adjacent karst depression, resulting in more lateral sediment accumulation in the NW–SE direction, rather than radial. The Suvaja River is a feeder channel that flows through the Badnjevice Canyon and is characterized by steep slopes made of uplifted limestone bedrock (Fig. 2B). DEM analysis and historical maps enabled mapping of the former Suvaja channels (paleochannels), spreading into the SE and NW directions (Fig. 2A).

4.1.2. Sinkholes

Sinkholes are the most apparent karst landforms in the Prološko Blato as they occur as a group of densely packed depressions (Fig. 3A). Three types of sinkholes were recognized: a) collapse sinkholes, b) subsidence sinkholes, and c) buried sinkholes.

4.1.2.1. Collapse sinkholes and Prološko Lake morphology. The collapse sinkholes are distributed within the Cretaceous limestone around the NW edge of the Prološko Blato. They have typical bowl- to funnel-shaped morphologies, with slopes ranging between 40° and 84°, flat bottoms filled with colluvial material, and irregular, elliptical or circular shapes in the plan view (Fig. 3A). Four of the collapse sinkholes form karst lakes: Prološko Lake, Galipovac Lake, Lokvičići Lake, and Mamića Lake.

Prološko Lake is a specific type of collapse sinkhole formed at the

karst polje boundary between limestone bedrock and Quaternary paleolake sediments (Fig. 3B). Its morphology is a result of dissolution processes and collapsing event in the eastern part and erosional processes in the polje in the western part. Thus, the lake has a typical bowl-like morphology, with a steep, nearly vertical E–NE slope (hanging wall) made of reddish, highly fractured limestone (Fig. 3C), similar to other sinkholes in the Imotsko Polje. In the western part, sediment erosion led to the formation of distinctive erosional channels, with one main channel spreading in the E–W direction and side channels branching toward the south in the direction of the Suvaja River (Fig. 3A). The formation of erosional channels is an active process related to seasonal flooding of the Prološko Blato, after which eroded sediments are transported through the main channel and deposited onto the lake floor; this process has been documented with the orthophoto image (Fig. 4A).

The bathymetric survey of the Prološko Lake revealed that its relatively flat bottom gently slopes toward the central, deepest part of the lake (−20.5 m relative depth), reflecting its bowl-like morphology (Fig. 4B). Side-scan mosaic images revealed several morphological features, such as pockmarks, lake terraces, submerged talus (colluvium) and submerged erosional channels (Fig. 4C). Pockmarks appear as dark, circular features on the lake bottom (Fig. 4C). The largest pockmark is 14 m wide and represents the deepest recorded point. A distinction between limestone bedrock and polje can be seen on the side-scan mosaic image due to a clear difference in acoustic signal between hard rock (bright color) and unconsolidated Quaternary sediments (dark color) (Fig. 4C).

Sub-bottom profiling in the eastern part of the lake revealed that the collapse sinkhole has bowl- to funnel-shaped morphology (Fig. 5). A maximum seismic penetration depth of ca. 25 m was observed in the central part of the lake, although the bottom could not be distinguished due to the highly karstified acoustic basement (limestone), with irregular morphology and acoustic signal dispersion (Fig. 5). Within the

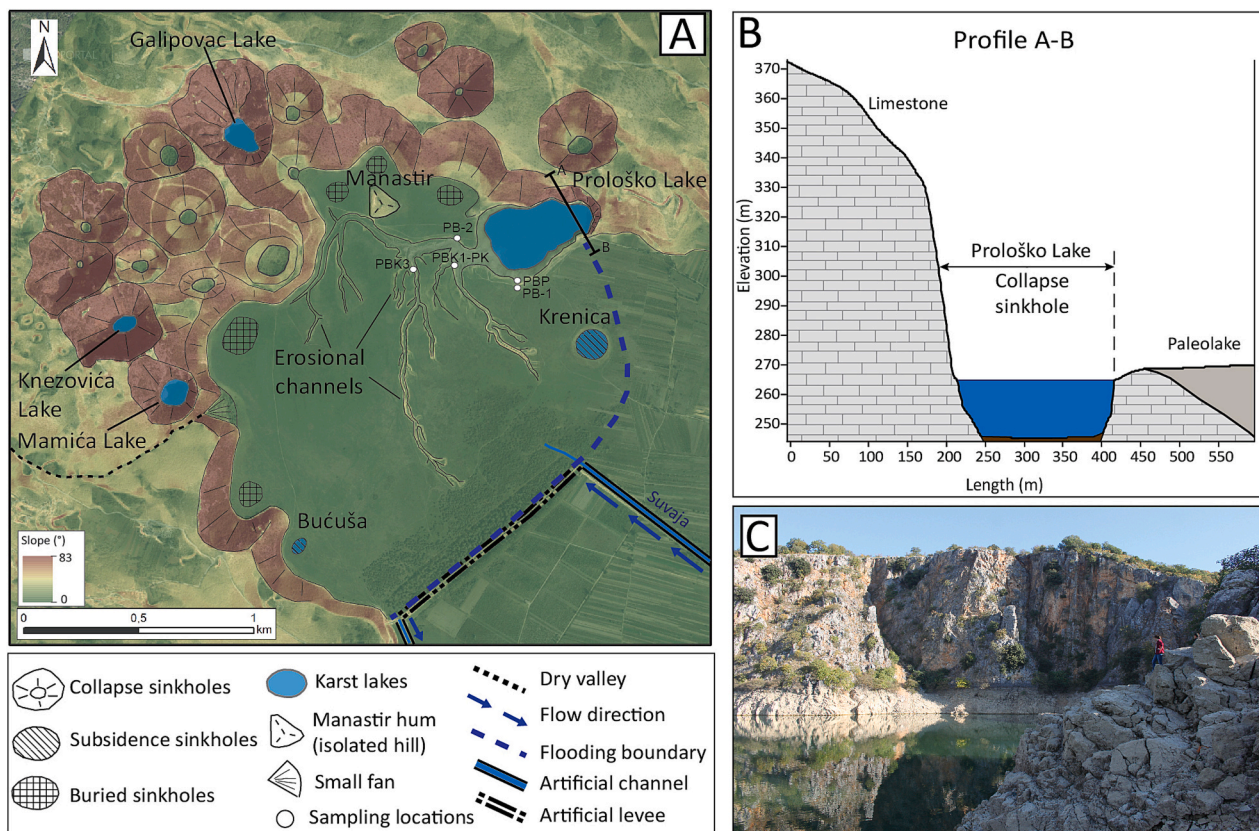


Fig. 3. (A) Morphology of Prološko Blato derived from slope analysis, (B) a typical bowl-like structure of the Prološko Lake collapse sinkhole and (C) field image of Prološko Lake.

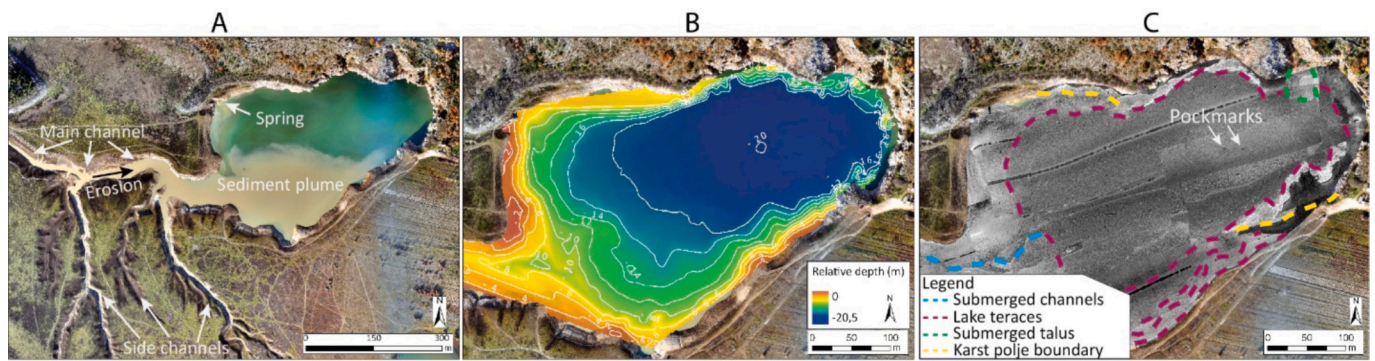


Fig. 4. (A) Orthophoto image, (B) bathymetric map and (C) sidescan mosaic image of Prološko Lake. Note the higher water turbidity in the vicinity of the karst spring and sediment plume from the erosional channels (A).

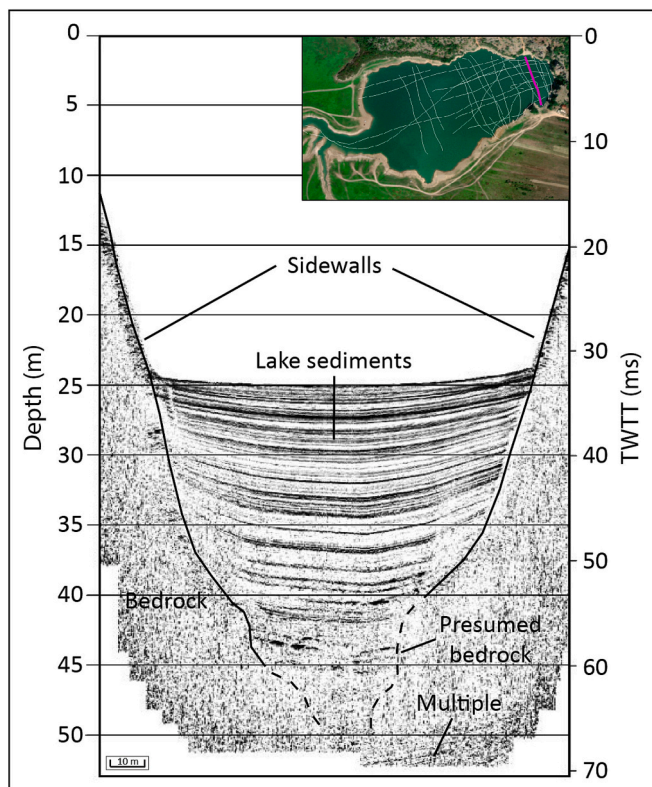


Fig. 5. Sub-bottom profile recorded in the eastern part of Prološko Lake (purple line on the map), showing the funnel-like morphology of the collapse sinkhole filled with 20 m thick, undisturbed lake sediments.

sinkhole we recognized laterally continuous, parallel and medium- to high-amplitude reflectors, without significant discontinuities (i.e., erosional surfaces/truncations, faults) corresponding to lake sediments (Fig. 5). A sublacustrine spring was recorded in the NW part of the lake (Fig. 6B), which is probably associated with karst spring visible on the orthophoto image (Fig. 4A). In the same spring zone, one unconformity was detected, which could represent a contact between the paleolake and Prološko Lake sediments (Fig. 6B). Collapsed blocks of limestone bedrock can be seen in the eastern part of the lake, with spaces in between them filled with lake sediments (Fig. 6B). Frequent acoustic blanking was observed throughout the lake basin, especially in its central part, which could be caused by free gas present in the sediments (Fig. 6B).

4.1.2.2. Subsidence sinkholes. Subsidence sinkholes occur as two small,

oval-shaped lakes, Bučuša and Krenica (Fig. 7). They are formed by the gradual sinking of the Quaternary sediments into an underground cavern (suffosion) and are very common in Imotsko Polje. Lake Bučuša has a typical funnel shape and a maximum depth of 9 m (Fig. 7-2B), while lake Krenica is more concave with the deepest point at about –2 m, which could represent a pockmark (Fig. 7-1B, 1C). Lake Bučuša was formed in 2004, making it the youngest of all lakes in Prološko Blato.

4.1.2.3. Buried sinkholes. Buried sinkholes in Prološko Blato are located in the limestone bedrock beneath the polje. The remnants of their morphology were detected with slope analysis of the polje margins, which are characterized by a sharp boundary between steep limestones (24–40°) and the relatively flat floor of the polje (Fig. 3A). In the northern part, three funnel-like and partially buried structures are divided with a small triangular hill called the Manastir. Similar forms can be found between adjacent collapsed sinkholes; these forms divide the sinkholes into individual depressions (Fig. 3A). Buried structures around Manastir were also detected by earlier researchers (Roglić, 1938; Zdilar, 2015). Morphology of the buried sinkholes suggests that they were formed similarly to adjacent collapsed sinkholes, but were subsequently buried with Quaternary sediments.

4.2. Paleolake of the Prološko Blato

The sedimentary succession of the paleolake Prološko Blato can be roughly divided into two units: the lower alluvial Unit 1 associated with the Suvaja alluvial fan and the upper paleolake Unit 2 (Fig. 8). Upper Unit 2 consists of fine-layered and lithologically uniform paleolake sediments, which can be easily mapped within erosional channels and correlated with sediment cores. This was advantageous in radiocarbon dating since suitable material (charcoal) was absent in sediment cores. Thus, additional profile PBK3 was investigated for charcoal material, focusing on crucial lithological boundaries. The obtained results are explained in the following section.

4.2.1. Paleolake sediment chronology

The results of the radiocarbon dating are listed in Table 1. The most reliable ages in the Holocene were obtained with charcoal samples PB-11 and PB-10 from profile PBK3. Sample PB-11 was taken above the boundary marked with an abrupt change from very dark greyish-brown clayey silt to light grey sandy silt and yielded an age of ca. 8000 cal yr BP (Fig. 8A). This is in relatively good agreement with the younger sample PBK1–1 taken at a slightly higher stratigraphic position in profile PBK1-PK (Fig. 8B). Likewise, sample PBK1–2 was taken at a slightly lower stratigraphic position and yielded an age of ca. 9000 cal yr BP (Fig. 8B). Sample PB-10 was taken in profile PBK3 above the boundary marked by a lithological change from light grey sandy silt to dark brown clayey silt and yielded age of ca. 800 cal yr BP (Fig. 8A). A similar age was obtained with sample PB-1102–103 taken from core PB-1, although at a lower

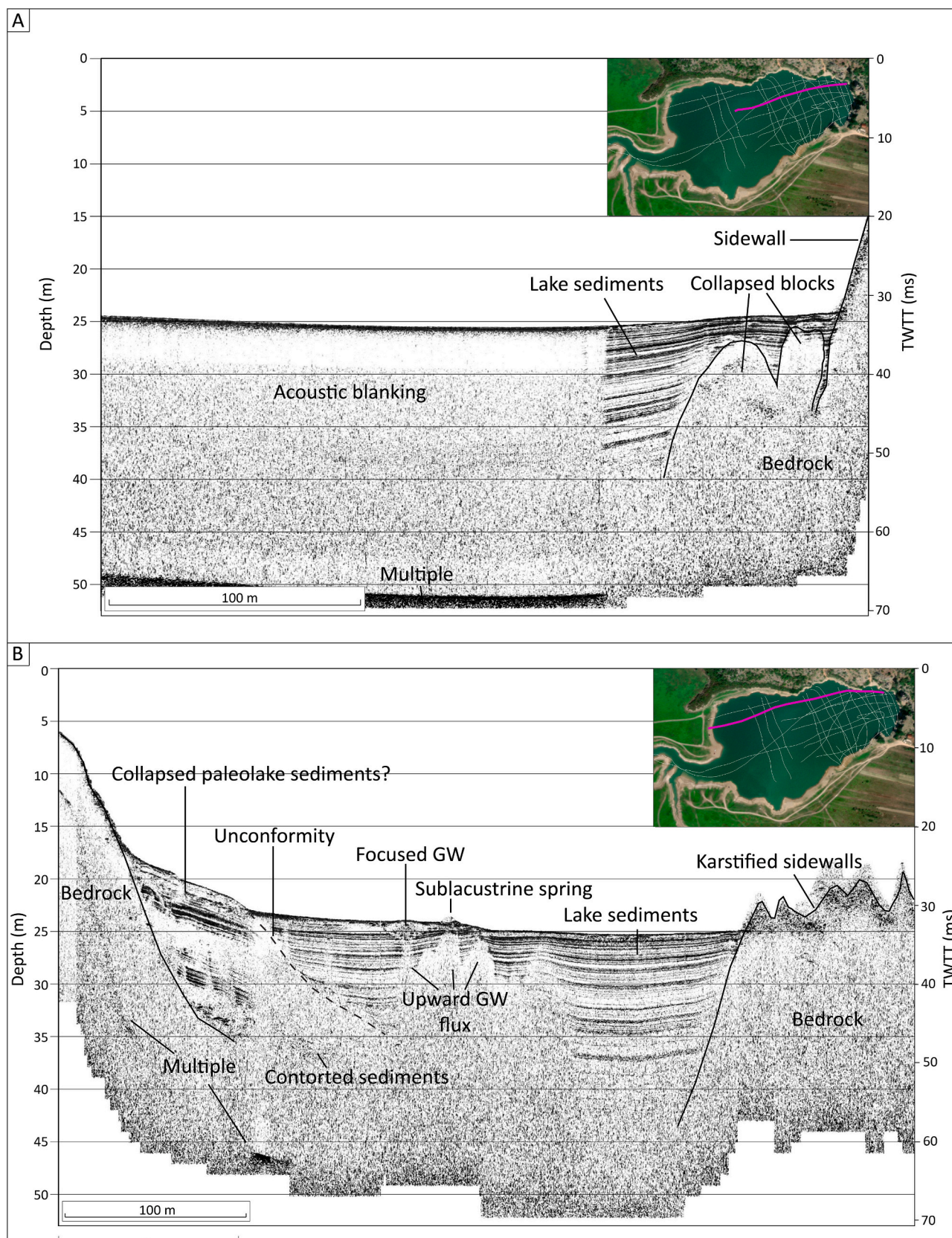


Fig. 6. Sub-bottom profiles of Prološko Lake showing features typical for (A) collapsed sinkholes (steep sidewalls and collapsed blocks of rock) and (B) karst lakes (karstified bedrock, sublacustrine springs). Note the unconformity that could represent a boundary between the older paleolake sediments and younger Prološko Lake sediments (B). Interpreted profiles are marked by purple lines on the map.

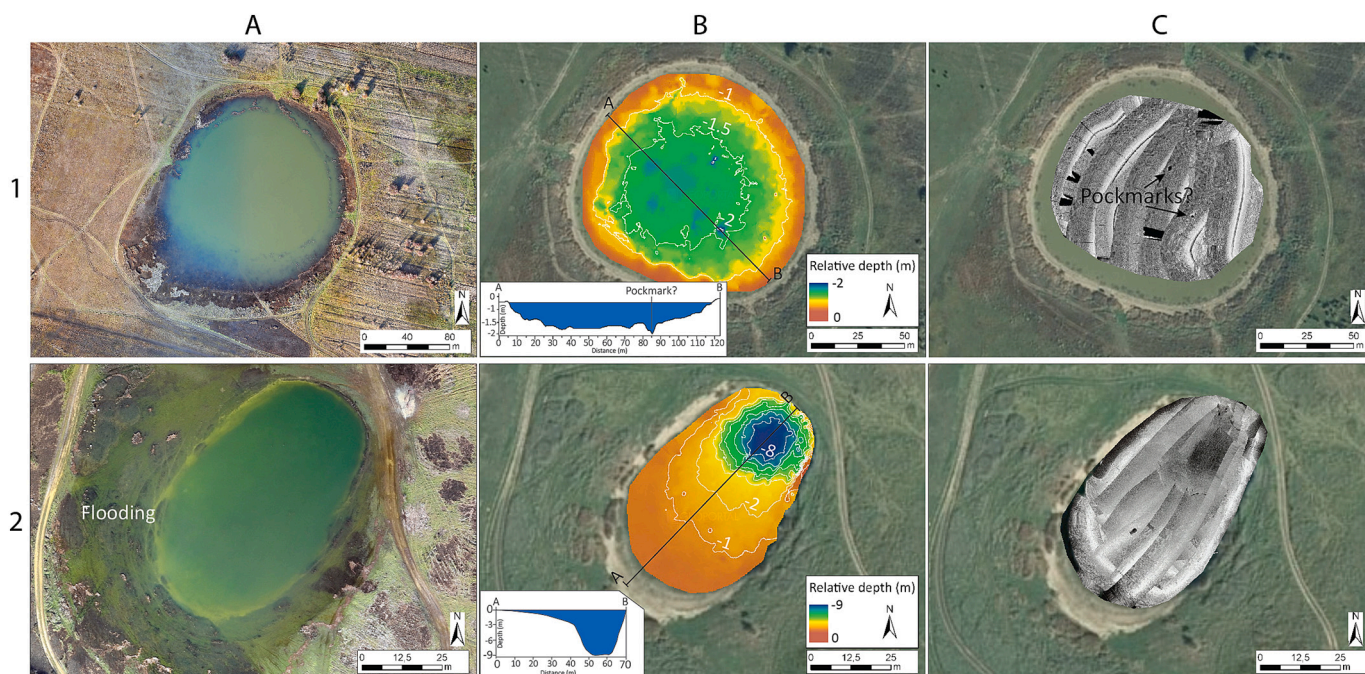


Fig. 7. (A) Orthophoto image, (B) bathymetric map and (C) sidescan mosaic image of subsidence sinkholes (1) Krenica and (2) Bučuša.

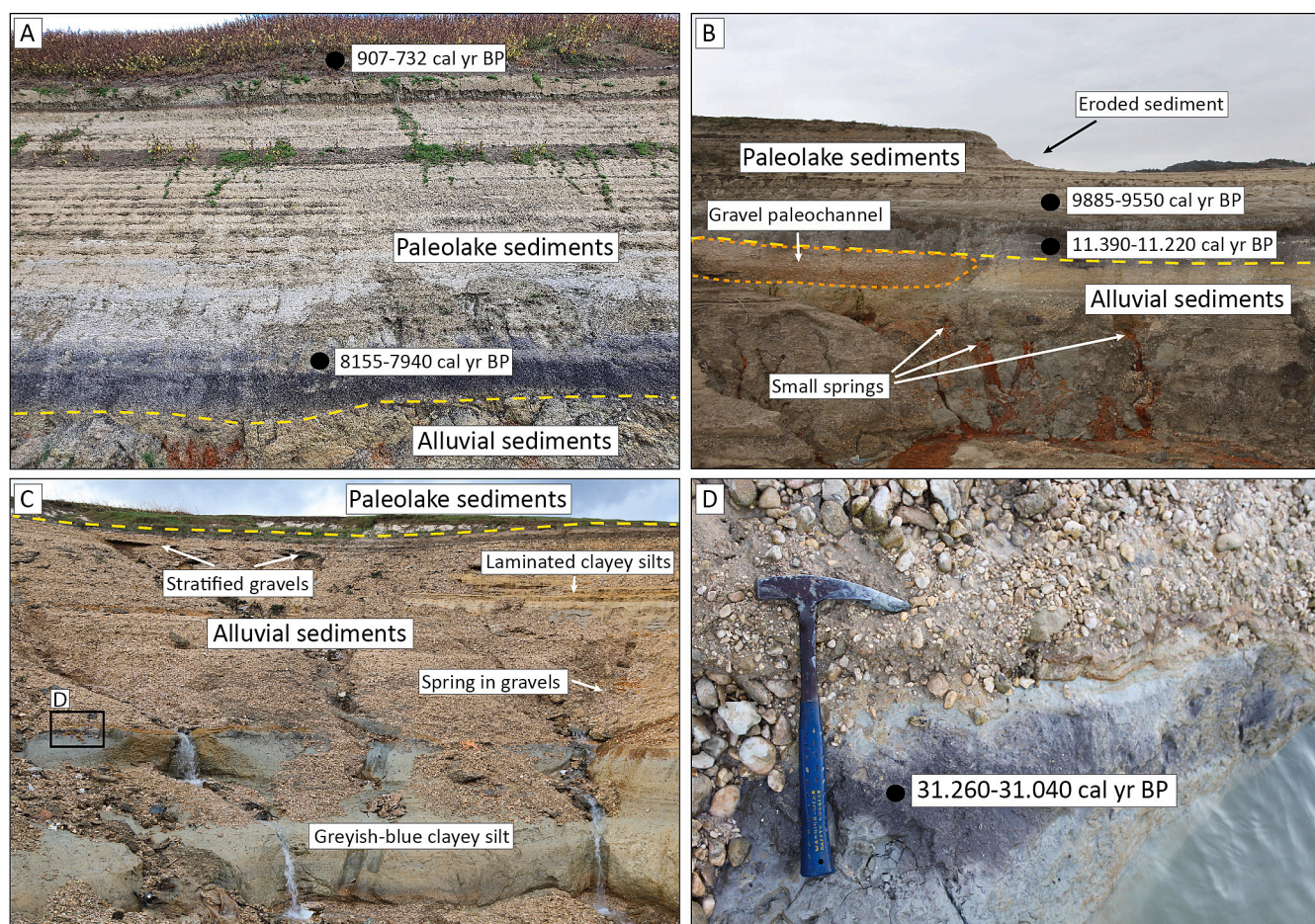


Fig. 8. Field images of the profiles (A) PBK3 and (B) PBK1-PK within erosional channels and (C) of the Prološko Lake shores near coring location PB-1 with detail of the oldest radiocarbon dated sediment (greyish blue clayey silt) (D). The boundary between two major lithological units is marked by a yellow dashed line. Suvaja paleochannels made of gravels are marked by the orange dashed line. Gravels on the Prološko Lake shores are partially lithified and stratified (C).

Table 1
List of radiocarbon ages taken from core PB-1 (PBP) and profiles PBK1-PK and PBK3 (Beta = Beta Analytic Inc., Miami, FL, USA; GdA = Silesian University, Gliwice, Poland). Calibrated ages are expressed as calibrated years before present (BP) with respect to the IntCal20 calibration curve (Reimer et al., 2020). Samples that are calibrated and corrected for the reservoir effect (FRE) are indicated in the last column.

Lab ID	Sample ID	Core/profile	Material	Conventional age (BP)	Calibrated age (cal BP)	Calibrated and FRE corrected age (cal BP)
Beta -573136	PB-10	PBK3	Charcoal	900 ± 30	907–732	
Beta -573135	PB-10	PBK3	Shell	2770 ± 30	2944–2782	907–732
Beta -559645	PB-1102–103	PB-1	Shell	2840 ± 30	3058–2865	927–793
Beta -515630	PBK1–1	PBK1-PK	Shell	8720 ± 30	9885–9550	7745–7610
Beta -573137	PB-11	PBK3	Charcoal	7200 ± 30	8155–7940	
Beta -515631	PBK1–2	PBK1-PK	Shell	9880 ± 30	11.390–11.220	9005–8730
Gda -7219	PB-2584–585	PB-2	Charcoal	15.930 ± 70	19.453–19.034	
Beta -559644	PB-GL-b	PB-1 (PBP)	Plant	27.050 ± 120	31.260–31.040	

* FRE = freshwater reservoir effect; FRE = 14C (PB-10 Charcoal) – ¹⁴C (PB-10 Shell) = 1870 yr BP.

stratigraphic position, resulting in a slightly older age (Table 1). The FRE was calculated by subtracting the radiocarbon ages of charcoal sample PB-10 and shell sample PB-10, which resulted in 1870 years. The reliability of radiocarbon ages obtained from shell samples could still be biased since the freshwater reservoir effect can change over time (Philippsen, 2013). Samples Beta-559644, taken from the lowermost greyish-blue clayey silt (Fig. 8C and D), and Gda-7219, taken from yellowish grey clayey silt in the sediment core PB-2, yielded a late Pleistocene age for the lower alluvial unit.

4.2.2. Paleolake sediment description

Core PB-1 stretches over 650 cm and has two lithological units, lower Unit 1 (310–650 cm) and upper Unit 2 (0–310 cm) (Fig. 9). The Munsell color of Unit 1 ranges from dark brown (10YR 3/6) to brownish grey (10YR 6/2) with pronounced admixtures of yellowish brown (10YR 5/

4–5/8). The color of Unit 2 ranges from very dark greyish brown (10YR 3/2) to light grey (10YR 7/1–7/2). Subunit 2a shows color variations caused by redoximorphic features (e.g., redox depletions, accumulation of Fe-masses, Fe-Mn nodules). The Munsell color is in good agreement with the *L*a*b** values (Fig. 9), and both reflect variations in mineral composition (e.g., carbonate versus siliciclastic and Fe-oxides content). The volume magnetic susceptibility (χ_{lf}) varies between –0,8 (Subunit 2b) and 81.5 (Subunit 2a) $\times 10^{-5}$ SI. The mass-specific (χ_{lf}) and frequency-dependent (χ_{fd}) magnetic susceptibilities show similar trends as volume MS. The major mineral phases are calcite and quartz, while the minor phases are muscovite/illite, clay minerals, aragonite, K-feldspar, and plagioclase (Table S2 in Supplementary material). Calcite predominates in Subunit 2b, while quartz predominates in Subunit 2a. Aragonite appears in Subunit 2b. Other subunits are composed of variable amounts of calcite and quartz as dominant phases. Clay minerals

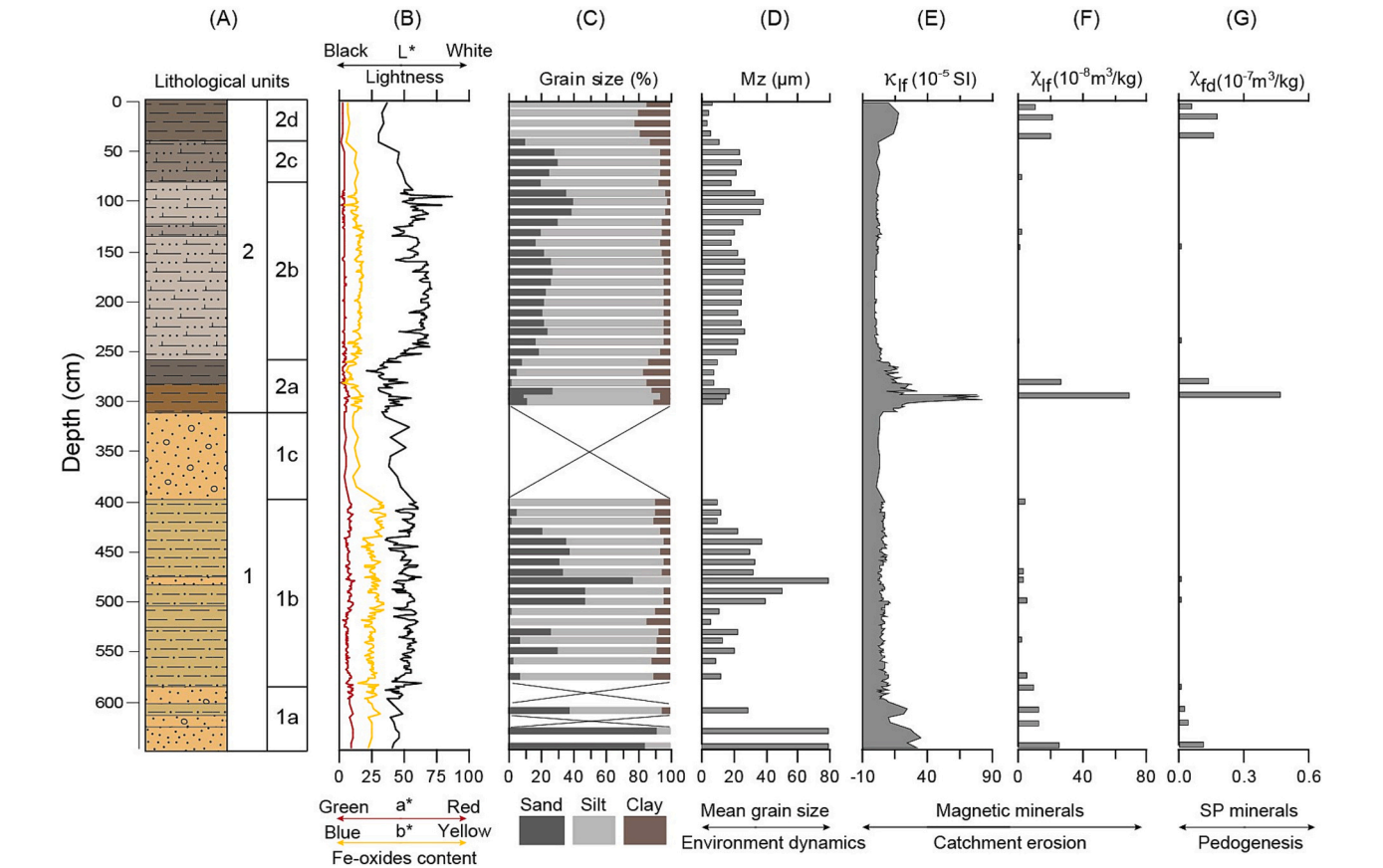


Fig. 9. (A) Lithological units of the PB-1 composite core, (B) sediment color expressed as *L*a*b** values, (C) grain size distribution, (D) mean grain size, (E) volume magnetic susceptibility measured with the MS2E sensor, (F) mass magnetic susceptibility, and (G) frequency-dependent magnetic susceptibility. For a description of the lithological units see Fig. 11.

throughout the core are represented by smectite, vermiculite, illite, and kaolinite. In Subunit 2a, mixed-layer illite-smectite appears as a swelling clay mineral. This subunit with the highest clay minerals content is characterized by the highest MS. MS increase is observed toward the topmost Subunit 2d. Yellowish coarse-grained sediments are underlain by thick, homogenous greyish-blue clayey silt sediments, which are visible on the Prološko Lake shores during the low lake level (Fig. 8C). Dominant mineral phases in greyish-blue clayey silts are calcite and quartz, while minor phases are clay minerals, plagioclase, and K-feldspars. Clay mineral composition reflects flysch sediments and the composition of marls from the Ričice area – smectite, chlorite, vermiculite, illite, and kaolinite (Table S3 in Supplementary material). In contrast, samples from the bottom of the lake have the same clay mineral composition as surrounding sediments from the core PB-1, units 1 and 2. The grain size distribution varies from fine silt to medium sand and gravel, with a mean grain size (Mz) varying between 4.6 and 278.8 μm .

The highest clay content is in subunits 2a (18.4 %) and 2b (22.5 %), while Subunit 2b is made mostly of silt (av. 70 %) and sand (av. 25 %).

Core PB-2 is 920 cm long and displays similar lithological properties (color, MS, mineral composition) as core PB-1 (Fig. 10, Table S4 in Supplementary material). Munsell color varies from very dark brown (10YR 2/2) in Subunit 2a to white and very pale brown (10YR 8/1–8/2) in Subunit 2b, with pronounced yellowish admixtures (10YR 6/8) throughout Unit 1. Variations in $L^*a^*b^*$ values are compatible with the Munsell color and reflect variations in mineral composition. Redox-imorphic features are present in Subunit 2a. MS is generally low throughout the core in both Units 1 and 2, with an evident increase in the topmost Subunits 2c and 2d. The lowest volume MS (κ_{IF}) is in Subunit 2b, where calcite is dominantly present. Major mineral phases throughout the core are calcite and quartz, while minor phases are muscovite/illite, aragonite, clay minerals, K-feldspar, and plagioclase (Table S4 in Supplementary material). Grain size in the core PB-2 ranges

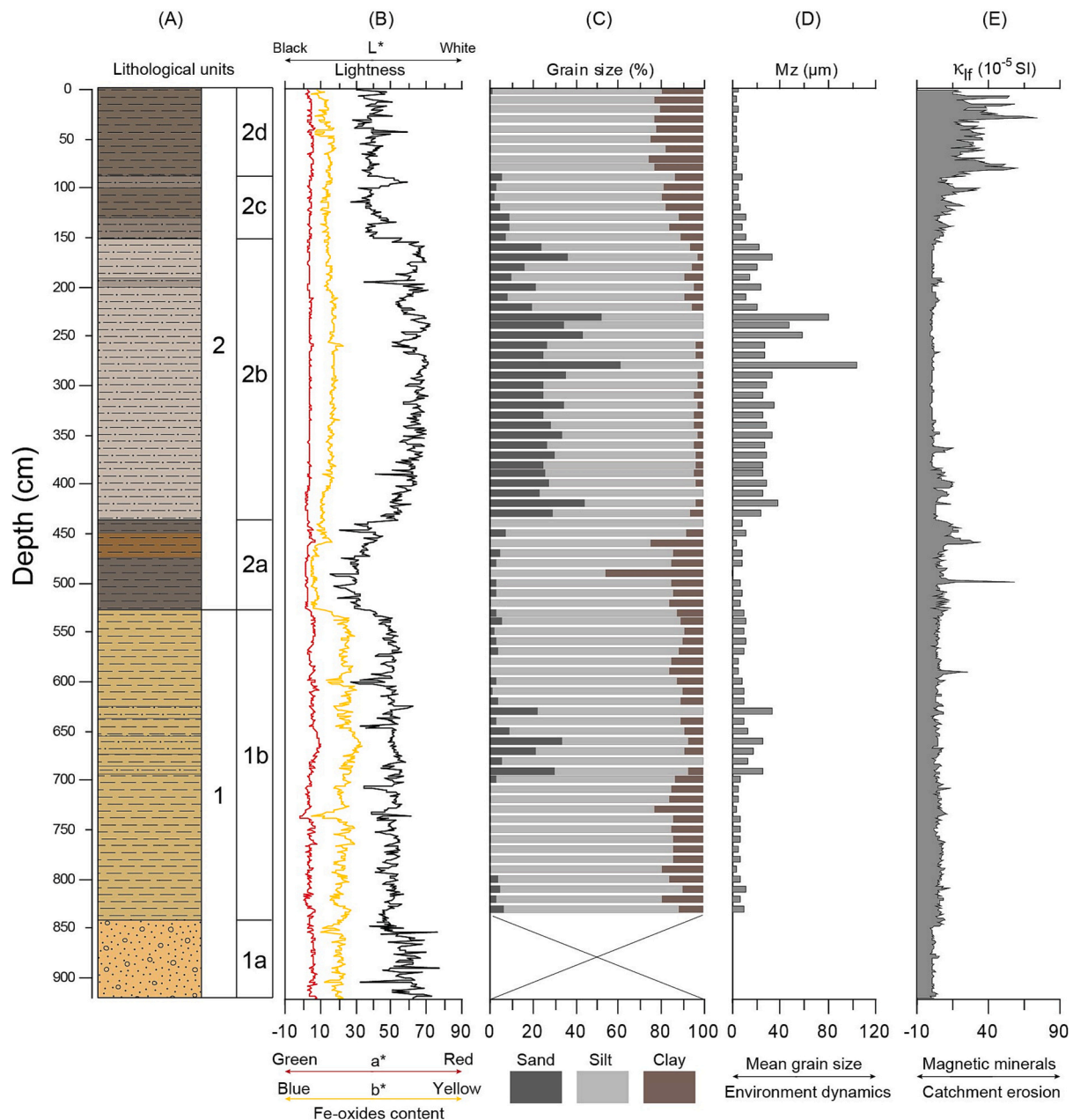


Fig. 10. (A) Lithological units of the PB-2 composite core, (B) sediment color expressed as $L^*a^*b^*$ values, (C) grain size distribution, (D) mean grain size, (E) volume magnetic susceptibility. For description of the lithological units see Fig. 11.

from fine silt to very fine sand, while gravel is present only at the bottom (840–920 cm). The highest clay (49.5 %) and silt (100 %) content is in Subunit 2a, while the highest sand content (61.4 %) is in Subunit 2b.

Profile PBK1-PK shows similar lithological characteristics as cores PB-1 and PB-2, and its detailed description can be found in Supplementary material. Lithological units from cores PB-1 and PB-2, as well as those from profile PBK1-PK, can be correlated based on their lithological properties (Fig. 11, Table S1 in Supplementary material). The main differences can be seen in the grain size of the lower unit, mainly due to the occurrence of gravel layers at different stratigraphic positions. In general, coarser-grained sediments are found in core PB-1, while finer-grained sediments are found in core PB-2, thus reflecting the reduced flow energy in the distal part of the alluvial fan. Gravels occur as 1) gravel lenses (paleochannels) in exposed outcrops within erosional channels (Fig. 8B), and 2) partially lithified layers on the southern shores of the Prološko Lake (Fig. 8C). Moreover, the observed correlation clearly shows the increasing thickness of the paleolake sediments (upper Unit 2) from east to west, i.e., from a shallower to a deeper paleolake environment.

4.2.3. GPR-derived paleolake sediment thickness

Generally, the GPR signal response primarily refers to the change in grain size. The GPR facies were depicted based on the method introduced by Neal (2004) and its later adaptations. Four main lithofacies were extracted (Fig. 12) based on signal characteristics such as signal shape, interrelationship, continuity, and strength of the reflex, units' surface characteristics (concordant, erosional, onlap), and units'

scattering characteristics. The top layer (layer A) shows a strong horizontally defined, continuous signal overlying the lower coarse-grained sediments. The GPR signal in the interval of coarser-grained size sediments (pale brown sandy silt, layer B) characterizes a non-defined, rather weak signal, and it is concordant with lower layer C, which shows a more defined GPR response. These layers were recognized in several GPR profiles, which points to their extension in the subsurface of the Prološko Blato. The yellowish-brown clayey/sandy silt (layer D) overlies the lower gravels.

5. Discussion

5.1. Late Quaternary evolution of the Prološko Blato

The evolution of the Prološko Blato throughout the Late Quaternary is shown in Fig. 13 and can be interpreted as follows.

5.1.1. Late Pleistocene lacustrine/alluvial phase (31.000–19.000 cal yr BP)

The lowermost sediments in the Prološko Blato are very thick, greyish blue, and organic-rich clayey silts visible on the south shores of the Prološko Lake during the low lake levels (Fig. 8C and D). The obtained age of 31.000 cal yr BP of the organic-rich layer (Fig. 8D) suggests that the lowermost clayey silts were deposited during the Marine Isotope Stage (MIS) 3 and MIS 2 periods. Preliminary micropaleontological analysis showed that they were rich in microfaunal remains (ostracods, molluscs) typical of shallow water bodies connected to springs (Ivkić

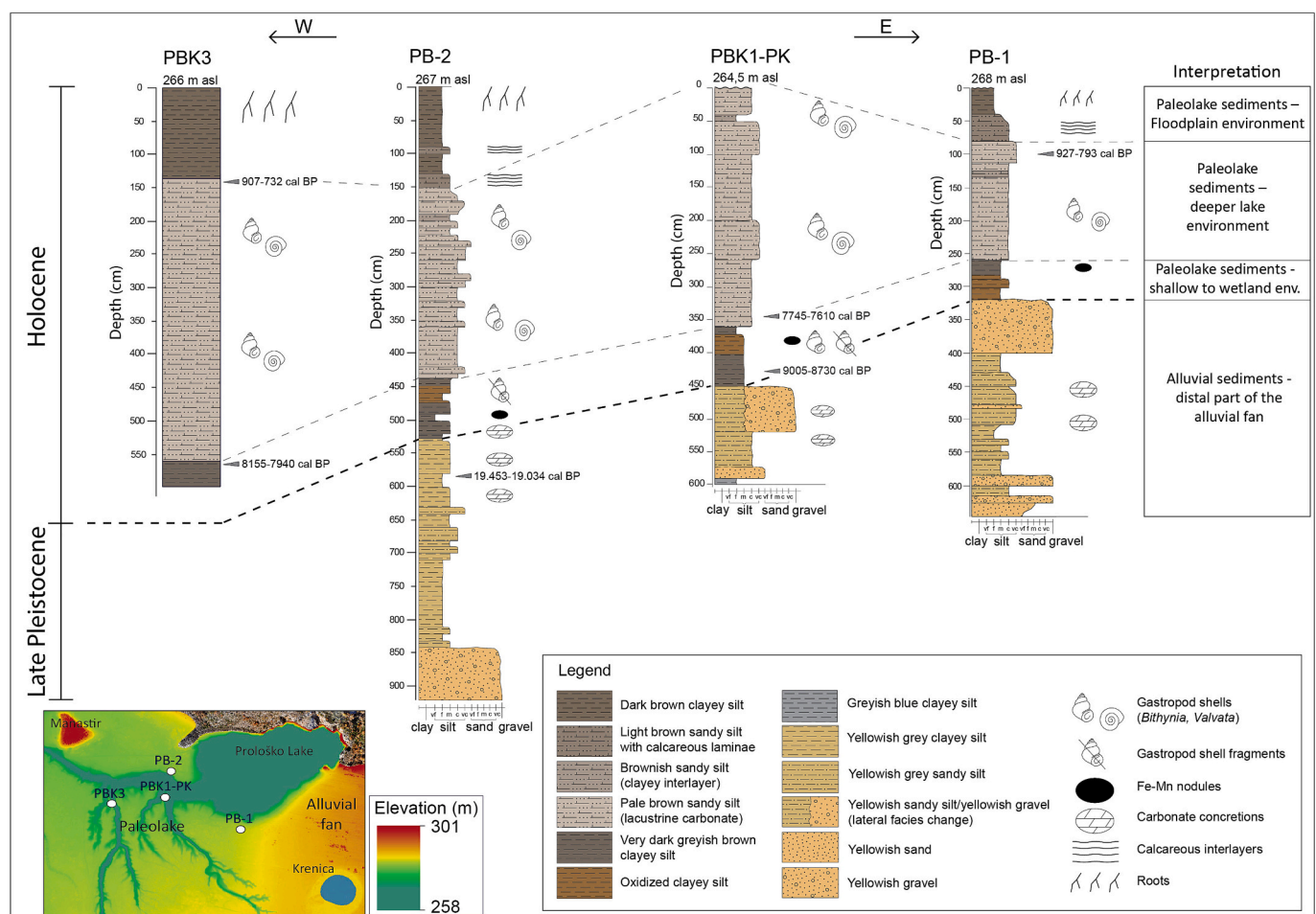


Fig. 11. Correlation of sediment cores and profiles. Sampling locations are shown on the high-resolution DSM retrieved with the UAS survey. Note the change in thickness of the paleolake sediments from E to W, i.e., from shallower to deeper lake environment and different stratigraphic positions of gravel layers relative to the alluvial fan.

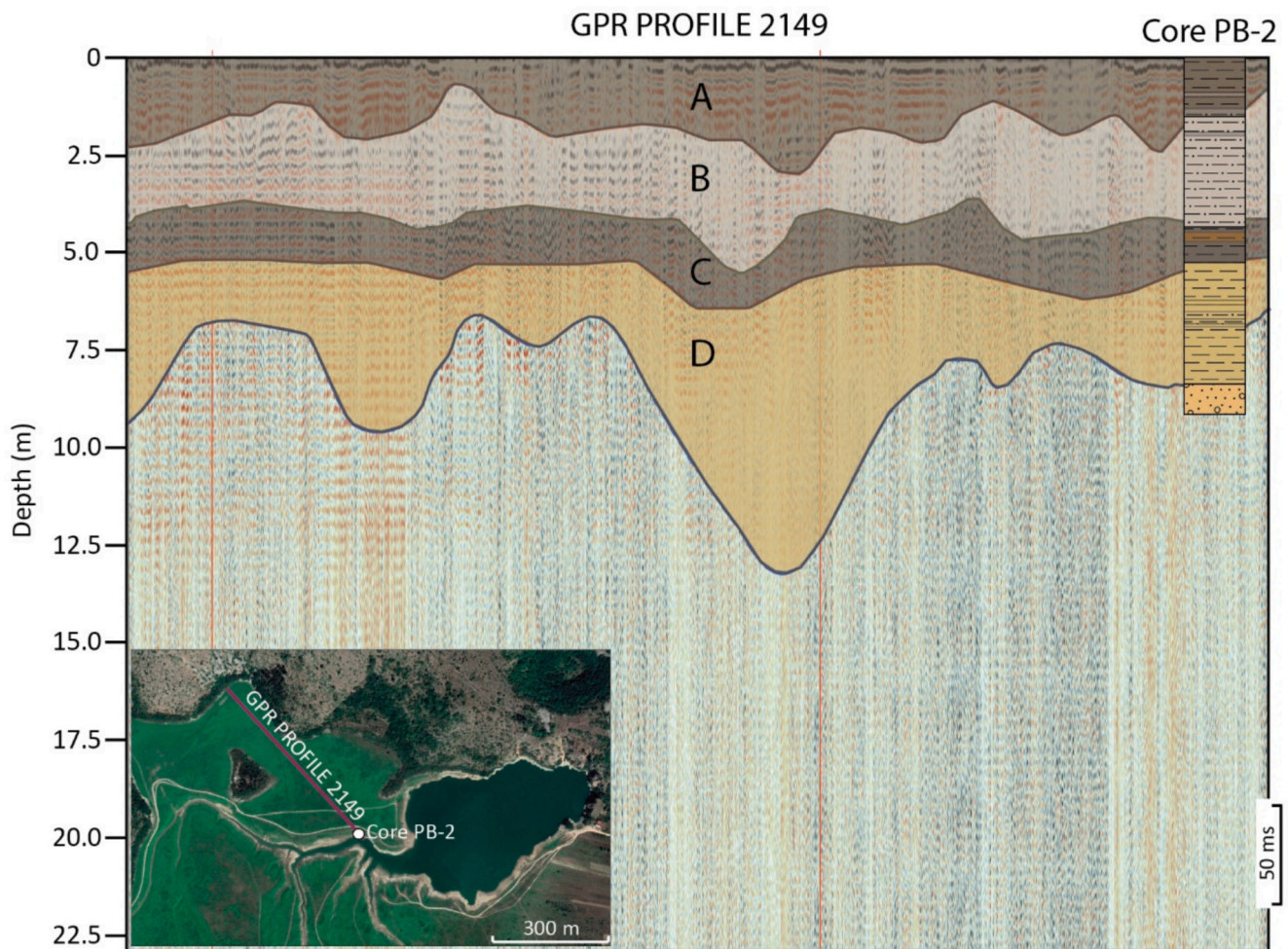


Fig. 12. Interpretation of selected GPR profile. For the lithological description of the core PB-2, see Fig. 11.

Filipović, unpublished data). Thus, it is possible that during this time an intermittent lacustrine environment prevailed, similar to modern conditions. Furthermore, these sediments likely extend even deeper beneath the exposed profiles, and thus potentially hold valuable paleoenvironmental/paleoclimate records for the Last Glacial Period (LGP), which are generally lacking in the Dinarides.

Greyish-blue clayey silts are followed by yellowish alluvial sediments (Unit 1) associated with the Suvaja alluvial fan (Fig. 13A) detected at the Imotsko Polje surface via DEM analysis (Fig. 2). Alluvial fans are aggradational sedimentary deposits formed at mountain fronts where an incised valley meets the lowland area (Blair and McPherson, 2009). According to Blair and McPherson (2009), three major criteria for alluvial fan development are 1) topographic setting with an upland drainage basin draining to a lowland valley, 2) sufficient sediment production in the drainage basin, and c) “triggering mechanism” in the uplands to activate sediment transport to the valley, such as high water discharge and, less commonly, earthquakes. The Imotsko Polje is a tectonic depression within the Dinarides made of Cretaceous carbonates, Paleogene clastic deposits (flysch and Promina beds), Miocene marls, and their Quaternary derivatives (Korbar, 2009; Raić and Papeš, 1978). Clastic flysch and Promina deposits found in the upland Ričice basin are predisposed to mechanical erosion and thus represent favorable source material for the alluvial fan. This was confirmed by clay mineral analysis of marl samples from flysch deposits, which is the same as samples from alluvial deposits taken in erosional channels (Table S3 in Supplementary material). Such a topographic and geological setting meets the first two criteria for alluvial fan development. The necessary “triggering

mechanism” for sediment discharge into the polje could be both high water discharge and earthquakes, considering the high seismic activity of the area (Dragičević et al., 1999; Kuk et al., 2000) which can lead to rock failures and landslides that can contribute to the clastic surplus in the catchment (Keefer, 1999).

The lower Unit 1 is comprised mostly of clayey and sandy silts, with occasional occurrences of sands and gravels (Fig. 11). The lithological differences observed by comparing the sediment cores and profiles (Fig. 11, Table S1 in Supplementary material) suggest that the lower Unit 1 belongs to the distal part of the Suvaja alluvial fan, characterized by well-stratified and laminated structure derived from sheetflood deposition (Bowman, 2019). These characteristics can be observed in exposed profiles as stratified gravels and laminated clayey silts (Fig. 8C). Stratified gravels alternate laterally with the uppermost yellowish grey clayey silts (Fig. 11), which were deposited at ca. 19,000 cal yr BP, i.e., during the latest part of the Last Glacial Maximum (LGM). This suggests that the active depositional lobe of the alluvial fan prevailed in the Prološko Blato during the LGM, and it ceased shortly afterward during the deglaciation period. Coarse-grained sediments (gravels) in the distal part of the alluvial fan imply high water discharge in the Imotsko Polje after the LGM, which can result from heavy or prolonged precipitation or rapid icemelt or snowmelt (Blair and McPherson, 2009). The increased water input could have occurred due to generally increased precipitation in the Mediterranean during the deglaciation period following relatively cold and dry conditions during the LGM (e.g., Bar-Matthews et al., 1999; Clark et al., 2012; García-Alix et al., 2021; Columbu et al., 2022). These regional changes in temperature and

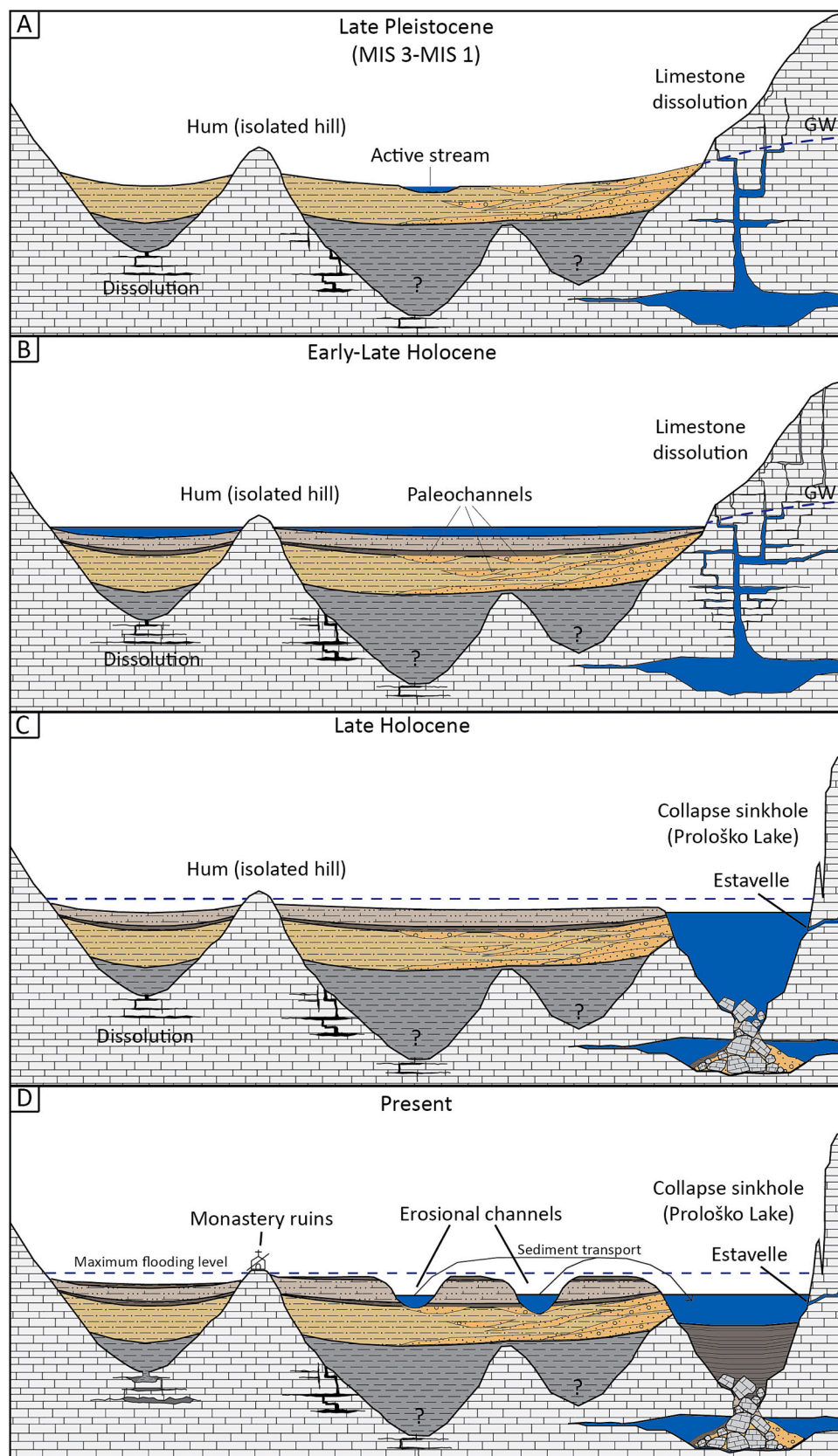


Fig. 13. Late Quaternary evolution of the Prološko Blato through four phases: (A) Late Pleistocene alluvial deposition in the karst polje, (B) Early-Late Holocene lacustrine sedimentation in a relatively shallow paleolake, (C) disruption of lacustrine sedimentation caused by the hypothetical collapse sinkhole on the karst polje boundary and formation of the modern Prološko Lake, and (D) modern environment with seasonal flooding (karst wetland). GWL = groundwater level, ? = extension of the greyish-blue clayey silts is presumed up to the paleorelief.

precipitation are also evident in speleothem records in the central (Surić et al., 2021) and southern (Lončar et al., 2022) parts of the Adriatic region. Furthermore, similar environmental conditions during the LGP (MIS 4 – MIS 2) were observed in the submerged Lošinj Channel on the eastern Adriatic coast, when the sea-level lowstand and concomitant decrease in the groundwater level enabled the formation of a karst polje characterized by fluvial incisions and, likely, intermittent lake environments due to flooding (Brunović et al., 2024). Thus, similar climatic/hydrological conditions during the LGP can be presumed for the Imotsko Polje. However, in addition to the precipitation changes, the increased water input could have also come from the icemelt on the Čvrsnica Mt. in western Herzegovina (main recharge zone), which was glaciated during the LGM (Činer et al., 2019). Glaciations are known to affect the hydrological conditions in the surrounding karst poljes and their catchments, mainly the groundwater and surface runoffs, and thus the sediment supply (e.g., Adamson et al., 2015; Žebre et al., 2016, 2019). Hence, the glacial activity could have influenced the recharge rates in the catchment and ensured additional sediment supply to the river drainage basin, as well as sufficient water transport energy to the distal part of the alluvial fan.

The radiocarbon age of 19,000 cal yr BP for the top of the alluvial Unit 1 in sediment core PB-2 and 9000 cal yr BP for the base of the paleolake Unit 2 in sediment profile PBK1-PK (Fig. 11) suggest a depositional hiatus before the paleolake development. The hiatus could have been caused by migration of the active depositional lobe on the alluvial fan further away from the Prološko Blato, e.g., in the S-SE direction, as evidenced by older paleochannels on the fan surface (Fig. 2). Moreover, the historical records of frequent flash floods from the Suvaja River (Ujević, 1991) suggest that the alluvial fan was active before the construction of the Ričice retention basin.

5.1.2. Early-Late Holocene paleolake phase (9000 cal yr BP – 800 cal yr BP)

The most apparent difference between the lower alluvial and upper lacustrine sediments is their color, from yellowish alluvial sediments to very dark greyish brown clayey silts (Subunit 2a) (Fig. 8A and B), marking a significant environmental change at ca. 9000 cal yr BP. The dark color of Subunit 2a is also evident in the relatively low values of color parameter L^* (lightness), which can indicate the lower carbonate content in sediment cores (Balsam et al., 1999). The mineral composition of Subunit 2a is dominated by quartz, calcite, feldspars, and clay minerals, which are considered detrital mineral phases in lake sediments (Håkanson and Jansson, 2002). However, calcite occurs as a major mineral phase alongside quartz in sediment core PB-2, while in Subunit 2a in sediment core PB-1 calcite is minor (Tables S2 and S4 in Supplementary material). The mineral composition is in agreement with relatively higher MS values in Subunit 2a associated with higher erosional input from the catchment, evidenced by the higher content of quartz and the presence of muscovite/illite and clay minerals. Carbonate concretions are numerous in Subunit 2a and continue downward in the alluvial Unit 1 in the sediment core PB-2 (Fig. 11). Similar carbonate concretions were found in Holocene paleolake sediments of the Pheneos polje and Assea valley in the Tripolis polje (Peloponnese, Greece), where they were interpreted as indicators of seasonal desiccation and pedogenesis (Unkel et al., 2014; Seguin et al., 2020). Pedogenesis can also be inferred from elevated frequency-dependent MS (χ_{fd}) (Fig. 9) associated with superparamagnetic (SP) minerals formed in soils (Maher and Thompson, 1999). Based on the observed sediment properties and the presence of fossil macro remains (*Bithynia tentaculata*) Subunit 2a is interpreted as a shallow lake/wetland with deposition of siliciclastic material. The redoximorphic features (Fe-Mn nodules, oxidized layer of clayey silt) observed in the Subunit 2a (Fig. 11) are formed by the reduction, movement, and oxidation of Fe and Mn in seasonally saturated soils (Gasparatos et al., 2019; Vepraskas and Vaughan, 2016). Seasonal saturation could have been governed by fluctuating groundwater levels, as it is today, but also by impounding the basin with surface water from

the Suvaja River. The erosional input inferred from siliciclastic mineral composition and elevated MS values suggests wetter climatic conditions during the Early Holocene. Enhanced erosional input due to wetter climatic conditions was also observed in the Bokanjačko Blato karst polje (eastern Adriatic coast) between 10,300 and 4200 cal yr BP (Ilijić et al., 2018). Although influenced by the Holocene sea level rise, Lake Velo Blato on the Island of Pag experienced a karst polje phase with strong erosional processes during the Early Holocene (ca. 10,000 to 8100 cal yr BP), when the sea level was ~40 m lower than today (Ilijić et al., 2022). Likewise, lake sediments in the Čepić Polje in Istria (northern Adriatic) indicate higher erosional input and formation of a lake fed by intermittent streams before 7000 cal yr BP (Balbo et al., 2006). In the northern Adriatic Sea, lake and marine sediments in Lake Vrana on the Island of Cres (Ilijić et al., 2024) and Lošinj Channel (Brunović et al., 2020) showed good correlation with the southern Adriatic Sea sediment records on the Island of Mljet (Razum et al., 2020, 2021), where the pluvial period is evidenced during the Early and Middle Holocene. Therefore, evidence from lake sediments in Croatian karst poljes suggests wetter climate conditions during the Early Holocene, which generally corresponds to the pluvial period observed in the wider region during that time (e.g., Bar-Matthews et al., 1999; Roberts et al., 2008; Combourieu-Nebout et al., 2013; Siani et al., 2013).

Subunit 2a is followed by light grey massive sandy silt (Subunit 2b) (Fig. 11), rich in gastropods and Charophytes, and characterized by homogeneous structure, oxidized traces of rhizoids, and without visible organic remains. Radiocarbon dating of the lower and upper lithological boundary revealed that Subunit 2b was deposited during the Mid-Late Holocene (ca. 8000–800 cal yr BP). The mineral composition is dominated by calcite, while aragonite and quartz are subordinate and clay minerals are present, as expected, near the boundaries with upper and lower clayey silts (Subunits 2a and 2c) (Tables S2 and Table S4 in Supplementary material). The MS values are the lowest in Subunit 2b due to the predominance of the calcite mineral phase. The absence of siliciclastic clay minerals indicates reduced erosional input from the catchment. This suggests that the calcite, as well as aragonite, is predominantly endogenic, and both mineral phases imply a more stable and deeper (open) lake environment during the Mid-Late Holocene (Fig. 13B). Higher sand content observed in Subunit 2b could result from the aggregation of carbonate mineral phases, both calcite and aragonite, which frequently appears in karst lakes with high carbonate production (Håkanson and Jansson, 2002). Based on the observed properties, Subunit 2b is interpreted as lacustrine carbonate. Its homogeneous structure, fossil content, oxidized traces of rhizoids, and poor preservation of organic matter all indicate a relatively shallow lake with intense bioturbation and a well-oxygenated water column. The presence of aragonite indicates drier climatic conditions since aragonite tends to precipitate in evaporative waters, with high Mg/Ca ratios (Deocampo, 2010). This agrees with the general aridity trend observed in Mediterranean paleoclimate records during the Mid-Late Holocene (e.g., Roberts et al., 2008; Lacey et al., 2015; Bar-Matthews et al., 2003). A more arid climate may have led to reduced detrital input from the Suvaja River, as indicated by low siliciclastic content and low MS values (Figs. 9 and 10). Alternatively, this could have been caused by changes in the river's pathway, as former paleochannels were identified through DEM analysis (Fig. 2). Lake formation was possible due to the underlying impermeable clayey sediment, thus enabling the impoundment of the basin. We estimated that the lake could not have been >10 m deep due to the surrounding karstified limestones and estavelles. Lacustrine carbonate was detected in the southern parts of erosional channels (269 m asl) and east of the Lake Krenica (270 m asl), suggesting that the paleoshoreline could have extended up to 270 m asl altitude. Furthermore, paleolake sediments were detected on the GPR profile (Fig. 12), pointing to the northward extension of paleolake sediments around the Manastir hum. Thus, the paleoshoreline was likely similar to the modern flooding levels (see paleolake extension in Fig. 2A).

5.1.3. Late Holocene post-paleolake phase (800 cal yr BP – present)

A facies change can be seen in Subunit 2c from lacustrine carbonate to dark greyish-brown clayey silts. Indicators of a gradual lithological boundary include mixed carbonate and clayey sediment (calcareous intercalations), gastropod shells and fragments, grain size decrease, variations in color parameter L^* (carbonate versus siliciclastic content), and a gradual increase in MS (Figs. 9 and 10). Elevated MS in Subunit 2d in sediment core PB-2 indicate sediment delivery into the Prološko Blato, likely as a result of increased agricultural activity and flash floods in the Imotsko Polje in the last 800 years (Ujević, 1991). Moreover, Subunit 2c within the core PB-2 contains an interval (126–135 cm) of disturbed clayey/carbonate intercalations, suggesting a disturbance in the paleolake environment. Thus, Subunit 2c is interpreted as a disruption in the paleolake's hydrology, a shift from nearly 8000 years of relatively stable carbonate sedimentation (Subunit 2b) to deposition of dark greyish-brown clayey silt (Subunit 2d). The lithological boundary between Subunits 2b and 2c was dated to 800 cal yr BP, which marks the end of the lacustrine (paleolake) phase and establishment of the modern environment, i.e., karst wetland with seasonal flooding. However, gradual changes in sedimentological properties (color, grain size, mineral composition, MS), as well as the presence of carbonate/clayey intercalations, suggest that this environmental shift was not abrupt.

It is possible that this environmental shift was initiated by sinkhole formation in the eastern part of the paleolake, at the polje boundary, and the subsequent formation of the Prološko Lake in its modern form (Fig. 13C). The Prološko Lake represents an estavelle, functioning as a spring in the wet and as a ponor (sink/swallow hole) in the dry part of the year. It is directly connected to the groundwater; thus, it represents a natural piezometer (Bonacci and Roje-Bonacci, 2000). Sub-bottom profiling in the Prološko Lake revealed the existence of sublacustrine springs on the lake bottom (Fig. 6B), suggesting that the karst process is active. Thus, any disturbance in the Prološko Lake sinkhole could produce changes in the paleolake's hydrology, such as the shift from a permanent lake condition to a seasonally flooded karst wetland. According to this hypothesis, the establishment of a new hydrological regime with seasonal flooding led to the desiccation of the paleolake and deposition of siliciclastic clayey silt, which is exposed to pedogenesis when the water retreats, as seen from numerous root traces in cores (Fig. 11) and elevated frequency-dependent MS (χ_{fd}) in Subunit 2d (Fig. 9).

Seasonal flooding is the main erosional process in the Prološko Blato, causing the formation of erosional channels within the paleolake and alluvial sediments (Fig. 13D). Eroded sediments are transported via the main channel into Prološko Lake. Therefore, the eroded sediments from the paleolake and alluvial sediments are deposited in the Prološko Lake (Fig. 13D). This is supported by the clay mineral composition of grab samples taken on the Prološko Lake bottom, which is the same as samples from core PB-1 (Tables S2 and S3 in Supplementary material). Additionally, high-resolution seismic data suggest the existence of a sediment depocenter in the Prološko Lake, without significant erosional events (Fig. 5). Erosion, or more precisely suffosion, of Quaternary sediments is also occurring in the subsurface of the polje, as evidenced by the existence of smaller lakes Bućuša and Krenica (subsidence sinkholes). This further supports the presumption that the karst process is active in the Prološko Blato and that new sinkholes can open in the future. Surface morphology around the Manastir hum points to the existence of buried sinkholes in underground (Fig. 3A), although they were not clearly visible via the GPR survey. Buried sinkholes can be reactivated due to the loss of fill material by suffusion into an underground void (Waltham et al., 2005).

5.2. Constraints of the Prološko Lake collapse hypothesis

The most obvious constraints regarding the Prološko Lake collapse hypothesis are the timing of the collapse sinkhole formation and the thick succession of the finely-laminated lake sediments within the

Prološko Lake. If the sinkhole existed during the paleolake phase, we can presume that it would lead to seasonal desiccation of the paleolake. We did not see such features (e.g., desiccation cracks) in sediment cores within Subunit 2b, i.e., during the paleolake phase. Furthermore, thick gravel deposits are outcropping on the Prološko Lake shores, which indicates that the alluvial fan deposition occurred in this area. Thus, we would expect to see coarse-grained sediments within the Prološko Lake sinkhole, but they are absent on seismic profiles. This indicates that Late Pleistocene alluvial sediments possibly collapsed in the underground cavern. Alternatively, the sinkhole could have been clogged by the sediment and later reactivated due to new subsidence or if the sediment was washed down the sinkhole, which can be a recurring process (Kindinger et al., 1999). This would explain the relatively thick (~20 m) lake sediment succession in the Prološko Lake and missing coarse-grained sediments on seismic profiles (Figs. 5 and 6). Therefore, the collapse did not have to happen when the paleolake was desiccated around 800 cal yr BP, but it could have occurred earlier and was subsequently buried. However, disturbed sediment within Subunit 2c with numerous intercalations suggests a disturbance in the paleolake's hydrology, while collapsed blocks of limestones and sublacustrine springs on seismic profiles suggest that karstification processes are active, meaning that they could have led to the disturbance in the paleolake's hydrology. Moreover, the absence of alluvial (coarse-grained) sediments from seismic profiles suggests that these sediments were either collapsed or washed away in the underground voids, as depicted in Fig. 13C. Based on the current sedimentological, geomorphological, and geophysical data, we hypothesize that the evolution of the Prološko Blato depicted in Fig. 13 is more plausible. The sinkhole formation and ground subsidence could have been triggered by the high seismic activity of the Imotsko Polje (Dragičević et al., 1999), as was documented in the past (Brčić et al., 2019; Ujević, 1951), or simply due to active dissolution processes in the underground.

6. Conclusion

The Prološko Blato evolution can be tracked from the Last Glacial Period, when alluvial fan sedimentation was the dominant process in the karst polje. Sufficient sediment production in the uplands, necessary for alluvial fan development, is associated with high-water discharges possibly related to climate changes during the deglaciation period but also from the meltwater in western Herzegovina, which was glaciated during the Last Glacial Maximum. The alluvial sedimentation ceased at the Late Pleistocene and Holocene transition, at least in the Prološko Blato, which enabled progressive paleolake formation from shallow wetland to a deeper lake with carbonate sedimentation. The paleolake phase lasted throughout the relatively stable and warm Holocene until it was disrupted by the karstification processes in paleolake's marginal part, which led to the formation of the modern Prološko Lake sinkhole, and the establishment of hydrological regime with seasonal flooding. It remains unclear whether the sinkhole was formed earlier than the paleolake or whether the collapse happened when the paleolake was desiccated. Thus, coring of the lake sediments in Prološko Lake in the future would offer valuable new data that would dispute or confirm the hypothesized collapse.

This research offers a new scientific contribution to our understanding of karst lake formation and the complex morphology of karst poljes as one of the largest karstic features in the Dinarides. We have demonstrated that multiple processes can affect sedimentation processes in karst poljes, from regional (climate and hydrological changes) to local (karstification processes, changes in the groundwater level, river pathway changes, tectonics). This implies that karst poljes potentially hold valuable terrestrial paleoclimate/paleoenvironmental archives, but their interpretation should be based on the comprehensive research approach. Moreover, we have shown a clear interplay of surface and subsurface processes in karst poljes, such as changes in depositional environments due to dissolution processes in karst. These processes can

greatly affect the hydrological conditions of karst poljes and thus potentially affect vulnerable areas within them, such as karst wetlands.

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CRediT authorship contribution statement

Ivona Ivkić Filipović: Writing – review & editing, Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Nikolina Ilijanić:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Slobodan Miko:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Ozren Hasan:** Writing – review & editing, Visualization, Software, Methodology, Investigation, Formal analysis. **Dea Brunović:** Writing – review & editing, Visualization, Software, Methodology, Investigation, Formal analysis. **Branko Kordić:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis. **Uroš Barudžija:** Writing – review & editing, Investigation, Formal analysis. **Željka Sladović:** Visualization, Software, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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Supplementary material to research paper 4

Supplementary material – Sedimentological description of profile PBK1-PK

Profile PBK1-PK comprises 632 cm thick sedimentary sequence composed of lower Unit 1 and upper Unit 2 (Fig. 3). Color of the Unit 1 ranges from white (10YR 8/1) and light grey (10YR 7/2-7/3) in the Subunit 2b to very dark greyish brown (10YR 2/2) in Subunit 2a. Color of the Unit 2 ranges from brownish yellow (10YR 6/8) to yellow (10YR 7/8) in subunits 1b and 1c to grey (10YR 5/1) sediments in Subunit 1a. Volume MS (κ_{lf}) varies from 0.9 to $37.2 \times 10^{-8} \text{ m}^3/\text{kg}$, while frequency-dependent MS varies from 0.0 to $0.2 \times 10^{-7} \text{ m}^3/\text{kg}$. MS values are highest in thin yellowish-brown interlayer (40-50 cm) in the Subunit 2b, and in the dark brown siliciclastic Subunit 2a (Fig. 8). Major mineral phases are calcite and quartz, except for the upper part of the Subunit 2a (360-369 cm) with quartz and clay minerals as dominant phases. Calcite predominates in the Subunit 2b, and it is accompanied by variable amounts of quartz and clay minerals. Lower Unit 1 has higher amount of calcite relative to quartz, K-feldspar, plagioclase, and clay minerals. Grain size varies from fine silt to very fine sand, with mean grain size (Mz) ranging from 4.9 to $75.5 \mu\text{m}$. Highest sand content (67.3%) is in the Subunit 1b, while highest silt (89.9%) and clay (22.1%) content are in the Subunit 2a (Fig. 8). Gravel layers were not present in this profile, but they were detected as lateral facies change within the erosional channel, between 450 and 520 cm (upper part of the Subunit 1c).

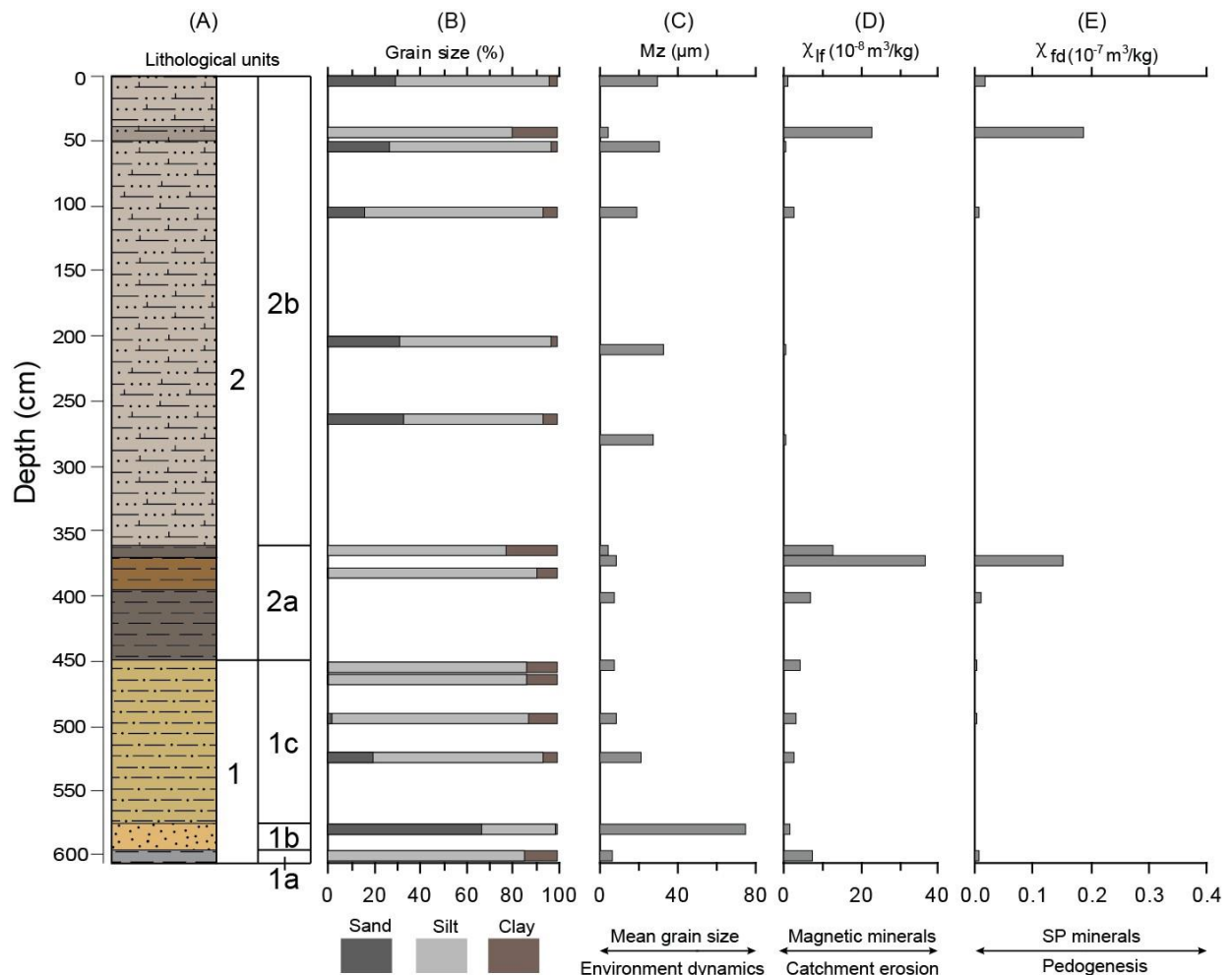


Fig. S1 (A) Lithological units of the profile PBK1-PK, (B) grain size distribution, (C) mean grain size, (D) mass and (E) frequency-dependent magnetic susceptibility.

Supplementary table S1 Visual description of core PB-1, comparison with core PB-2 and profile PBK1-PK and environmental interpretation.

Units	Subunits	Sediment description in the core PB-1	Comparison remarks (PB-1, PB-2, PBK1-PK)	Interpretation
2	2d	Clayey silt with dark greyish brown color (10YR 4/2), contemporary roots, no fossil remains, Fe-depletions and concentrations	Subunits 2d and 2c absent in profile PBK1-PK due to erosion.	Paleolake sediments – Floodplain environment
	2c	Greyish to yellowish brown (10YR 5/2-5/4) clayey silt with calcareous intercalations and gastropod fragments	Contacts between subunits 2b and 2d is gradual and described as subunit 2c, with intercalations of subunit 2b occurring in subunit 2d.	Paleolake sediments – erosional input
	2b	Light grey to pale brown (10YR 7/1-7/3) homogenous and massive sandy silt, rich in gastropods (<i>Bithynia tentaculata</i> , <i>Valvata</i> sp.) and Charophytes, no visible organic macro remains, oxidized rhizoid traces	Dark yellowish brown (10YR 4/4) clayey interlayer is present in the upper part of the subunit 2b. Lithological contacts between subunits 2a and 2b is sharp, planar to irregular.	Paleolake sediments – deeper lake environment
	2a	Very dark greyish brown (10YR 2/2) clayey silt with oxidized dark yellowish brown (10YR 4/6) layer, minerogenic, no visible organic remains, clayish, visible redoximorphic features, abundant gastropod fragments	Ca concretions present in the lower part of the subunit 2a in core PB-2, and they continue in the subunit 1c.	Paleolake sediments - shallow to wetland environment
1	1c	Disturbed yellowish brown (10YR 5/6) gravel, with fining upward sequence, from coarse grained (325-400 cm) to mud supported (310-325 cm) matrix, rounded to subrounded clasts made of foraminifera limestone	Subunit 1C is absent in core PB-2, and in PBK1-PK is represented by yellowish (10YR 6/8) clayey to sandy silt with Ca concretions; lateral facies change to gravel was detected within erosional channels.	Alluvial sediments - distal part of the alluvial fan
	1b	Light brownish grey (10YR 6/2) clayey silt with pronounced admixtures of yellowish brown (10YR 5/8), yellowish sand from 479-482 cm, irregular Ca concretions	In PB-2, subunit 1b is made of brownish yellow (10YR 6/8) clayey to sandy silt with Ca concretions. In PBK1-PK subunit is made of brownish yellow sand	
	1a	Yellowish brown (10YR 5/4-5/8) couplet made of alternating coarser and finer grained layers: gravel 585-600 cm; clayey silt 600-617 cm; gravel 617-627 cm; sand 627-645	In PB-2, subunit 1a is made of very pale brown (10YR 7/3-7/4) gravel with rounded to subrounded clasts and fining-upward sequence. In PBK1-PK subunit is made of oxidized greyish clay (10YR 5/1), laminated, with organic-rich layers	

Table S2 Mineral composition of selected samples from core PB-1 (Cal=calcite, Qtz=quartz, Kfs=K-feldspar, Pl=plagioclase, Arg=aragonite, Ms=muscovite, Ill=Illite, Sm=smectite, V=vermiculite, Kln=kaolinite).

Samples	Units	Subunits	Major minerals	Minor minerals	Clay minerals
PB-1 10-20			Cal, Qtz	Ms/Ill, Sm/Chl/V, Kln, Pl, Kfs	
PB-1 30-40		2d	Cal, Qtz	Ms/Ill, Sm/Chl/V, Kln, Pl, Kfs	Sm, V, Ill, Kln
PB-1 70-80		2c	Cal	Qtz	
PB-1 110-111			Cal	Qtz, Arg	
PB-1 130-131			Cal	Qtz, Sm/V/Chl, Kln, Ms/Ill	Sm, V, Ill, Kln
PB-1 140-150	2	2b	Cal	Qtz, Arg, Kfs	Sm, V, Ill, Kln
PB-1 170-171			Cal	Qtz, Arg	Sm, V, Ill, Kln
PB-1 240-241			Cal	Qtz, Arg	Sm, V, Ill, Kln
PB-1 280-281			Qtz	Cal, Sm/Chl/V, Ms/Ill, Kln, Pl, Kfs	I-S, Ill, Kln
PB-1 295-296		2a	Qtz	Cal, Kfs, Ms/Ill, Sm/Chl/V, Kln	
PB-1 310-320			Qtz	Cal, Sm/Chl/V, Ms/Ill, Kln, Pl, Kfs	
PB-1 350-360			Cal	Qtz, Pl	
PB-1 380-392		1c	Cal, Qtz	Sm/Chl/V, Ms/Ill, Pl	
PBP 400-401			Cal	Qtz, Ms/Ill, Sm/V/Chl, Kln, Pl, Kfs	Sm, V, Ill, Kln
PBP 470-471			Cal	Qtz, Ms/Ill, Sm/Chl/V, Kln, Pl, Kfs	
PBP 480-481			Cal, Qtz	Ms/Ill, Sm/Chl/V, Kln, Pl, Kfs	
PBP 500-501	1	1b	Cal, Qtz	Ms/Ill, Sm/Chl/V, Kln, Pl, Kfs	Sm, V, Ill, Kln
PBP 540-541			Cal, Qtz	Ms/Ill, Sm/Chl/V, Kln, Pl, Kfs	Sm, V, Ill, Kln
PBP 575-576			Qtz, Cal	Ms/Ill, Sm/Chl/V, Kln, Pl, Kfs	Sm, V, Ill, Kln
PBP 610-611			Qtz, Cal	Ms/Ill, Sm/Chl/V, Kln, Pl, Kfs	Sm, V, Ill, Kln
PBP 645-646		1a	Cal, Qtz	Ms/Ill, Sm/Chl/V, Kln, Pl, Kfs	

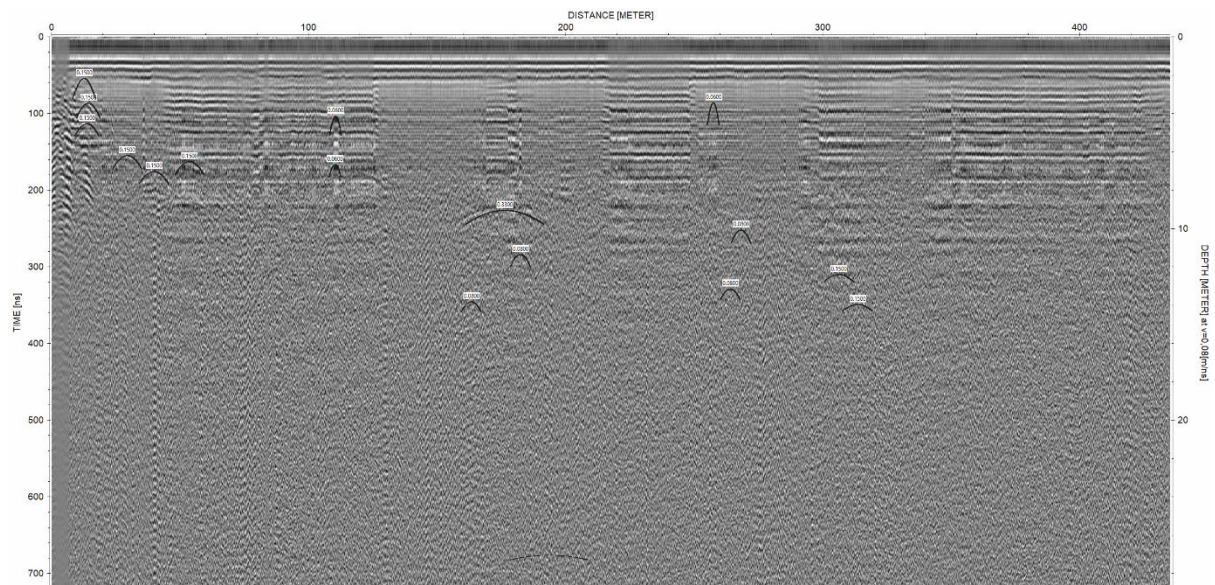
Table S3 Mineral composition of additional samples taken within erosional channels (alluvial deposits), grab samples from the Proložsko Lake and marl samples from the catchment (Cal=calcite, Qtz=quartz, Kfs=K-feldspar, Pl=plagioclase, Arg=aragonite, Ms=muscovite, Ill=Illite, Sm=smectite, V=vermiculite, Kln=kaolinite).

Samples	Description	Major	Minor	Clay minerals
Greyish brown clayey silt	Pleistocene alluvial deposits from erosional channels	Cal, Qtz	Ms/I, Sm/Chl/V, Kln, Pl	Sm, Chl, V, Ill, Kln
Greyish blue clayey silt		Cal, Qtz	Ms/I, Sm/Chl/V, Kln, Pl, Kfs	Sm, Chl, V, Ill, Kln
PR-1 GRAB	Grab samples from the bottom of the Proložsko Lake	Cal	Qtz, Sm/V/Chl, Kln, Ms/I	Sm, V, Ill, Kln
PR-2 GRAB		Cal	Qtz, Sm/V/Chl, Kln, Ms/I	
PR-4 GRAB		Cal	Qtz, Ms/I, Sm/V/Chl, Kln	
PR-5 GRAB		Cal	Qtz, Ms/I, Sm/V/Chl, Kln, Pl, Kfs	Sm, V, Ill, Kln
Marl Ričice (grey)	Marl samples from Ričice retention basin in the catchment	Cal, Qtz	Ms/I, Sm/Chl/V, Kln	Sm, Chl, V, Ill, Kln
Marl Ričice (yellow)		Cal, Qtz	Ms/I, Sm/Chl/V, Kln	Sm, Chl, V, Ill, Kln

Table S4 Mineral composition of selected samples from core PB-2 (Cal=calcite, Qtz=quartz, Kfs=K-feldspar, Pl=plagioclase, Arg=aragonite, Ms=muscovite, Ill=Illite, Sm=smectite, V=vermiculite, Kln=kaolinite).

Samples	Units	Subunits	Major minerals	Minor minerals
PB-2 0-1			Cal, Qtz	Ms/I, Sm/Chl/V, Kln, Pl
PB-2 30-31		2d	Cal, Qtz	Ms/I, Sm/Chl/V, Kln, Pl
PB-2 50-51			Cal, Qtz	Ms/I, Sm/Chl/V, Kln, Pl
PB-2 100-101			Cal, Qtz	Ms/I, Sm/Chl/V, Kln, Pl, Kfs
PB-2 120-121		2c	Cal	Qtz, Ms/I, Sm/Chl/V, Kln
PB-2 130-131			Cal	Qtz, Sm/Chl/V, Ms/I, Kln
PB-2 150-151			Cal	Qtz, Sm/Chl/V, Ms/I, Kln, Pl, Kfs
PB-2 210-211			Cal	Qtz
PB-2 220-221			Cal	Qtz
PB-2 300-301	2		Cal	Qtz, Pl
PB-2 360-361		2b	Cal	Qtz, Arg, Pl
PB-2 380-381			Cal	Qtz, Arg, Pl
PB-2 390-391			Cal	Arg, Qtz, Pl
PB-2 400-401			Cal	Arg, Qtz, Pl
PB-2 420-421			Cal	Arg, Qtz, Pl
PB-2 430-431			Cal	Arg, Qtz, Sm/Chl/V, Ms/I, Kln
PB-2 440-441			Qtz	Ms/I, Sm/Chl/V, Kln, Kfs
PB-2 450-451		2a	Qtz, Cal	Ms/I, Sm/Chl/V, Kln, Kfs
PB-2 480-481			Qtz, Cal	Ms/I, Sm/Chl/V, Kln, Pl
PB-2 520-521			Qtz, Cal	Ms/I, Sm/Chl/V, Kln, Pl
PB-2 540-541			Cal, Qtz	Ms/I, Sm/Chl/V, Kln, Pl
PB-2 600-601			Qtz, Cal	Ms/I, Sm/Chl/V, Kln, Pl, Kfs
PB-2 660-661	1	1b	Cal, Qtz	Ms/I, Kfs, Pl
PB-2 680-681			Cal, Qtz	Ms/I, Sm/Chl/V, Kln, Pl, Kfs
PB-2 730-731			Cal, Qtz	Ms/I, Sm/Chl/V, Kln, Pl, Kfs
PB-2 800-801			Cal, Qtz	Ms/I, Sm/Chl/V, Kln, Pl

Supplementary figures – processing workflow for GPR profiles



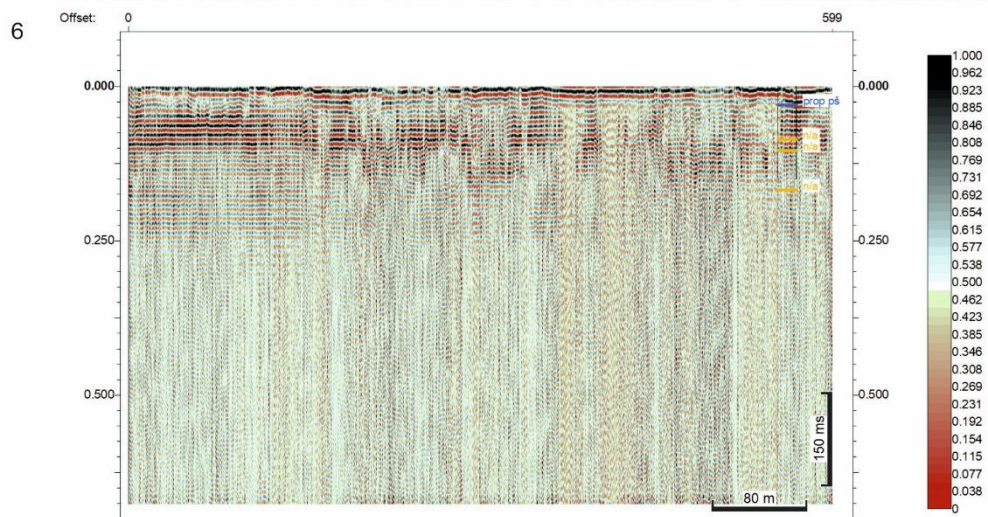
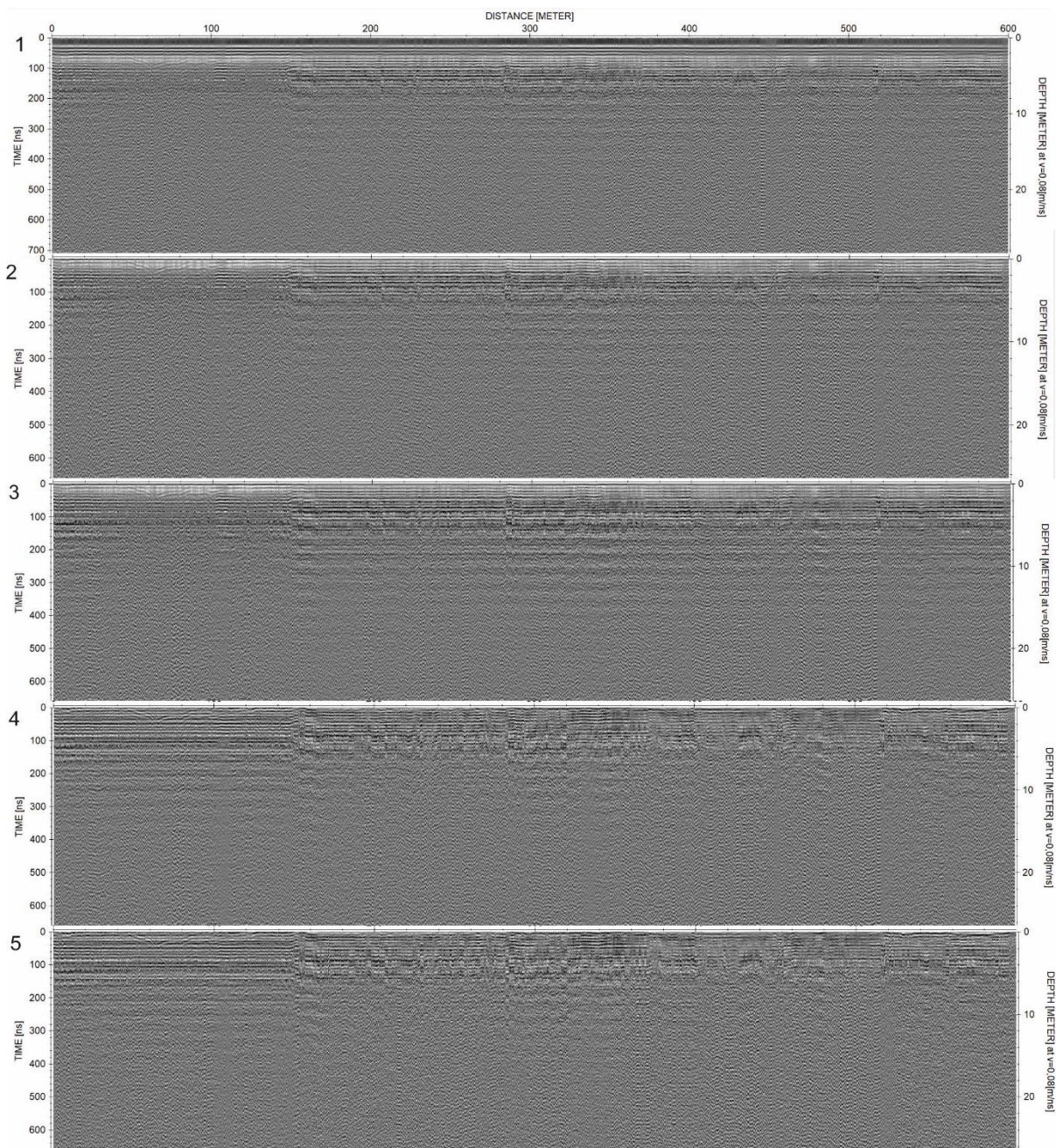
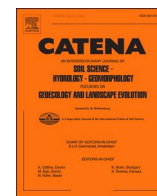


Fig. S3 Example of processing workflow applied to GPR profile include several filters (in ReflexW) and interpretation (in Kingdom). 1. Move start time – static correction of each each trace, shifted by 35; 2. Stack traces – dense data set was surveyed, stacked set of 6 traces; 3. Background removal – filter subtracted averaged trace in whole y direction (758.59 ns); 4. Energy decay – filter is applied on the complete profile based on the mean amplitude decay curve, value of energy decay filter is 10; 5. Time to depth – applied 0.08 m/ns for all profiles, for carbonate basement part 0.15 m/ns; 6. Processed profiles were imported into Kingdom software; interpretation was performed on structural attribute pseudorelief.

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Geomorphological influence on the Holocene climate signal from a karst wetland in the Central Mediterranean

Ivona Ivkić Filipović^{a,b}, Nikolina Ilijanić^{a,*}, Slobodan Miko^a, Melanie J. Leng^{c,d}, Jack H. Lacey^c, Valentina Hajek-Tadesse^a, Tamara Marković^a, Martina Šparica Miko^a

^a Croatian Geological Survey, Sachsova 2, 10000 Zagreb, Croatia

^b Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, 10000 Zagreb, Croatia

^c British Geological Survey, Nottingham NG12 5GG, United Kingdom

^d School of Biosciences, University of Nottingham, Sutton Bonington, Loughborough LE12 5RD, United Kingdom

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ABSTRACT

Lake sediments from the Dinaric karst region (Central Mediterranean) hold valuable paleoenvironmental records, yet remain underexplored compared to other Mediterranean areas. This study presents a multiproxy analysis of Holocene paleolake sediments from Prološko Blato karst wetland in Dalmatia (Croatia), using geochemistry, ostracods, and radiocarbon dating to reconstruct past hydroclimate variability. Proxy records indicate intermittent lake conditions during the wetter Early Holocene, contrasting with other lake level records, probably due to high surface and subsurface connectivity in the karst. The Middle to Late Holocene is characterized by lake deepening and lacustrine carbonate sedimentation, decreased run-off and increased ostracod abundances, indicating the development of permanent lake conditions. The oxygen and carbon isotope data suggest progressive aridification towards the Late Holocene, in line with other Mediterranean records. However, a pronounced shift to lower isotope values between 2100 and 500 cal yr BP indicates wetter conditions in the lake, in contrast to the lower lake levels and more arid conditions reported for the Roman and Medieval Warm Periods in other Mediterranean records. The sudden shift was linked to the opening of a sinkhole in the paleolake's marginal part, which caused hydrological disturbance and the formation of a modern, seasonally flooded wetland. This research provides a new Holocene hydroclimate record for the Dinarides, while highlighting the influence of geomorphological processes in karst on paleoclimate interpretation.

1. Introduction

Lake sediments represent one of the best terrestrial archives of past environmental and climatic change (Last and Smol, 2001). However, interpretation of proxies in lake sediments is not always straightforward, since many other non-climatic and often local factors can influence their stratigraphic profiles. In that regard, human impact is often recognized as one of the local influencers, for example, via land cover changes and agricultural activity leading to eutrophication (Roberts et al., 2008). In sensitive areas, such as karst, other local (geomorphological) processes can also dictate the distribution of environmental proxies through time, which could be wrongly attributed to climate change. Deciphering climatic from non-climatic signals is therefore crucial for proper interpretation of past climatic variability and correlation between lake records, especially in the Mediterranean basin, where many lake isotope

records are from karstic settings (Leng et al., 2010a).

Numerous paleoenvironmental studies have been conducted in the Mediterranean, and there is relatively good coverage of lacustrine (see the synthesis by Roberts et al., 2008), speleothem (e.g., Bajo et al., 2016; Bar-Matthews et al., 1997, 2000; Drysdale et al., 2006; Regattieri et al., 2014; Surić et al., 2021; Zanchetta et al., 2007a, 2016), and marine sediments (Comboureu-Nebout et al., 2013; Goudeau et al., 2014; Siani et al., 2013). In the Central Mediterranean, there are lake sediment data for Italy (e.g., Baroni et al., 2006; Francke et al., 2022; Magny et al., 2007, 2011; Marchegiano et al., 2018; Zanchetta et al., 2007b) and South-Eastern Europe (e.g., Francke et al., 2013; Frogley et al., 2001; Lacey et al., 2015; Leng et al., 2010b, 2013; Mazzini et al., 2016; Zanchetta et al., 2012). Data from lake sediments in the Adriatic region are emerging (e.g., Hajek-Tadesse et al., 2018a; Ilijanić et al., 2018, 2022; Razum et al., 2021), but there is still relatively poor coverage in terms of

* Corresponding author

E-mail address: nilijanic@hgi-cgs.hr (N. Ilijanić).

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paleoclimate studies (see Finné et al., 2019). This is especially the case for oxygen and carbon isotope ($\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$) data from lacustrine carbonates, which may be due to a high possibility of detrital carbonate load (Leng et al., 2010a), as most of the lakes are on karst. In Croatia, karst lakes are primarily located along the eastern Adriatic Coast, where marine influence can further complicate the interpretation of stable isotope data. Nevertheless, good potential exists in lakes situated more inland, which are often associated with karst poljes, one of the largest surface karst landforms, and very common for all parts of the Dinaric karst belt (Ford and Williams, 2007).

This research aims to provide multiproxy data from lake sediment cores from Prološko Blato karst wetland, situated in one of the largest karst poljes in Croatia, Imotsko Polje. The data include sedimentology (color, grain size, magnetic susceptibility), geochemistry (major and trace elements, TOC, TN, TOC/TN, $\delta^{18}\text{O}_{\text{calcite}}$, and $\delta^{13}\text{C}_{\text{calcite}}$), and micropaleontology (ostracods). The results presented here build on previous research based on geomorphological and geophysical data (Ivkić Filipović et al., 2025), and support the interpretation of past hydrological and environmental changes, improving our understanding of past climatic variability. Finally, by comparison with other lacustrine and non-lacustrine records in the Mediterranean, we show how local geomorphological factors and processes in karst can affect the hydrological record.

2. Study area

The Prološko Blato is a seasonally flooded karst wetland situated in the NW part of the Imotsko Polje in the Dalmatian hinterland, at the border between Croatia and Bosnia and Herzegovina (Fig. 1A). The Imotsko Polje represents a typical Dinaric karst polje where almost all karst landforms are developed, such as karst springs, estavelles, ponornica rivers, and ponors. However, the area is best known for numerous sinkholes and karst lakes (e.g., Red Lake, Blue Lake) formed due to carbonate dissolution processes and cavern collapse. These lakes are renowned hydromorphological features and have a great ecological and economic value for the region. The catchment is comprised of Cretaceous carbonates (limestones and dolomites), Paleogene clastic flysch and Promina beds (conglomerates, sandstones and marls), and

Miocene marls, while the polje is filled with 105–145-m-thick Quaternary alluvial sediments (clays, sands and gravels) (Raić and Papes, 1978; Roglić, 1938; Sakač and Jović, 1958). The region is characterized by complex tectonics and is seismically very active (Dragičević et al., 1999; Kuk et al., 2000).

Groundwater and surface water dynamics in the area are primarily controlled by regional precipitation in the western Herzegovina mountains. Infiltration, recharge, and runoff processes are governed by the intensity and distribution of rainfall, as well as the highly permeable carbonate rocks. These factors collectively influence the direction and behavior of groundwater flow, which generally moves from the elevated recharge zones in the mountains towards the lower karst depressions, including the Imotsko Polje (Filipović et al., 2023). The main surface water input to this system is the Suvaja River, which traverses the Badnjevice canyon and discharges into the Imotsko Polje and the Prološko Blato depression (Fig. 1B) (Bonacci and Roje-Bonacci, 2008; Bonacci and Roje-Bonacci, 2000). Prološko Blato is part of the broader Lokvičići Lake System, a complex of closely spaced karst depressions and sinkholes that are hydrologically connected through subterranean pathways (Bojanić et al., 1981). Seasonal hydrological variability is pronounced. During the winter, increased precipitation and limited infiltration due to high groundwater tables lead to frequent flooding, transforming Prološko Blato into a shallow, temporary lake with associated wetland vegetation. A single hill, known as Manastir, remains emergent above the floodwaters and hosts the remnants of a 16th-century Franciscan monastery. Floodwaters typically enter the polje through a network of estavelles located along its northwestern boundary and via the Prološko Lake itself. In contrast, during the dry summer months, water retreats through the same estavelles, and the entire area transforms into a dry polje (Ivkić Filipović et al., 2025). The Prološko Lake, Krenica Lake, and Bučuša Lake retain water year-round due to their hydraulic connection to deeper, saturated zones (Brčić et al., 2019).

Prološko Lake is the most significant estavelle in the system, functioning as a karst spring in wet periods and as a ponor during dry periods. The lake is 20 m deep in its eastern part, with a muddy bottom gently sloping from the western to the central part (Ivkić Filipović et al., 2025). Its E-NE side comprises a steep hanging wall of highly fractured

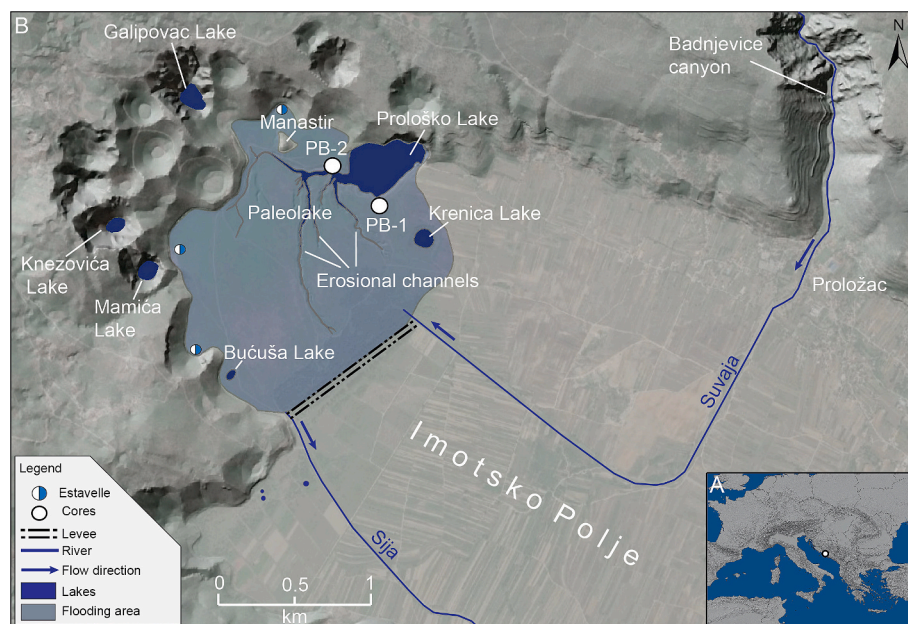


Fig. 1. Geographical position of the Prološko Blato area (A), hillshade map showing karst lakes (collapsed sinkholes), main hydrological features, and sampling locations (note the boundary between paleolake and Prološko Lake in green dotted line). Source of the satellite image in the background: World Imagery by ESRI, Maxar, Earthstar Geographics, and the GIS User Community (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

limestones, while the S-SW shore is made of unconsolidated Quaternary sediments. This sharp contact of limestones and Quaternary sediments, along with a steep hanging wall, indicates the lake's collapsed nature (Ivkić Filipović et al., 2025). Seasonal flooding is the main erosional process in the area, creating distinctive erosional channels (Fig. 1B) that contain exposed paleolake sediments. Eroded material is then transported via erosional channels and deposited onto the Prološko Lake floor (Ivkić Filipović et al., 2025). The Prološko Blato is partially fed by groundwater and partially by a man-made stream from the Suvaja River (Fig. 1B) (Bonacci and Roje-Bonacci, 2000). The Suvaja River had a greater influence on the polje hydrology before the 20th century. Historical records testify to frequent flooding at the intersection of the Badnjevice canyon and polje (Fig. 1B), causing damage to houses and crops (Ujević, 1991). Flooding was regulated in the 20th century with the construction of a retention basin in the upland. The flooding in the Prološko Blato is controlled by an artificial levee and surface outlet called Sija.

Imotsko Polje has a Mediterranean climate with continental influence, classified as Cfb in the Köppen climate classification, and exhibits unique characteristics. The polje is separated from the Adriatic Sea by the Biokovo Mountain (1762 m asl), which prevents direct penetration of the Mediterranean climate to the hinterland. On its eastern side, towards the mountainous region of western Herzegovina, the polje has no mountain barriers, which leaves it open to continental influence. The specific geographical position and topography result in a higher temperature range between summer highs and winter lows, with typical Mediterranean hot summers, but cold and often intense continental winters. The highest temperature is in August (av. 25 °C), and the lowest in January (av. 5 °C), while the highest precipitation occurs in November (av. 186 mm), and the lowest in July (av. 45 mm) (Vrsalović et al., 2023). The lowest recorded temperature is –12 °C.

3. Methods

Two sediment cores were taken from the Prološko Blato paleolake, core PB-1 (0–310 cm, 43°28'23"N, 17°7'5"E), where we presumed a shallower paleolake, and the core PB-2 (0–520 cm, 43°28'30"N, 17°6'54"E), where we presumed a deeper paleolake. Sub-sampling was conducted at 1 cm resolution, with subsamples collected approximately every 10 cm along the sediment core. Sedimentological analysis has previously been described, focusing on physical properties (color, magnetic susceptibility, grain size, mineral composition) (Ivkić Filipović et al., 2025). Here, we focused on geochemical analyses of sediment core PB-2 and ostracod analysis conducted on both sediment cores to observe the potential differences between shallower and deeper paleolake.

The chronology of lake sediments was established using radiocarbon dating. It is based on four samples throughout the core PB-2: three gastropod shells and one plant material, which was discarded as it yielded modern age. To strengthen the chronology, three samples from outcrops (Beta-573,136, Beta-573,137, and Beta-515,631) were correlated with sediment core PB-2, using the same marker layers described in Ivkić Filipović et al. (2025). These correlated ages, together with four

new radiocarbon dates from PB-2, were used to construct the final age-depth model (Table 1). To correct the freshwater reservoir effect (FRE), we collected two paired charcoal and shell samples from paleolake sediments exposed in erosional channels near the core site. These exposures are easily recognized by their dark-colored, clayey marker layers, thus enabling their correlation with the sediment core (see Ivkić Filipović et al., 2025). The FRE was quantified by calculating the age difference between paired charcoal and shell samples and then applied to shell ages obtained from core PB-2. Radiocarbon dating was conducted at Beta Analytics Laboratory (Miami, USA) and the Radiocarbon Laboratory, Institute of Physics, Centre for Science and Education, Silesian University of Technology (Gliwice, Poland). Age-depth modelling was conducted in R v.4.3.1 (R Development Core Team, 2013) using rBacon v.3.1.0 (Blaauw and Christen, 2011) and the IntCal20 calibration curve (Reimer et al., 2020).

For ostracod analysis, about 10 g of freeze-dried sediment from both cores, PB-1 (27 samples) and PB-2 (53 samples), was washed with tap water using 263 µm and 125 µm sieve sizes and a fine brush. Sieved samples were filtered on Munktell filter paper and oven-dried at 40 °C. Quantitative ostracod analysis was performed on the 263 µm fraction, while the 125 µm fraction was examined qualitatively for estimation of in situ fauna, and both analyses were carried out using a stereomicroscope. Ostracod shells were further analyzed and photographed using scanning electron microscope JEOL JSM-35 CF at the Croatian Geological Survey. Identification of species was based on Fuhrmann (2012), Meisch (2000), Hajek-Tadesse (2018b), and Mazzini et al. (2014).

Total organic carbon (TOC), total inorganic carbon (TIC), and total nitrogen (TN) of the bulk sediments (53 samples) were measured using a Thermo Scientific™ Flash 2000 NC Analyser at the Croatian Geological Survey. The instrument allows measurements of the total carbon (TC) and total nitrogen (TN) in a sample, while the TOC can be measured after the sample treatment with 8 ml 4.2 M HCl. TIC is then calculated as $TIC = TC - TOC$. The TOC/TN mass ratio was multiplied by 1.167 to yield the TOC/TN atomic ratio (Meyers and Teranes, 2001).

Major and trace elements of the bulk sediments (28 samples) were analysed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the Bureau Veritas commercial laboratory in Vancouver, Canada. About 1 g of samples was dissolved with a four-acid digestion method (HCl-HNO₃-HClO₄-HF) at 200 °C. Reference standard materials were STD OREAS25A-4 A, STD OREAS45H, STD OREAS501D, and STD OREAS45E. Geochemical data of discrete samples were statistically treated using the Principal Component Analysis (PCA). The PCA analysis was performed in R (R Development Core Team) to discriminate element groupings related to sedimentary processes. Prior to the analysis, raw concentrations of selected elements were centered-log-ratio (clr) transformed using the zCompositions package (Palarea-Albaladejo and Martín-Fernández, 2015) to account for the compositional nature of the geochemical data.

For stable isotope analysis of lake carbonate (20 samples), around 0.5 g of each sample was treated with 5% sodium hypochlorite for 24 h to remove the organic matter and sieved with deionized water at 80 µm to remove any potential shell fragments (Leng et al., 2013). The sieved

Table 1

Radiocarbon ages used for age-depth modelling of lake sediments. The freshwater reservoir effect (FRE) was taken from Ivkić Filipović et al. (2025). Samples with "Beta" Lab ID were analysed at Beta Analytics Laboratory (Miami, USA), and samples with "GdA" Lab ID were analysed at the Radiocarbon Laboratory, Institute of Physics, Centre for Science and Education, Silesian University of Technology (Gliwice, Poland).

Lab. ID	Sample ID	Depth (cm)	Material	¹⁴ C age	Applied FRE	FRE corrected ¹⁴ C age	Calibrated age (2σ)
GdA-7215	PB-2 92–94	92	Shells	2260	1870	390 ± 30	509–320
Beta – 573,136	PB-10	150	Charcoal	900			909–732
GdA-7216	PB-2222–223	222	Shells	3995	1870	2125 ± 30	2292–2000
GdA-7217	PB-2299–300	299	Shells	5575	1870	3705 ± 30	4149–3930
GdA-7218*	PB-2359–360	359	Plant	F ¹⁴ C = 1.0405 ± 0.0034			Modern
Beta – 573,137	PB-11	440	Charcoal	7200			8159–7938
Beta – 515,631	PBK1–2	500	Shells	9880	1520	8360 ± 30	9470–9293

* Excluded from age-depth modelling because of the modern age.

sediment (<80 µm) was filtered on Munktell filter paper, air-dried, and powdered in an agate mortar. The proportion of CaCO₃ was calculated from TIC values as CaCO₃ (%) = TIC (%) × 8.33. This enabled the estimation of the sample weight that contains 10 mg of CaCO₃ required for the analysis. In general, 30 mg of the <80 µm fraction was reacted with anhydrous phosphoric acid at a constant 25 °C for 16 h, and the product CO₂ was purified and collected cryogenically. The sample CO₂ was analysed using a Sercon Geo HS2022 dual inlet isotope ratio mass spectrometer at the British Geological Survey. Isotope values ($\delta^{13}\text{C}_{\text{calcite}}$, $\delta^{18}\text{O}_{\text{calcite}}$) are reported as per mille (‰) deviations of the isotopic ratios ($^{13}\text{C}/^{12}\text{C}$, $^{18}\text{O}/^{16}\text{O}$) calculated to the VPDB scale using laboratory standards (MCS, CCS) that have been calibrated against NBS-19 and NBS-18. The acid fractionation factor applied to the gas values was 1.01025 (Sharma and Clayton, 1965). The Craig correction is also applied to account for ^{17}O (Craig, 1957). Overall analytical reproducibility for these samples is, on average, better than 0.1‰ for $\delta^{13}\text{C}_{\text{calcite}}$ and $\delta^{18}\text{O}_{\text{calcite}}$ (1σ).

To confirm the presence of endogenic calcite in our samples, we performed SEM analysis on the <80 µm fraction. In addition, we analysed stable isotope composition ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) of Cretaceous limestone from the catchment and of spherulitic aragonites found within the lake sediments to evaluate potential mixing of the isotopic signal of endogenic calcite with these components. These carbonate samples were analysed using an Elementar iso DUAL and precisiON isotope ratio mass spectrometer with a reaction temperature of 90 °C. The acid fractionation factor used for the catchment limestones was 1.00813 (calcite) and for the aragonitic spherules 1.00854 (Kim et al., 2007). The mineralogical composition of powdered spherulitic aragonites was analysed using the PANalytical X'Pert Powder X-Ray Diffractometer (XRD) using Ni-filtered CuK α radiation (at 45 kV and 40 mA), at the Croatian Geological Survey. XRD patterns were interpreted using X'Pert High Score Plus software and International Centre for Diffraction Data (ICDD) mineral database (PDF-4/Minerals).

Lake water and spring water samples were collected in autumn 2018 for characterisation of modern water chemistry. In Prološko Lake, samples were taken by depth, while temperature (T), electrical conductivity (EC), pH, and dissolved oxygen (O₂) profiling were conducted using a multiparameter WTW probe. One sample was taken from shallow Krenica Lake, situated south of the Prološko Lake (Fig. 2). Another sample was taken from a small spring in gravels exposed on the Prološko Lake shores, which represents an alluvial aquifer of the karst polje from which the groundwater seeps during low lake level. Chemical

analyses (anions, cations) were conducted on an Ion Chromatograph Dionex ICS 6000 (Thermo Fisher Scientific, Waltham, MA, USA). Alkalinity was determined by titration with 1.6 N H₂SO₄, using phenolphthalein and bromocresol green-methyl red as indicators, and converted to equivalent HCO₃⁻ concentrations. Water isotopes were analysed using the Picarro L2130-I Isotope and Gas Concentration Analyser (Picarro, Santa Clara, CA, USA) at the Croatian Geological Survey, and results are reported as per mille (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) scale. Analytical precision was 0.1‰ for $\delta^{18}\text{O}$ and 0.5‰ for $\delta^2\text{H}$. To characterise modern isotope hydrology, the isotopic composition of lake and spring water was plotted against the local meteoric water line (LMWL). The isotope composition (both O and H) of water from the karst spring Opačac, the main spring supplying the Imotsko Polje, was taken from an earlier environmental impact study (Kapelj et al., 2005). The Imotski region has no permanent monitoring of the stable isotopes in rainfall, lake waters, or groundwater. Therefore, for the construction of the LMWL, we used IAEA-GNIP data (IAEA WISER) from the Zadar station (Vreća et al., 2006), and the OIPC estimates for the study site (https://wateriso.utah.edu/waterisotopes/pages/data_access/oipc.html) (Bowen and Wilkinson, 2002; Bowen and Revenaugh, 2003; Bowen et al., 2005). Although this is the closest station available, the Imotski region has a greater continentality and altitude influence in contrast to Zadar, which is situated on the Adriatic coast, so hydrological data may not fully reflect climate conditions at the study site.

4. Results

4.1. Water analyses

4.1.1. Chemistry

The results of modern water chemistry are shown in Tables 2 and 3. At the time of sampling, Prološko Lake was about 20 m deep, whereas Krenica Lake was only 1–2 m deep.

Vertical temperature profiling in Prološko Lake at the end of the dry season (early October) revealed clear stratification: a warm epilimnion (17.6 °C) overlays a cool hypolimnion (10 °C), with the thermocline situated between 5 and 10 m in the metalimnion (Fig. 2A). The pH values decrease from 8.1 in the epilimnion to 7.5 in the hypolimnion, as well as dissolved oxygen (from 9.9 to 4.8 mg/l) (Fig. 2A). Electrical conductivity ranges from 379 in the surface sample to 399 µS/cm near the lake bottom. Much smaller and shallower Krenica Lake has a higher

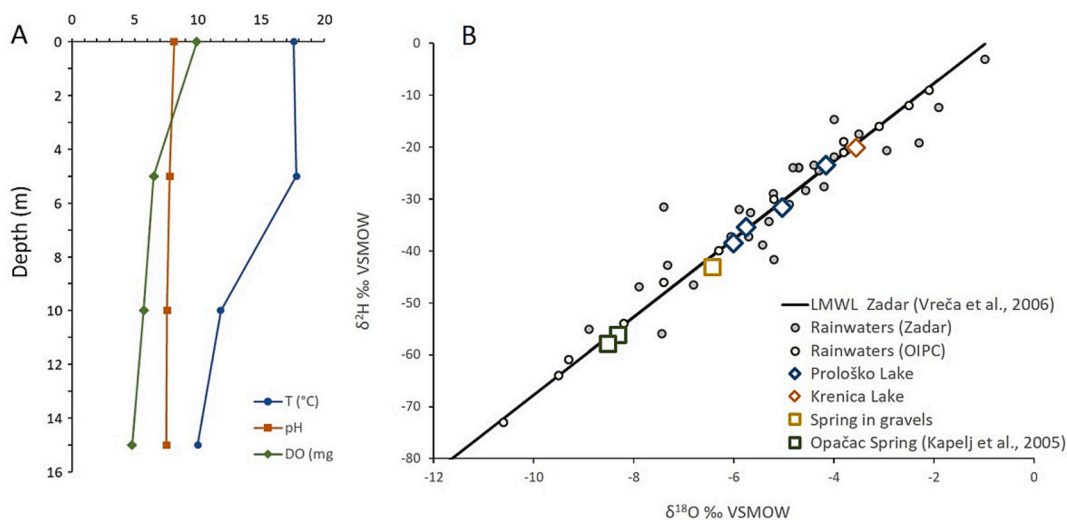


Fig. 2. a) Temperature (T), pH, and dissolved oxygen (DO) profiles in Prološko Lake, b) $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ of modern waters (precipitation, lake waters, spring waters). The isotopic composition of precipitation was taken from the IAEA-GNIP data (Zadar station, Vreća et al., 2006) and the OIPC estimations for the study site (Bowen and Wilkinson, 2002; Bowen and Revenaugh, 2003; Bowen et al., 2005).

Table 2

Results of physical-chemical parameters in water samples from Prološko Lake, Krenica Lake, and a spring in gravels (alluvial aquifer of the karst polje).

Water samples	T (°C)	EC (μS/cm)	pH	O ₂ (mg/l)	HCO ₃ ⁻ (mg/l)	F ⁻ (mg/L)	Cl ⁻ (mg/L)	Br ⁻ (mg/L)	NO ₂ ⁻ (mg/L)	NO ₃ ⁻ (mg/L)	PO ₄ ³⁻ (mg/L)	SO ₄ ²⁻ (mg/L)
Prološko Lake 0 m	17.6	379	8.1	9.9	178	0.6	4.2	3.7	b.d.	3.7	0.1	10.2
Prološko Lake 5 m	17.8	396	7.8	6.5	220	0.6	5.1	3.7	2.7	3.7	0.1	10.1
Prološko Lake 10 m	11.8	391	7.6	5.7	230	0.6	4.2	3.4	b.d.	3.7	0.1	9.5
Prološko Lake 15 m	10.0	399	7.5	4.8	230	0.6	4.2	3.9	4.1	3.9	0.1	9.4
Spring in gravels	16.0	492	7.2	3.2	132	0.6	4.3	3.7	2.7	3.8	0.1	9.7
Krenica lake	18.6	226	8.7	11.7	238	0.6	4.5	3.7	b.d.	6.1	b.d.	11.4

T = temperature; EC = electrical conductivity.

Element concentrations below the detection limit are indicated as “b.d.”

Table 3Cations, molar ratios, calcite saturation index (SI), partial pressure of CO₂, and isotopes (δ¹⁸O, δ²H) in water samples from Prološko Lake, Krenica Lake, and the gravel spring (alluvial aquifer of the karst polje).

Water samples	Ca ²⁺ (mg/l)	Mg ²⁺ (mg/l)	Na ⁺ (mg/l)	K ⁺ (mg/l)	Mg/Ca (molar)	SI (calcite)	logp (CO ₂)	δ ¹⁸ O (‰)	δ ² H (‰)
Prološko Lake 0 m	50.3	6.6	2.0	0.4	0.2	0.7	-2.9	-4.2	-23.5
Prološko Lake 5 m	64.5	6.7	2.6	0.5	0.2	0.6	-2.5	-5.0	-31.6
Prološko Lake 10 m	67.9	6.5	1.9	0.5	0.2	0.3	-2.3	-5.8	-35.4
Prološko Lake 15 m	68.4	6.5	1.9	0.5	0.2	0.2	-2.3	-6.0	-38.5
Spring in gravels	35.3	5.3	2.3	5.8	0.3	-0.5	-3.7	-3.6	-20.1
Krenica lake	73.4	4.0	2.5	0.6	0.1	1.6	-1.9	-6.4	-43.3

surface temperature (18.6 °C), pH (8.7), and DO (11.7), while the EC is lower (226 μS/cm) compared to Prološko Lake. Spring discharging from the gravels on the Prološko Lake shores displays relatively higher temperature (16 °C) and EC (492 μS/cm), and lower pH (7.2), and DO (3.2 mg/l).

As expected, calcium and bicarbonate are the dominant ions in all samples, while Mg/Ca ratios are low (<1) (Table 3), thus indicating that groundwater flowing through limestone karst is the principal source of solutes in these lakes. Somewhat different solute composition is encountered in springs in gravels, for example, lower calcium and higher potassium, likely reflecting the more complex clastic composition of the alluvial aquifer in the karst polje. The calcite saturation index (SI) is highest in Krenica Lake, while in Prološko Lake, SI decreases with depth from 0.7 to 0.2. Similarly, the CO₂ partial pressure (log pCO₂) is highest in Krenica Lake (-1.9), while in Prološko Lake, it increases with depth from -2.9 to -2.3 (Table 3).

4.1.2. Stable isotopes

The stable isotope composition of oxygen and hydrogen (δ¹⁸O and δ²H) in modern lake and spring waters is presented in Fig. 2B, plotted against the LMWL for Zadar and OIPC estimates for the study site. The OIPC estimates fit well with the LMWL Zadar, indicating that, despite its inland location, precipitation in the Imotski region is governed by the same dominant moisture sources.

Lake water samples plot on or near the LMWL and correspond closely to the weighted mean isotopic composition of local precipitation (δ¹⁸O = -5.3‰; δ²H = -32.2‰). In Prološko Lake, isotope values decrease with depth, from δ¹⁸O = -4.2‰ and δ²H = -23.5‰ at the surface to δ¹⁸O = -6.0‰ and δ²H = -38.5‰ at a depth of 15 m, indicating stratification. Surface waters exhibit enriched isotopic signatures characteristic of summer precipitation, similar to the sample from Krenica Lake.

Isotopic compositions of the gravel spring and the karst spring (Opačac) occupy distinct positions along the LMWL. The gravel spring shows relatively enriched δ-values, closely aligned with the average isotopic composition of local rainfall. In contrast, the Opačac spring is more isotopically depleted, falling within the winter precipitation range.

4.2. Core lithology, chronology, and laboratory analyses

4.2.1. Lithology and chronology

The age-depth model for sediment core PB-2 is shown in Fig. 3. All dates fit well with the age-depth model and fall within the 95% confidence intervals (grey dotted lines). For plotting the paleoenvironmental proxies against depth, we used mean age estimates in calibrated years before present (cal yr BP), where before present is 1950 CE. The paleolake environment in the Prološko Blato started to form around 9000 cal BP in a distal part of the alluvial fan that was active in the Imotsko Polje during the Late Pleistocene (Ivkić Filipović et al., 2025). The paleolake sequence starts with very dark greyish brown clayey silts with low CaCO₃ content (<50%), rich in clays and sticky to the touch, with abundant gastropod fragments. This is followed by relatively thick pale brown sandy silt (lacustrine carbonate) with an average of 90% CaCO₃, rich in gastropods, ostracods and Charophytes (Fig. 3). Carbonate sedimentation started at ca. 8000 cal BP and lasted until ca. 800 cal BP when it was replaced by dark brown clayey silts, similar to the lowermost dark greyish brown clayey silts, although with higher CaCO₃ content of around 42%.

Spherulitic carbonates occur throughout the core and are most abundant between 430 and 300 cm. The mineralogical analysis of these carbonate forms showed they are made of aragonite and calcite. The spherules have radial or fan-like structure made of needle-like (acicular) aragonite crystals and are thus described as spherulitic aragonite (Fig. 3). SEM analysis of the bulk samples showed predominantly fine-grained calcite crystals and their aggregates (Fig. 3), along with minor fragments of detrital grains and encrusted Chara remains.

4.2.2. Organic and elemental geochemistry

The lake sediments have relatively low TOC values, averaging 0.6% (Fig. 4). TOC correlates negatively with the grain size, i.e., lowest values are in sandy silts (zones II-IV), while the highest values are in clayey silts (zones I and VI). TN values are also relatively low and range from 0.0 to 0.2% (av. 0.1). TOC/TN values range from 3.9 to 29.0 throughout the whole core. The very dark brown clayey silt (zone I) has an average TOC/TN of 20.7, while the upper zones II-VI have a relatively lower and

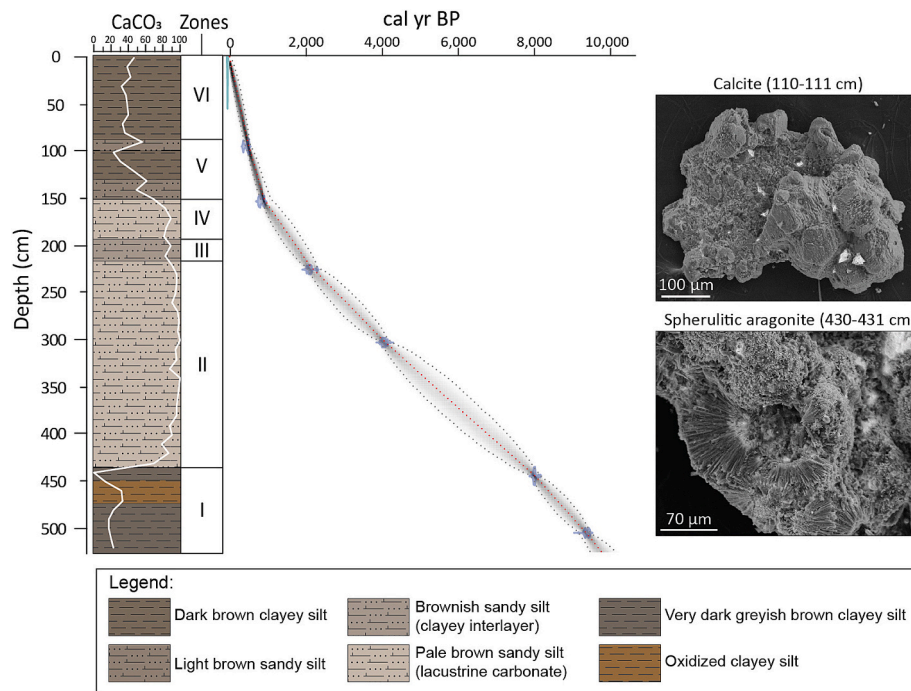


Fig. 3. Age-depth model for sediment core PB-2 against core zones, lithological units, and CaCO_3 variations with depth. SEM images of the two carbonate forms found in the lake sediment are on the right.

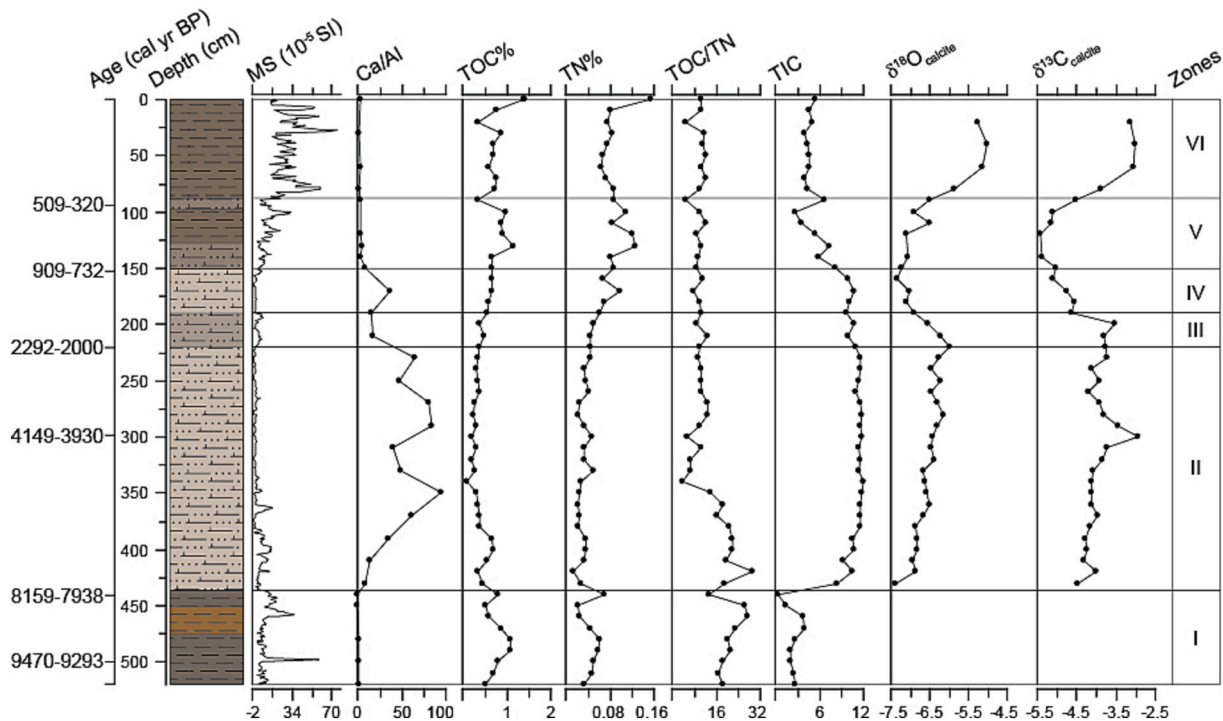


Fig. 4. Distribution of magnetic susceptibility (MS), Ca, Al, TOC, TN, and TOC/TN, TIC, and $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ measured on calcite in core PB-2. MS values are taken from Ivkić Filipović et al. (2025). Stable isotope data provided by BGS © UKRI 2026.

constant TOC/TN ratio of 11.9. TIC values range between 0.4 (zone I) and 11.9% (zone II) (av. 7.7%).

The compositional biplot of selected major and trace elements reveals a clear geochemical separation along axis PC1, which explains the majority of the variance in the dataset (82.2%) (Fig. 5). Ca and Sr show strong positive loadings on PC1 axis, while Fe, Al, Ti, and Zr display strong negative loadings, thus separating carbonate and siliciclastic

(detrital) components. Mg shows moderate positive loading on PC1, but deviates from Ca and Sr vectors, indicating a mixed origin from carbonate precipitation and detrital input (from siliciclastic material).

4.2.3. Isotope data

The $\delta^{18}\text{O}_{\text{calcite}}$ record in core PB-2 ranges from -7.4‰ in the lower part of the zone II (ca. 8000 cal yr BP) to -6.0‰ in the upper part of the

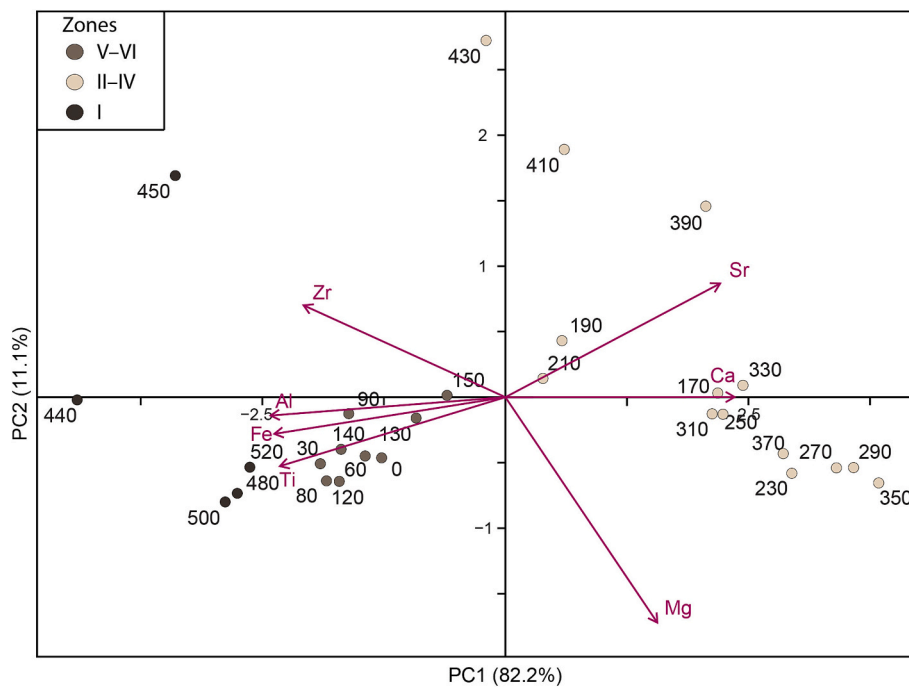


Fig. 5. Compositional biplot of selected major and trace elements in analysed samples, showing the separation of carbonate-associated elements (Ca, Sr) from siliciclastic-associated elements (Fe, Al, Ti, Zr). Mg is partly related to carbonate and partly to siliciclastic components.

zone III (ca. 2000 cal yr BP), with an increasing upward trend (Fig. 4). However, a pronounced shift to lower $\delta^{18}\text{O}_{\text{calcite}}$ (to $<7\text{‰}$) occurs in zones IV-V, which corresponds to time interval between 2000 and 500 cal yr BP. $\delta^{18}\text{O}_{\text{calcite}}$ values increase again at the top of the core (zone VI) to -5.0‰ . $\delta^{13}\text{C}_{\text{calcite}}$ varies from -5.4‰ to -3.0‰ and shows a strong positive correlation with $\delta^{18}\text{O}_{\text{calcite}}$ ($r = 0.8$) throughout the core (Fig. 4).

$\delta^{18}\text{O}$ values of limestone rocks from the catchment vary between -3.9‰ and -3.7‰ , while $\delta^{13}\text{C}$ values vary between -1.5‰ and $+$

1.4‰ (Fig. 3). Spherulitic aragonites have $\delta^{18}\text{O}$ values between -8.1‰ and -7.1‰ , and $\delta^{13}\text{C}$ values between -3.0‰ and -2.6‰ (Fig. 3). As the sediments were sieved at $80\text{ }\mu\text{m}$ this most likely removed any larger spherulitic aragonite and detrital grains prior to the analysis. The scatter plot of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ for these carbonate forms shows that they occupy distinct positions on the plot, with more negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values compared to the lake carbonates (Fig. 6). However, three lake carbonate samples have higher $\delta^{18}\text{O}$ values and are shifted towards the limestone (Fig. 6). These are the topmost samples from zone VI (Fig. 4). Although

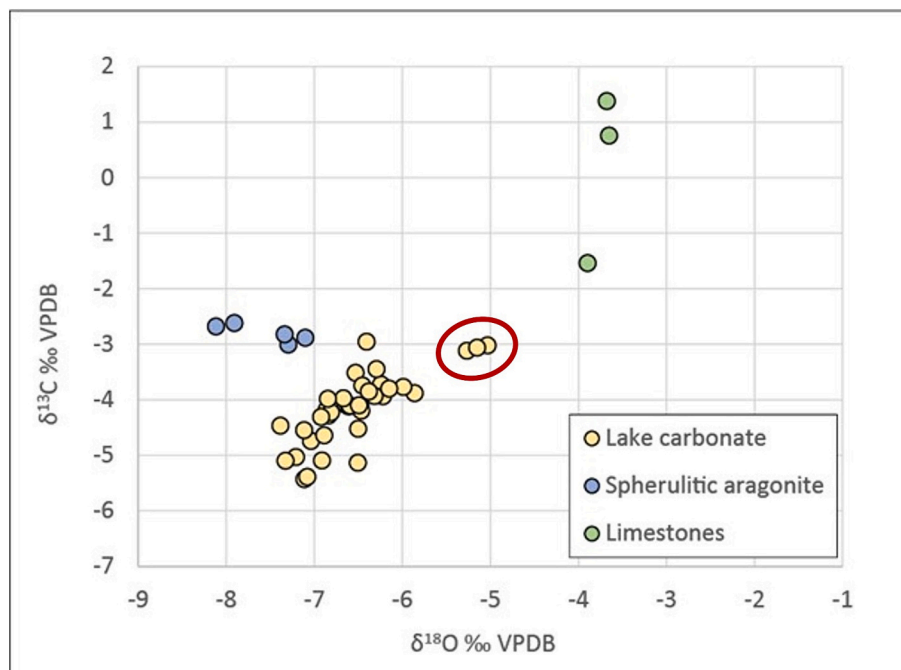


Fig. 6. Stable isotope plot of the different carbonates identified in sediment core PB-2. Note the circled samples (zone VI) with a slight deviation in trend towards the limestones, which could form a mixing line, possibly indicating some contamination (BGS © UKRI 2026).

the catchment limestone isotope values have been corrected as calcite (average $\delta^{18}\text{O} = -3.7\text{‰}$), if these were 100% dolomite this would shift to a lower average $\delta^{18}\text{O}$ of -4.7‰ , with no change in $\delta^{13}\text{C}$, and therefore still indicates that only the upper samples from zone VI contain a component of detrital carbonate (Fig. 6).

4.2.4. Ostracod analysis

In total, 15 species were recovered belonging to 9 genera (Fig. 7): *Candona neglecta* Sars, *Candoniella* sp., *Pseudocandona compressa* (Koch), *Pseudocandona marchica* (Hartwig), *Pseudocandona* sp. (pitted juvenile valves), *Cypridopsis vidua* (O.F. Müller), *Darwinula stevensoni* (Brady & Robertson), *Ilyocypris bradyi* Sars, *Ilyocypris gibba* (Ramdohr), *Ilyocypris salebrosa* Stepanaitys, *Ilyocypris* sp. (indefinable juveniles and/or fragments), *Juxilyocypris kempfi* Hajek-Tadesse, *Limnocythere inopinata* (Baird), *Limnocytherina* cf. *sanctipatricii* (Brady & Robertson), *Paralimnocythere psammophila* (Flössner). Core PB-1 showed greater species richness than core PB-2 (Figs. 8 and 9). The most abundant species are *C. neglecta*, *L. cf. sanctipatricii*, *L. inopinata*, *D. stevensoni*, *I. bradyi*, and *I. gibba*, although *C. neglecta* predominates all other species, with most samples containing more than 80% valves of *C. neglecta*. Although 15 species were recognized, individual cores show relatively low species diversity.

Additional macro- and microfossil remains include calcified parts of Charophyte algae (gyrogonites and thalli), gastropod shells, opercula and fragments (*Bithynia tentaculata*, *Valvata* sp., *Planorbis* sp.), bivalve (*Pisidium* sp.), and charcoal, Fe-Mn nodules, Ca-concretions, and spherulitic carbonate grains (aragonite). Charcoal was found in samples from zone I (very dark greyish brown clayey silt).

5. Discussion

5.1. Impact of basin morphology on paleoenvironmental interpretation

The paleoenvironmental data indicate that during the Holocene, the paleolake and Proložsko Lake are two morphologically different basins with different formation ages, as elaborated in Ivkić Filipović et al. (2025). Such morphological disparity implies there may have been different hydrological conditions in the two lake basins (Fig. 10), which will impact paleoenvironmental interpretation, mainly the stable isotope data.

Based on geomorphological characteristics of the area, the paleolake was a relatively shallow lake with a maximum possible lake depth of 10 m and an extension up to 270 m asl, which roughly corresponds to the modern flooding area of 2.5 km² (see flooding levels in Fig. 1) (Ivkić Filipović et al., 2025). Thus, the paleolake morphology resembles that of a shallow flat-floored lake basin with a relatively large surface area/volume ratio, meaning that evaporation most likely had a greater impact on its water balance (Fig. 10A). The main hydrological inputs into the paleolake were groundwater through the estavelles along the edges of the polje and direct rainfall on the lake's surface. Major outputs would have been sinks into the karstic underground and evaporation. The Suvaja River could also have had an impact. Interestingly, siliciclastic input in paleolake sediments during the carbonate sedimentation is less pronounced, and thus the river likely had no significant influence on water balance during this phase. Therefore, the paleolake can be considered a semi-closed lake system in which hydrology was mainly governed by groundwater inputs/outputs through the karst and

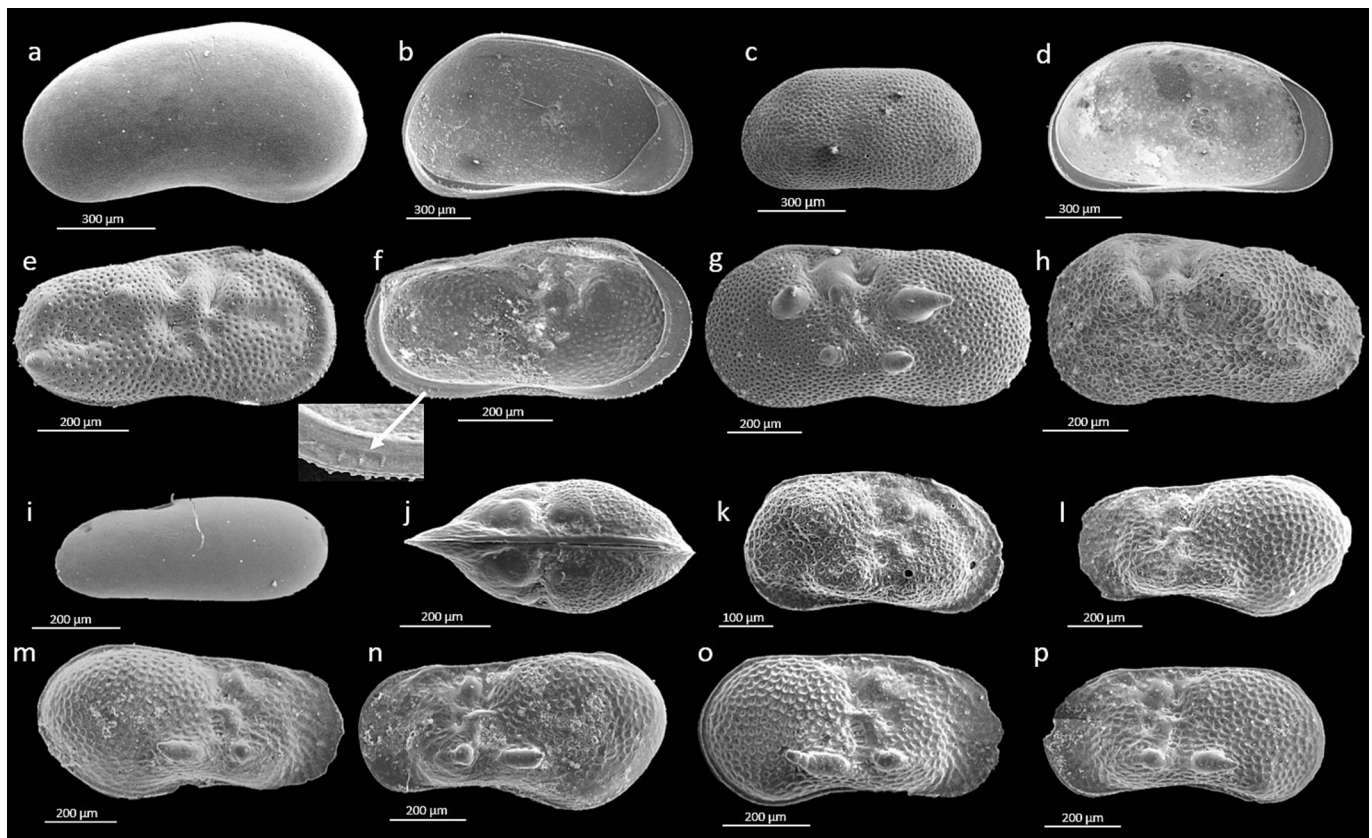


Fig. 7. SEM photos of Holocene ostracods from the Proložsko Blato lake sediments. (a) *Candona neglecta*, male left valve, external view; (b) *Pseudocandona marchica*, female left valve, internal view; (c) *Pseudocandona* sp. (juvenile); (d) *Pseudocandona compressa*, female right valve, internal view; (e) *Juxilyocypris kempfi*, female right valve; (f) *Ilyocypris bradyi*, female left valve, internal view with marked postero-ventral marginal rippled; (g) *Ilyocypris gibba*, female left valve, external view; (h) *Ilyocypris salebrosa*, female left valve, external view; (i) *Darwinula stevensoni*, female left valve, external view; (j) *Paralimnocythere psammophila*, female carapace, dorsal view; (k) *Limnocythere inopinata*, female right valve, external view; (l-p), *Limnocytherina* cf. *sanctipatricii*, male left valve without tubercles (l), male right (m) and left (n) valve with tubercles, female right (o) and left (p) valve with tubercles, external view.

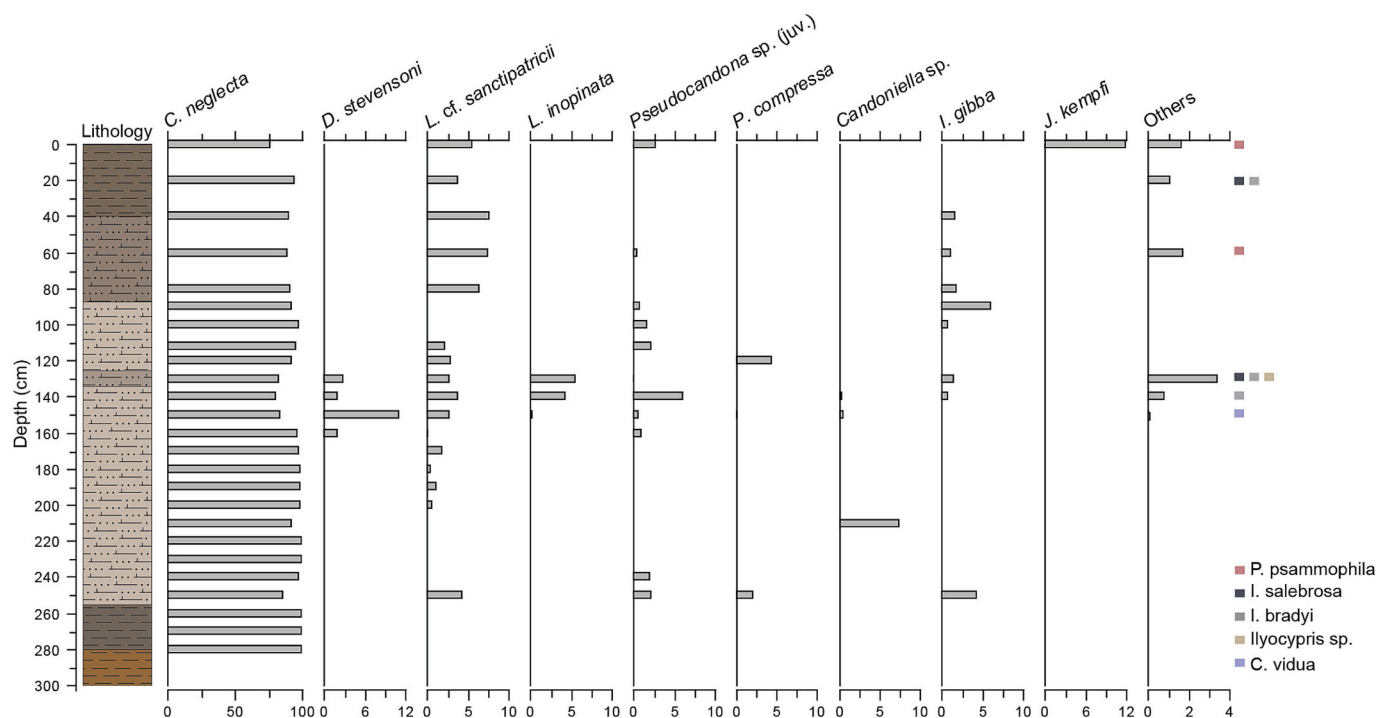


Fig. 8. Relative ostracod abundances in core PB-1. Others are represented by species with abundances of <5% (rare species) and unidentifiable (broken or juvenile) valves of *Ilyocypris*.

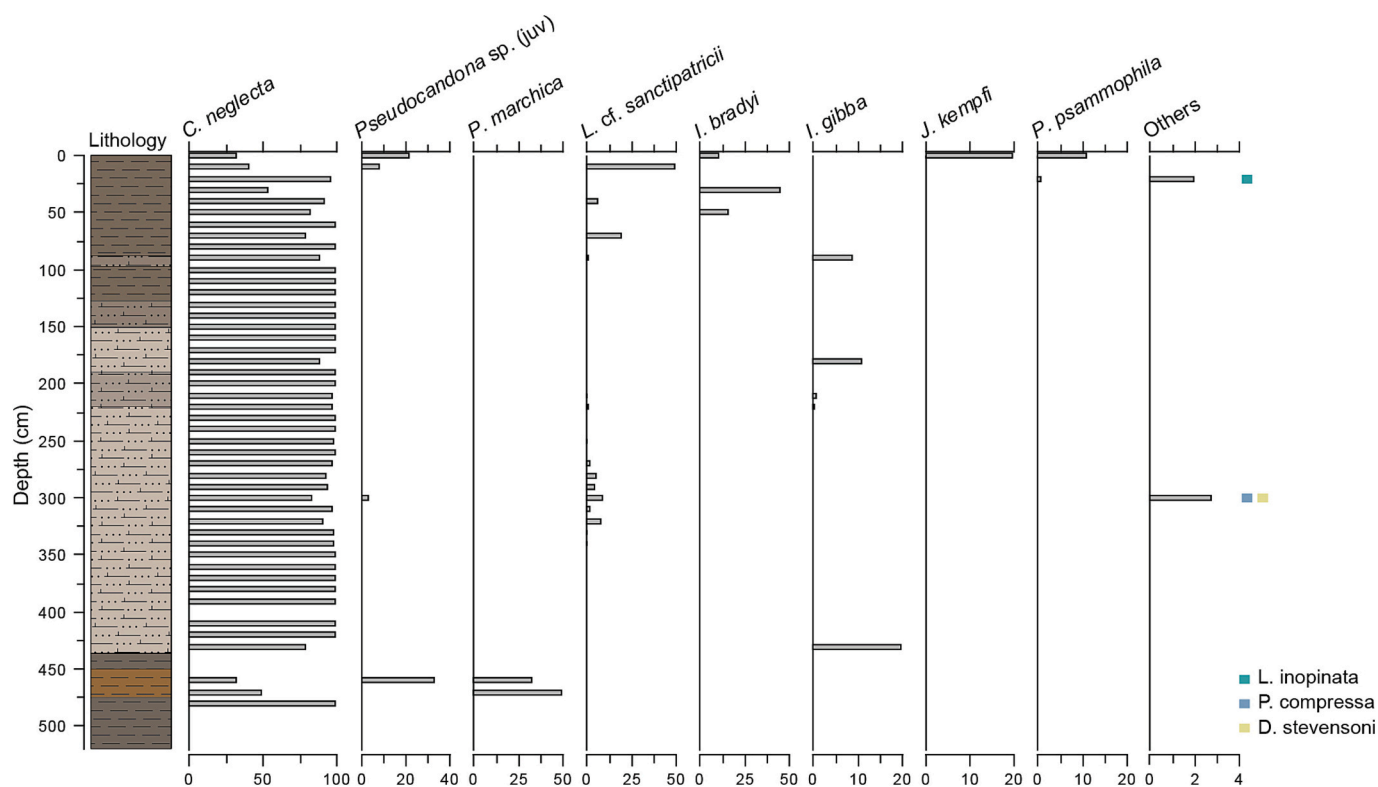


Fig. 9. Relative ostracod abundances in core PB-2. Others are represented by species with abundances of <5% (rare species).

precipitation/evaporation (P/E) ratio (Fig. 10A). A good analogue is the paleolake Kopais in central Greece, which was a shallow and flat-floored basin in karst before it was artificially drained. Here, the lake water balance was controlled by the inflowing rivers, outflow through marginal sinkholes (*katavothrae*), and evaporation (Griffiths et al., 2002).

Consequently, winter precipitation with more negative δ values would dilute the lake water during winter, whereas increased evaporation in summer would result in more isotopically evolved lake water (Griffiths et al., 2002). According to Ivkić Filipović et al. (2025), the paleolake disappeared around 800 cal yr BP presumably due to the sinkhole

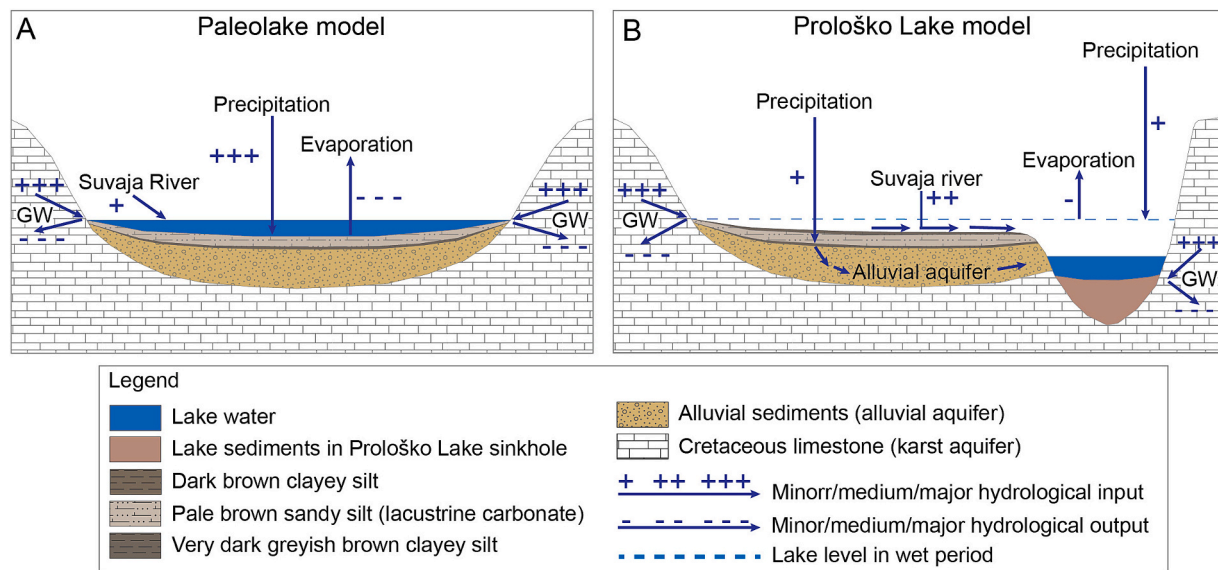


Fig. 10. A model of the paleolake versus Prološko Lake basin morphology and its effect on lake hydrology. For a more detailed evolution model, see [Ivkić Filipović et al. \(2025\)](#).

opening in its marginal part (Prološko Lake), which led to the formation of a modern, seasonally flooded karst wetland.

The Prološko Lake is a deeper sinkhole with a bowl-like morphology (Fig. 10B). It is, in fact, an estavelle, acting as a spring in winter and as a sink in summer, making the lake a major contributor of fresh groundwater for the present-day karst wetland. Our measurements of physical and chemical parameters show that the lake is seasonally stratified, with a thermocline sitting between 5 and 10 m (Table 1). The lake is predominantly fed by groundwater flowing through the limestone. Although dolomite occurs in the catchment, low Mg/Ca ratios (<1) (Table 3) imply minimal dolomite dissolution. Our measurements agree with earlier hydrogeological studies, which classify Imotsko Polje groundwater as Ca-HCO₃-type (Brčić et al., 2019). Modern stable isotope data confirm that the lake water closely reflects the isotopic signature of the surrounding groundwater, effectively the weighted mean of meteoric precipitation (Fig. 2), and any evaporation effect on the overall water balance is negligible. Similar observations were made in the Blue Lake near the city of Imotski, which is also a sinkhole filled with water (Bonacci et al., 2013). All other water inputs are meteoric, including direct rainfall onto the karst polje that infiltrates the alluvial aquifer feeding the Prološko Lake, and occasional inflow from the Suvaja River. Input from the alluvial aquifer via small springs in gravels on the Prološko Lake shores is minor, as evidenced by their different solute compositions (Table 3). The river's influence was greater before the construction of a dam in 1985, when flash floods at its mouth were documented (Ujević, 1991). After impoundment, the Suvaja was diverted to Prološko Blato through an artificial channel (Fig. 1). Because releases from the reservoir are sporadic, the river contribution is difficult to quantify without continuous monitoring, but it is probably subordinate to the karst groundwater. Given this substantial groundwater throughflow, Prološko Lake can be considered an open-system lake.

5.2. Proxy interpretation

The PCA analysis of selected major and trace elements revealed a clear separation of carbonate and siliciclastic components along axis PC1, and that calcium is predominantly related to the endogenic carbonate (Fig. 5). Hence, the Ca/Al ratio was used as a proxy for authigenic carbonate precipitation versus detrital input from the catchment. In general, a high Ca/Al ratio corresponds to zones II-IV (lacustrine carbonate), characterized also by low MS, TOC, and TOC/TN. On the

other hand, a low Ca/Al ratio corresponds to zones I (very dark greyish brown clayey silt) and V-VI (dark brown clayey silt), marked by elevated MS, TOC, and TOC/TN (Fig. 4).

Endogenic calcite is thought to be precipitated in the epilimnion in response to summer photosynthesis by lake algae, which leads to CO₂ decrease in surface waters and supersaturation with respect to calcite (Kelts and Hsü, 1978; Leng and Marshall, 2004). For equilibrium mineral precipitation, the $\delta^{18}\text{O}$ of the calcite mineral is controlled by the temperature and isotope composition of the lake water (Leng and Marshall, 2004). As the paleolake was relatively shallow, evaporation probably had a much greater influence on the isotopic composition of the lake water (see previous Section 5.1). Thus, the paleolake would be recharged in winter/spring through estavelles along the edges of the polje, while in summer it would be exposed to evaporation and groundwater outflow. Therefore, we can presume that the $\delta^{18}\text{O}_{\text{calcite}}$ record in the paleolake likely reflects regional hydroclimate change, that is, higher $\delta^{18}\text{O}_{\text{calcite}}$ reflects less winter recharge and/or more summer evaporation, and vice versa.

The $\delta^{13}\text{C}_{\text{calcite}}$ data reflect the $\delta^{13}\text{C}$ of the dissolved inorganic carbon (DIC) in the lake water, which is controlled by three main factors: the isotopic composition of inflowing waters, CO₂ exchange between the atmosphere and the lake water, and photosynthetic activity/respiration (Leng and Marshall, 2004). Inflowing groundwaters and river waters typically have lower $\delta^{13}\text{C}_{\text{DIC}}$ due to increased input of CO₂ derived from the oxidation of organic matter in soils (Leng and Marshall, 2004; Zanchetta et al., 2012). However, in karst regions, $\delta^{13}\text{C}_{\text{DIC}}$ values in groundwater can be much higher due to the dissolution of carbonate rocks, which usually have higher $\delta^{13}\text{C}$ values (Andrews et al., 1997). $\delta^{13}\text{C}_{\text{DIC}}$ can increase in lakes due to increased equilibration with the atmosphere, and also from increased lake productivity by preferential uptake of isotopically lighter CO₂ by aquatic plants during photosynthesis (Leng and Marshall, 2004). Therefore, lower $\delta^{13}\text{C}_{\text{calcite}}$ values in Prološko Blato paleolake could reflect increased input of CO₂ from soils, while higher $\delta^{13}\text{C}_{\text{calcite}}$ values could indicate increased equilibration between the atmosphere and lake water DIC, increased productivity, and more groundwater recharge from surrounding karst springs (estavelles).

Detrital carbonates in lake sediments pose a significant challenge when interpreting stable isotope data from bulk samples, particularly in karstic regions. Therefore, their relative contribution must be assessed before interpreting stable isotope data (Leng et al., 2010a). In this

regard, we note that: 1) SEM analysis showed that bulk samples are composed predominantly of prismatic (endogenic) calcite and their aggregates (Fig. 3), without significant detrital contribution; 2) periods with elevated TIC are also marked by very low MS (zones II–IV), indicating low in-wash from the catchment which would bring detrital components (Fig. 4); 3) the $\delta^{18}\text{O}_{\text{calcite}}$ vs. $\delta^{13}\text{C}_{\text{calcite}}$ biplot shows limited mixing trends (limited to just three samples) between the isotope composition of lake carbonate and catchment limestones (Fig. 6), suggesting that our $\delta^{18}\text{O}_{\text{calcite}}$ signal comes predominantly from endogenic carbonates. However, the topmost three samples from the sediment core deviate from bulk lacustrine carbonate towards the limestones, suggesting some detrital carbonate contamination in zone VI. The origin of spherulitic aragonites, which are most abundant between 430 and 350 cm (7800–5550 cal yr BP), remains uncertain, but their morphology suggests rapid growth on the substrate, potentially associated with microbial mats (Ge et al., 2021). Interestingly, there is a negative

correlation between the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in the spherulitic aragonite, which suggests that other, more local processes controlled the lake water DIC, thus reflecting microenvironmental conditions during aragonite precipitation. While a minor contribution from spherulitic aragonites cannot be entirely excluded, as residual needle-like fragments remained in the $<80\ \mu\text{m}$ fraction after the sieving, these precipitates reflect authigenic components formed under similar lacustrine conditions. Consequently, any such mixing reflects internal lake variability, in contrast to external contamination from limestone catchment, which can lead to fundamental misinterpretation of the paleohydrological record (e.g., Leng et al., 2010).

5.3. Paleoenvironmental and paleoclimatic interpretation

5.3.1. Early – Middle Holocene (520–436 cm; 9700–8000 cal yr BP)

The paleolake sequence starts with very dark greyish brown clayey

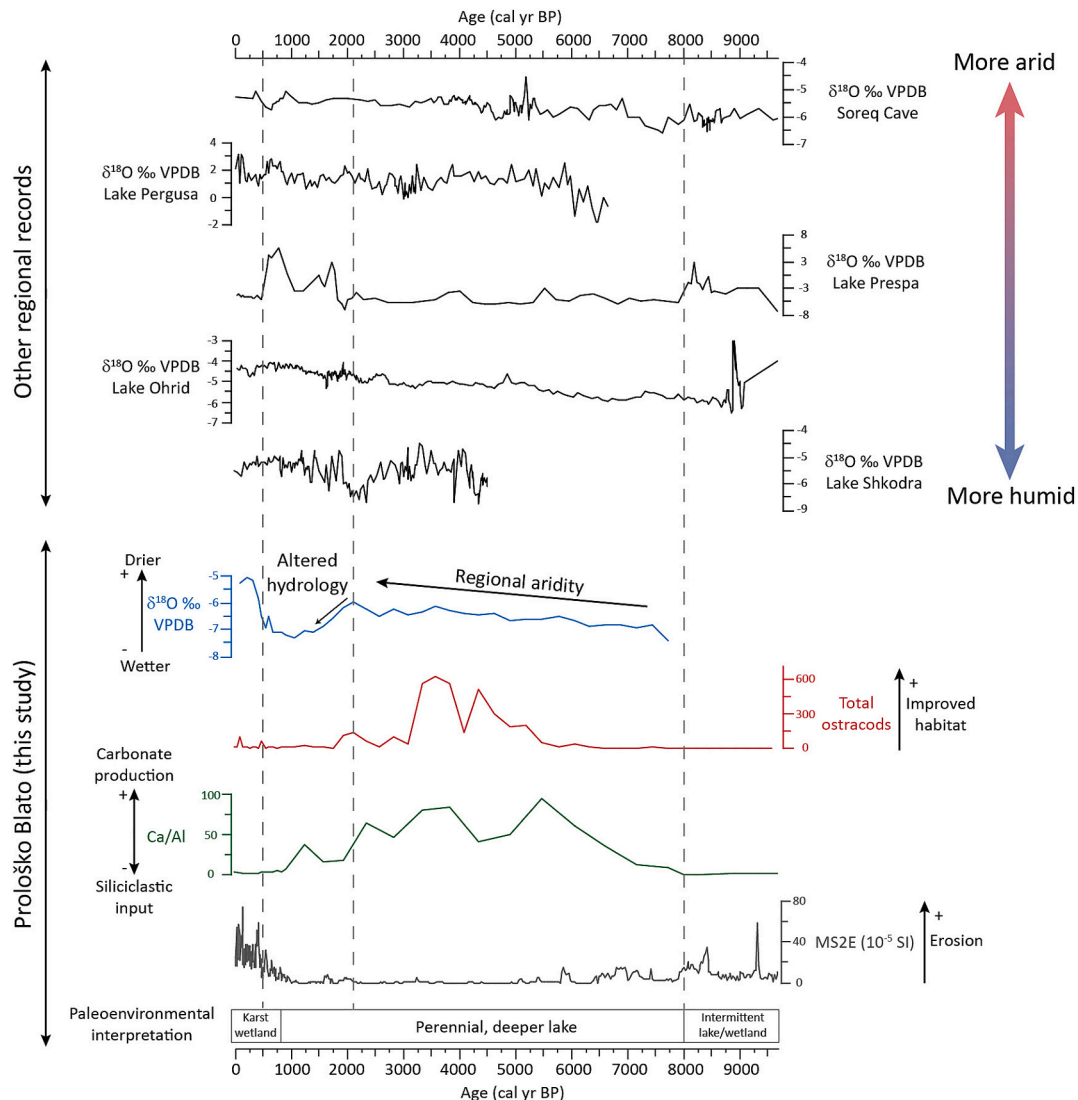


Fig. 11. Selected proxies from lake sediments in Prološko Blato and their comparison with other records from the Mediterranean region (Lake Shkodra, Zanchetta et al., 2012; Lake Ohrid, Lacey et al., 2015; Lake Prespa, Leng et al., 2013; Lake Pergusa, Zanchetta et al., 2007b; Soreq Cave, Bar-Matthews et al., 2003). $\delta^{18}\text{O}_{\text{calcite}}$ is missing between 9700 and 8000 cal yr BP due to low carbonate content, although wetter conditions can be inferred from higher erosional input (higher MS, lower Ca/Al). During the Middle-Late Holocene (8000–2100 cal yr BP), higher Ca/Al, lower MS, and the highest ostracod content indicate formation of a deeper lacustrine environment with endogenic carbonate production and decreased run-off. The $\delta^{18}\text{O}_{\text{calcite}}$ progressively increases, suggesting increased aridity in line with other regional records. Note a distinct wet phase between 2100 and 500 cal yr BP, as indicated by a sudden shift to more negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values. This phase contrasts sharply with regional records, which generally indicate warm and dry conditions during this interval. The discrepancy suggests a strong influence of local factors (karst processes) on the stable isotope hydrology. Increased MS in the last 500 years corresponds to intensified agricultural activity and siliciclastic input from the catchment. The MS values are taken from Ivkić Filipović et al. (2025). The $\delta^{18}\text{O}$ data for Prološko Blato are provided by BGS © UKRI 2026.

silt (Zone I) characterized by relatively high magnetic susceptibility (MS), TOC, TN, and TOC/TN (Fig. 11). In contrast, Ca/Al and TIC are comparatively low (Fig. 4). Due to very low carbonate content, stable isotope analyses were not done in this interval. Nonetheless, elevated MS and TOC/TN values indicate enhanced detrital input from the catchment (Meyers and Teranes, 2001; Sandgren and Snowball, 2002). Ostracods are almost absent in this zone, with very few juveniles of *C. neglecta*, while gastropods are abundant, yet fragmented, suggesting dynamic conditions. All the evidence stated above implies an early stage of the paleolake development, likely an intermittent lake/wetland, in agreement with earlier interpretation based on a sedimentological approach (Ivkić Filipović et al., 2025).

During the Early-Middle Holocene, most central and eastern Mediterranean lakes are characterized by low $\delta^{18}\text{O}$ (e.g., Eastwood et al., 2007; Frogley et al., 2001; Lacey et al., 2015; Roberts et al., 2001) associated with generally warmer and wetter climatic conditions. Similarly, a shift to lower $\delta^{18}\text{O}$ values is observed in speleothem records, which coincides with the formation of sapropel S1 in the Mediterranean (Ariztegui et al., 2000; Bar-Matthews et al., 2000; Zanchetta et al., 2007). Wetter climate conditions during the Early-Middle Holocene are furthermore recognized in marine and lake sediment records and speleothems from the Adriatic region (e.g., Brunović et al., 2020; Combourieu-Nebout et al., 2013; Razum et al., 2021; Schmidt et al., 2000; Smrkulj et al., 2025; Ilijanić et al., 2024, 2025; Surić et al., 2025), in the close vicinity of our study site. However, our data demonstrate that a deeper lacustrine environment in Prološko Blato has not yet been established at this time, which is at odds with the maximum lake levels recognized in the central Mediterranean (e.g., Magny et al., 2011; Marchegiano et al., 2018). This implies that other non-climate-related processes may have played a role and that alternative explanations should be sought to explain the observed disparity in lake levels under the same climatic conditions. One likely solution lies in the peculiar geomorphological and hydrogeological features of karst poljes, primarily karst springs and estavelles, situated along the edges of these enclosed depressions. Dinaric karst poljes are typically flooded from autumn to late spring, when the groundwater level rises and/or when the inflow exceeds the maximum capacity of the ponors (Bonacci, 2013). Due to these features, permanent lake conditions could not be established until a sufficient amount of impermeable material (clays) was deposited, which would clog the ponors and enable impounding of a deeper water body. Our proxy data (low carbonate, high MS, high TOC/TN, absence of ostracods) suggest such sealing had not yet occurred during the Early Holocene. It is worth mentioning that this disparity in low lake levels has already been documented in other karst lakes in the Dinarides. For example, the discrepancy between the lake level low stand and the humid period was first recognized in Bokanjčko Blato near Zadar in Dalmatia (Ilijanić et al., 2018), as well as in shallow lake Vrana near Biograd (Hajek-Tadesse et al., 2018a). An alternative explanation could be that our study site, located more inland compared to Bokanjčko Blato and Lake Vrana, was susceptible to cold northern air mass incursions, similar to those documented at Lake Ohrid during the Early-Middle Holocene. At Lake Ohrid, this interpretation was inferred from the ice-rafted debris in the sediment core (Vogel et al., 2010), as well as low primary productivity and carbonate precipitation, and higher $\delta^{13}\text{C}_{\text{organic}}$, possibly related to the lower input of soil-derived carbon into the lake (Lacey et al., 2015). Increased aridity was also inferred from pollen reconstructions, however, centred around the “8.2 ka event”, in Lake Maliq in southern Albania (Bordon et al., 2009), in Tenaghi Philippon in northeastern Greece (Pross et al., 2009; Peyron et al., 2011), and in Lake Prespa (Panagiotopoulos et al., 2013). Cold and dry conditions could have promoted low lake levels in Prološko Blato, as less winter precipitation (mainly snow) in the mountains of western Bosnia and Herzegovina would lead to less groundwater supply to the surrounding poljes, including Imotsko Polje. However, if winter precipitation was indeed low, the erosional input from the catchment would be low as well (lower MS, lower siliciclastic input, lower TOC/TN), in

contrast to our proxy record (Fig. 11). Based on these evidences we argue that cold northern air mass incursions are not the cause of the observed low lake levels in Prološko Blato during the Early Holocene. This argument is further supported by the results of a previously published study, where the presence of redoximorphic features (Fe-Mn nodules, Ca concretions) was documented in the very dark greyish brown clayey silt (Ivkić Filipović et al., 2025), which were also observed in this study in sieved samples during the ostracod analysis. An oxidized layer of clayey silt between 450 and 460 cm (Fig. 3) further indicates shifts in redox conditions during the early lake phase. Such features are strong indicators of seasonally saturated soils and fluctuating water tables (Gasparatos et al., 2019; Vepraskas and Vaughan, 2016). Frequent changes in redox conditions likely created an unstable benthic environment, which could explain the absence of ostracods in this interval (Fig. 11). The occurrence of charcoal, likely from natural wildfires rather than anthropogenic sources, suggests fire-prone climatic conditions, such as dry and warm summers (Peyron et al., 2011; Vannière et al., 2011). Overall, our proxies are consistent with a generally wetter Early Holocene but with substantial landscape instability that increased clastic supply.

5.3.2. Middle – Late Holocene (436–220 cm; 8000–2100 cal yr BP)

This period is characterized by deposition of pale brown sandy silt, termed as lacustrine carbonate (Zones II–IV). In contrast to Zone I, lacustrine carbonate has low values of MS, TOC, TN, and TOC/TN, while Ca/Al and TIC are higher (Fig. 11), thus indicating abundant carbonate production within the lake, with limited siliciclastic supply. The TOC/TN ratio is generally low (TOC/TN $\approx$ 12) during this period compared to the rest of the core, suggesting both algal- and land-derived organic matter (Meyers and Teranes, 2001). There is a distinct lithological change between zones I and II, especially in terms of color and grain size (from very dark greyish brown clayey silt to pale brown sandy silt). However, a more gradual decrease of TOC, TN, and MS between 436 and 350 cm suggests a progressive environmental change during the early Middle Holocene. This transition is probably related to the sealing of ponors and lake deepening following unstable conditions during the Early Holocene (zone I).

The ostracod record is interesting from the aspect of paleolimnology, as it shows a clear domination of one species, *Candona neglecta*, in both sediment cores (Figs. 8 and 9), which is adapted to wide ranges of habitats and environmental conditions (Meisch, 2000; Wysocka et al., 2000). They prefer relatively cold waters, so they are widespread in springs, as well as ponds and brooks connected to the springs (Meisch, 2000). *C. neglecta* is one of the dominant species in Pyrenean springs (Mezquita et al., 1999; Roca and Baltanás, 1993) and helocene springs from Turkey (Külköylüoğlu and Yılmaz, 2006), but is also common in karstic Lake Banyoles in Spain (Rieradevall and Roca, 1995). In Croatia, *C. neglecta* is the most abundant species of Dinaric karst poljes (Sokač, 1975) and is often found in lake sediments situated along the Adriatic Coast, e.g., in Lake Vrana near the city of Biograd (Hajek-Tadesse et al., 2018a), in Bačina Lakes (Hajek-Tadesse et al., 2017; Hajek-Tadesse et al., 2019), in the lakes of Mljet Island (Hajek-Tadesse, 2011, 2013), as well as in Velo Blato on Pag Island (Ivkić Filipović et al., 2026), Lake Visovac in the National Park Krka, and Bribir-Ostrovica paleolake in the Dalmatian hinterland (Ivkić Filipović, unpublished data). These findings suggest that *C. neglecta* in the Dinarides thrives in oligotrophic karst lakes connected to springs, where water temperature is balanced via groundwater discharge. In sediment core PB-1, taken where we presumed a shallower paleolake (Fig. 1), *C. neglecta* is accompanied mostly by *D. stevensoni*, *L. cf. sanctipatricii*, and *L. inopinata* (Fig. 8). *D. stevensoni* is a well-known parthenogenetic species that occurs in a wide range of habitats, such as ponds, lakes, and slow streams (Meisch, 2000). It occurs in waters less than 8 m (but more often less than 3 m) deep, probably due to elevated oxygen requirements needed to brood-pouch its young (Griffiths and Holmes, 2000). Moreover, the species does not tolerate seasonal desiccation (Griffiths and Butlin, 1994), which

confirms that this part of the paleolake was relatively shallow and well-oxygenated, but more importantly, that the paleolake was a permanent water body during this period. This is also confirmed by the presence of *L. cf. sanctipatricii*, an indicator species of oligotrophic lake environments (Namiotko et al., 2012), as well as by the presence of *L. inopinata*, a typical species of the lacustrine littoral zone (Griffiths and Holmes, 2000). In sediment core PB-2, taken in the presumed deeper paleolake (Fig. 1), there is almost exclusive dominance of *C. neglecta* (Fig. 9), which could indeed be due to a greater water depth (>3 m) at the core location. A clear dominance of one species (*C. neglecta*) in both sediment cores is unclear, but we propose that the paleolake was characterized by low nutrient status and poor habitat availability, as inferred from very low TOC and TN content, as well as lower contribution of terrestrial organic detritus (lower TOC/TN) (Fig. 11).

Overall, the period between 8000 and 2100 cal yr BP marks a relatively shallow (but deeper than between 9700 and 8000 cal yr BP), oligotrophic lake environment with enhanced carbonate production. $\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$ record display an increasing trend during the Middle to Late Holocene, with a strong positive correlation ($r = 0.8$, $p < 0.05$), suggesting similar driving mechanisms for both isotopes (Li and Ku, 1997; Talbot, 1990). In summers, when part of the lake water outflows via the underground karst, lake volume decreases and evaporation is high, there is preferential loss of lighter ^{16}O and ^{12}C into the atmosphere, resulting in higher $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of the lake water. Thus, the progressively increasing trend in both $\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$ likely indicates a progressive decrease in the lake volume. This general 'aridification' trend broadly corresponds to the increasing aridity seen in other Mediterranean lacustrine and non-lacustrine records (Zanchetta et al., 2012, 2022; Lacey et al., 2015; Leng et al., 2013; Bar-Matthews et al., 2003), although there is higher variability in the $\delta^{18}\text{O}_{\text{calcite}}$ record from the Lake Prespa due to site-specific variations (Leng et al., 2013). These trends fit well with the overall aridification trend of the Mediterranean suggested by climate models (Brayshaw et al., 2011) and with a synthesis of Mediterranean paleoclimate proxy data (lacustrine, marine, speleothem) (Finné et al., 2019). The aridification in the Adriatic region is inferred from pollen-based reconstructions from a marine core from the southern Adriatic Sea, which documented decreasing summer and increasing winter precipitation after 6000 cal yr BP, suggesting the onset of Mediterranean climate conditions (Combouret-Nebout et al., 2013). The region experienced the highest summer rainfall between 8000 and 7000 cal yr BP, resulting in permanent moisture throughout the year (Combouret-Nebout et al., 2013). Such conditions could have increased recharge in the karst and formation of a deeper, permanent lake environment in Prološko Blato at around 8000 cal yr BP.

5.3.3. Late Holocene (220–0 cm; 2100 cal yr BP – modern period)

Progressive aridity during the Middle to Late Holocene was interrupted by a change in hydrological balance, corresponding to a lithological shift from pale brown lacustrine carbonate (zone IV) to dark brown clayey silt (zone V) around 800 cal yr BP (Figs. 3 and 4). Decreasing $\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$ correspond to decreasing TIC and Ca/Al, while MS, TOC, and TN increase (inwash). Together, these changes suggest a significant shift in environmental conditions. Earlier research based on geomorphology, sedimentology, and geophysics linked the lithological change to the opening of a sinkhole, which led to the transformation of a permanent paleolake into a seasonally flooded karst wetland (Ivkić Filipović et al., 2025). Although the true timing of the subsurface collapse remained uncertain, Ivkić Filipović et al. (2025) argued that the sinkhole opening could have been gradual and that the permanent paleolake conditions could not be established if the large sinkhole already existed in its marginal part, since it would lead to seasonal desiccation as it does today. Alternatively, a large sinkhole may have pre-existed and become clogged with sediment during the paleolake phase, thereby preventing seasonal desiccation, and was later reactivated, for example, by a new subsidence (Ivkić Filipović et al., 2025). Both cases would result in a new hydrological input from karst,

which could explain the significant shift to lower $\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$ (Fig. 11). Another possibility could be changes in the intensity of recharge in the Herzegovinian mountains, which would presumably lead to higher lake levels, in contrast to seasonal desiccation found in this study.

The $\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$ data presented here suggest that the hydrological change was rapid and started earlier (around 2100 cal yr BP) than the lithological change at around 800 cal yr BP, corresponding to the Roman Warm Period. The decrease in $\delta^{18}\text{O}_{\text{calcite}}$ between 2100 and 500 cal yr BP, with a minimum at ca. 1000 cal yr BP, contradicts a clear drying trend between 2000 and 500 cal yr BP recorded in other lakes and speleothems in the Mediterranean region (Fig. 11). For example, driest conditions and probably very low lake levels were recorded in Lake Prespa during this period (Leng et al., 2013). In Lake Shkodra, the main wet interval occurred between 2500 and 2000 cal yr BP (Zanchetta et al., 2012), starting earlier and lasting for a shorter duration than in Prološko Blato. In the Adriatic region, this interval encompasses the Roman Warm Period and the Medieval Warm Period, both characterized by warm and dry climatic conditions (Piva et al., 2008; Rudzka et al., 2012). Overall, our regional comparison reveals no clear correlations between the prominent wet phase in Prološko Blato (2100 and 500 cal yr BP) and other Mediterranean paleoclimate records. Instead, it indicates anticorrelation, suggesting a significant influence of local processes on lake hydrology.

Aside from natural karst processes, major human interventions in the catchment may have also led to changes in the paleolake hydrology, particularly those aimed at increasing the size of arable land, a common practice in flooded karst poljes. However, there are no historical records of major modifications of karst hydrology during the Roman times. Deforestation in the catchment is also less plausible since the wider region is characterized by a barren karst landscape. The only recorded modifications in the Prološko Blato are related to the 16th-century Franciscan monastery, whose remains are found on the isolated hill (Manastir) in the northern part (Fig. 1). According to local folklore, the Franciscans used to bury the ponors with leather and wood around the edges of Prološko Blato to prevent seasonal desiccation, which served as a protection from the Turkish attacks (Ujević, 1991). However, this suggests that the seasonal flooding was already established during the Medieval times. Therefore, the available evidence points to a significant hydrological change, likely controlled by geomorphological processes in karst.

The hydrology of the modern karst wetland is dependent on the groundwater input/output through the Prološko Lake sinkhole and estavelles along the edges of the polje (Fig. 10B), which occurs seasonally, and so we infer a short residence time for the lake water. The $\delta^{18}\text{O}_{\text{calcite}}$ data in the uppermost zone VI should reflect the recharge water, hence regional precipitation over the lake catchment. A good modern analogue is the karstic Lake Shkodra at the boundary between Albania and Montenegro, with its short residence time and its recharge by sublacustrine springs (Zanchetta et al., 2012). Assuming that carbonate precipitation occurs in the epilimnion during summer when algal productivity is highest, calcite precipitated in isotopic equilibrium with lake water ($\delta^{18}\text{O} = -4.2\text{‰}$, $T = 17.6\text{ °C}$) would have a $\delta^{18}\text{O}_{\text{calcite}}$ value of around -5‰ (using Leng and Marshall (2004) modification of the equation from Kim and O'Neil (1997)). This is very similar to the $\delta^{18}\text{O}_{\text{calcite}}$ values from the upper part of the sediment core (last 500 years), which are the highest values recorded during the Holocene. Thus, the last 500 years probably reflect modern water conditions. Flooding in Prološko Blato occurs during the winter months, and the entire area turns into a shallow wetland, which remains flooded into late spring or even summer (July/August). Thus, the lake water could initially have lower $\delta^{18}\text{O}$ values, but the subsequent exposure of the shallow, stagnant wetland to high summer temperatures could lead to higher evaporation. In addition, detrital carbonate (limestone) could also have contributed to the bulk carbonate content, as evidenced by the highest MS values in the last 500 years, as evidenced by mixing of

isotopic compositions between limestone and lake carbonates (Fig. 6). A general increase in MS, lithogenic elements, TOC, TN, as well as Pb, Zn, Cu, and P coincides also with the intensified agricultural activity in Imotsko Polje during the Medieval times and frequent flash floods from the Suvaja river in the modern period (Ujević, 1991).

Although the ostracod community is still dominated by *C. neglecta*, its relative proportion starts to decline during this time as more species appear, most notably *Ilyocypris bradyi*, *Juxilyocypris kempfi*, and *Paralimnocythere psammophila* (Fig. 9). *Ilyocypris bradyi* prefers springs and water bodies connected to springs, while in lakes, they are usually discharged from nearby springs (Meisch, 2000). For example, in Lake Ohrid, *I. bradyi* was found in the littoral zone near the springs (Lorenschat et al., 2014), and in the eastern Iberian Peninsula, it was found in the bicarbonate-rich springs associated with a wetter climate and limestone bedrock and characterized by relatively low water temperature and low mineralisation (Mezquita et al., 1999). Ecological preferences of *P. psammophila* are poorly determined, although it is reported that the species was found in the littoral zone of several lakes where it colonized sandy substrates and the algal mats on stones (Flössner, 1965; Meisch, 2000). It was also found in a small temporary freshwater pool with mud cracks at the bottom, which suggests desiccation, meaning that the species can produce drought-resistant stages (Smith and Horne, 2004). This shift in ostracod assemblages further supports the environmental change from a permanent paleolake to a seasonally flooded karst wetland. This newly developed karst wetland was likely nutrient-enriched, as suggested by rising TOC and TN values (Fig. 4), which could explain changes in relative ostracod abundances. The occurrence of *Juxilyocypris kempfi* in this period is a peculiarity, since it is considered a cold climate indicator, described for the first time in the transitional Late Pleistocene-Holocene sedimentary sequence of coastal lake Vrana and Pirovac Bay on the Eastern Adriatic Coast in Croatia (Hajek-Tadesse, 2018b). Specimens of *Juxilyocypris kempfi* in the Proložko Blato paleolake are found only in the topmost part of sediment cores (samples 0–1 cm), which suggests that this is the youngest find of this species so far. Additional sampling for possible living forms is needed to confirm this finding and to exclude possible redeposition from the older sediment. The confirmation of living representatives could open a new question about the species' survival at the Pleistocene-Holocene transition, such as the possibility of utilizing karst environments (e.g., caves and springs) to avoid extinction, as Dinaric karst, with its extensive network of subterranean drainage, offers stable environmental conditions during climate upheaval and thus is considered an important refugia (Karanovic and Petkovski, 1999; Kurečić et al., 2022).

6. Conclusion

The lake sediments from the Proložko Blato karst wetland provided a new Holocene hydroclimate record from the underexplored Dinaric region. We demonstrated that karst poljes present a valuable paleoenvironmental archive in otherwise barren karst terrains. However, care must be taken when interpreting the stable isotope records from endogenic carbonates in karst lakes, as karstification processes, such as the opening of new sinkholes, springs, and ponors, can lead to hydrological disturbances and affect the paleoclimate interpretation. For example, in Proložko Blato, a significant decrease in $\delta^{18}\text{O}_{\text{calcite}}$ and $\delta^{13}\text{C}_{\text{calcite}}$ between 2100 and 500 cal yr BP suggests a sudden wetter condition in the lake, corresponding to the warm and arid Roman and Medieval Warm Period. This shift could have been wrongly interpreted as a contrasting pattern in the climate during that time, which would complicate comparisons with other Mediterranean records. In addition to karst processes, contamination of bulk lake sediments by detrital carbonates must be assessed using SEM, MS, and stable isotope analysis of rocks, as it can lead to fundamental misinterpretation of hydrological records in Dinaric karst lakes.

CRediT authorship contribution statement

Ivona Ivkić Filipović: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nikolina Ilijanić:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Slobodan Miko:** Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Melanie J. Leng:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Jack H. Lacey:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Valentina Hajek-Tadesse:** Writing – review & editing, Validation, Supervision, Methodology. **Tamara Marković:** Writing – review & editing, Resources, Investigation, Formal analysis. **Martina Šparica Miko:** Writing – review & editing, Resources, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Stable isotopes in calcite (Original data) (Zenodo)

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8. BIOGRAPHY OF THE AUTHOR

Ivona Ivkić Filipović was born on October 7, 1992, in Vinkovci, Croatia. She attended elementary school and high school at the General Gymnasium in Županja. In 2011, she began her undergraduate studies in Geology and Geological Engineering at the Faculty of Mining, Geology, and Petroleum Engineering, University of Zagreb, and graduated in 2014. She continued her graduate studies in Geology at the same Faculty, graduating in 2017. Afterward, she pursued her interests in geology and science, starting to volunteer at the Croatian Geological Survey. There, she worked on sample preparation of marine and lake sediment cores from the eastern Adriatic coast and developed an interest in paleoenvironmental sciences. In 2018, she received a doctoral scholarship from the Faculty of Mining, Geology and Petroleum Engineering and enrolled in the PhD program in Geology. In 2019, she was employed at the Croatian Geological Survey as a senior technician and later advanced to senior expert associate, working on various scientific, EU, and commercial projects in the Department for Mineral Resources and Marine Geology. During her doctoral studies, she expanded her professional expertise through numerous courses and training programs at several European universities and research institutes, including coursework in geometric morphometrics at the Faculty of Biology, University of Belgrade, participation in the European School on Ostracoda at the University of Jena, and specialization in stable isotope analysis of lake carbonates and ostracods at the Stable Isotope Facility of the British Geological Survey (Nottingham), and speleothem calcite at the Max Planck Institute for Chemistry (Mainz). So far, she has published 8 scientific papers and participated in numerous workshops and congresses, including the 6th and 7th Croatian Geological Congress, the Regional Scientific Meeting on Quaternary Geology: Seas, Lakes, and Rivers, INQUA Roma 2023, as well as the IAS Meeting of Sedimentology in Dubrovnik in 2023, where she also volunteered in the meeting organization.

List of published papers:

- Ilijanić, N., **Ivkić Filipović, I.**, Miko, S., Hajek-Tadesse, V., Šparica Miko, M., McClure, S., Kennett, D., Sladović, Ž., Podrug, E. (2026). Holocene paleolake evolution of the Bribir-Ostrovica karst polje (Dalmatia, Croatia): A multi-proxy lake sediment record. Quaternary. <https://doi.org/10.3390/quat9040048>.
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